Full title:

Distinct causal influences of dorsolateral prefrontal cortex and posterior parietal cortex in multiple-option decision making

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Brief running title:

Causal roles of prefrontal and parietal cortices in multiple-option decision making

Abstract

Our knowledge about neural mechanisms underlying decision making is largely based on experiments that involved few options. However, it is more common in daily life to choose between many options, in which processing choice information selectively is particularly important. The current study examined whether the dorsolateral prefrontal cortex (dlPFC) and posterior parietal cortex (PPC) are of particular importance to multiple-option decision making. Sixty-eight participants received anodal high definition-transcranial direct current stimulation (HD-tDCS) to focally enhance dlPFC or PPC in a double-blind sham-controlled design. Participants then performed a multiple-option decision making task. We found longer fixations on poorer options were related to less optimal decisions. Interestingly, this negative impact was attenuated after applying anodal HD-tDCS over dlPFC, especially in choices with many options. This suggests that dlPFC has a causal role in filtering choice-irrelevant information. In contrast, these effects were absent after participants received anodal HD-tDCS over PPC. Instead, the choices made by these participants were more biased towards the best options presented on the side contralateral to the stimulation. This suggests PPC has a causal role in value-based spatial selection. To conclude, the dlPFC has a role in filtering undesirable options, whereas the PPC emphasizes the desirable contralateral options.

Keywords: decision making, dorsolateral prefrontal cortex, multiple option, non-invasive brain stimulation, parietal cortex

Decision making in everyday life involves choosing among a large number of options, i.e. multiple-option decision making. This is the case not just for important decisions, such as career selection, but often for apparently trivial decisions, such as grocery selection. Due to limited cognitive capacity, it is difficult to process information relating to all possible choices simultaneously. Although a considerable amount is known about the general neural mechanisms underlying decision making, much of this knowledge was obtained from experiments in which participants were offered only a few options. For example, when an option is presented alone or in the presence of only a few alternatives, signals that reflect the value of the option can be found in various regions in the prefrontal cortex (PFC) (Chau et al. 2014, 2018; Hunt et al. 2018; Juechems and Summerfield 2019). Recent neurophysiology data also suggested that similar PFC regions also contain signals that guide the sampling of choice information, at least by guiding gaze patterns (Akaishi and Hayden 2016; McGinty et al. 2016; Rich and Wallis 2016). However, one pressing issue is that, compared to similar decisions with smaller choice sets, the amount of choice information is much greater in many cases of multiple-option decision making. When there are plenty of options, it is unclear whether and how additional neural mechanisms identify and use information pertaining to particularly important options to guide decision making. The current study focuses on investigating the dorsolateral prefrontal cortex (dlPFC) and posterior parietal cortex (PPC), two strongly connected regions that are often associated with attentional processes, working memory and cognitive control.

DlPFC could be critical to multiple option decision-making. In neuroimaging studies, although decision-related signals are not reliably found in the dlPFC, these signals are particularly robust in experiments that involve the presence of information that is irrelevant to the decisions. For example, dlPFC activity was correlated with the value of the choices when participants were asked to select healthy food rather than unhealthy but tasty food and also with the overall value of all options during multiple-option decision making (Hare et al. 2009; Hutcherson et al. 2012; Reutskaja et al. 2018). While learning about an option's value, the activity of an anterior dlPFC region is related to the suppression of irrelevant reward information (Scholl et al. 2015). In addition, patients with dlPFC

lesions are more easily distracted by information that is irrelevant to their choices and often misuse such information to guide their decisions (Vaidya and Fellows 2016). During decision making, it is important to focus on information related to better options and ignore information related to poorer options. Thus, it is possible that the dlPFC is particularly important for determining attentional focus onto decision-related information from the most important options during multiple-option decision making. In addition, if the dlPFC can be enhanced using non-invasive brain stimulation methods, such as high definition-transcranial direct current stimulation (HD-tDCS), it can potentially improve decision making by reducing distractions from irrelevant options.

PPC, which is strongly connected to dlPFC (Dima et al. 2014), is also an important region for decision making. Neurophysiology data showed that when monkeys are choosing between two options, PPC neurons accumulate evidence associated with the choice of an option presented in their receptive field, which is often in a space contralateral to the neurons (Platt and Glimcher 1999; Shadlen and Newsome 2001; Dorris and Glimcher 2004; Sugrue et al. 2004). Reversible inactivation of unilateral PPC in macaques has been reported to impair decision making when choice information was presented in the contralateral visual field (Zhou and Freedman 2019). However, there has been considerable debate about whether or not PPC guides decision making and there are two alternative views of the precise function of PPC. One view argues that PPC is central not to decision making but to a post-decisional process, such as spatial selection. For example, in the study by Katz and colleagues (Katz et al. 2016), despite the identification of decision-related activity in PPC neurons, inactivation of the PPC did not cause impairment in decision making in monkeys. Impairment was only observed when they performed another task that required accurate oculomotor response towards a remembered position, suggesting that the PPC is involved in precise spatial selection of a particular location rather than the initial decision about where to look. Another view suggests that the PPC encodes option salience rather than value (Leathers and Olson 2012; Chen et al. 2020). Since the debate mainly involves evidence from monkeys rather than humans, experiments that involve stimulation of the PPC in humans are critical for understanding PPC function.

The current study revealed dissociable causal roles for both dlPFC and PPC in multiple-option decision making. Our results provide causal evidence suggesting that the dlPFC has a role in filtering choice-irrelevant information relating to options that were particularly poor in value, thereby making it possible to focus on the most important decision options. In contrast, the PPC has a causal role in value-based spatial selection. In addition, our findings demonstrate that it is possible to enhance these processes by applying HD-tDCS over the corresponding brain regions.

Materials and Methods

Participants

Sixty-eight healthy right-handed young adults were recruited in this study. Thirty-three participants received HD-tDCS on the right dlPFC (aged 18-30 years, 17 females) and 35 participants received HD-tDCS on the right PPC (18-26 years; 19 females). All participants had no current or history of neurological/psychiatric conditions and had normal or corrected-to-normal vision. Written informed consent was obtained from each participant before the test. The Human Subjects Ethics Committee of the Hong Kong Polytechnic University approved this study.

The sample size was decided by making reference to previous tDCS studies that involved 27-30 participants (Hecht et al. 2010; Ballard et al. 2018; Spooner et al. 2019). Although no power analysis was done before the experiment was conducted, a posteriori power analysis suggests that the sample size of our study provides sufficient power. In particular, the analysis was conducted using G*Power 3.1.9.6 according to the three-way ANOVA in Figure 4 with an effect size in Cohen's d=0.047 and alpha=0.05 (two-tailed) (Faul et al. 2007). The estimated power is 94%, which exceeds the conventional standard of power at 80% or 90%.

Procedures

This study involved a double-blinded cross-over HD-tDCS design, in which participants were tested in two experimental sessions at least one week apart. To motivate participants to be engaged in the subsequent decision making task that involved food choices, they were requested not to consume any food from two hours before the experiment. Each session started with a Becker-DeGroot-Marschak (BDM) auction procedure in order to measure participants' food preferences. Participants then received either anodal or sham HD-tDCS. The order of anodal/sham stimulation sessions was randomized between participants and double-blinded to both participants and experimenter. The identity of the stimulation was decided by a second experimenter and revealed only after the end of the whole experiment. The average duration of the decision making task was 22.527 minutes (standard deviation: 5.234 minutes). In this study, participants' decision making were tested 15 minutes after receiving HD-tDCS. This procedure was adopted based on previous observations that the neuromodulation effect is strongest approximately 25 – 60 minutes after HD-tDCS is applied over the motor cortex (Kuo et al. 2013). However, due to anatomical variations across brain regions, it is unclear whether applying HD-tDCS over other brain regions would result in the same neuromodulation time course. Nevertheless, the current study showed that a neuromodulation effect can be observed when participants were tested in a window between 15 and 38 minutes after the HD-tDCS is applied over the dlPFC or PPC. Methodological studies should be conducted in the future to document the time course of HD-tDCS effect across different brain regions such that the testing window can be better determined to maximize the effectiveness of the experimental design.

Becker-DeGroot-Marschak (BDM) auction

A BDM auction procedure was adopted to assess the participant's subjective value of a total of 64 snack items (Becker et al. 1964). Participants were allowed to view all the actual snacks before the start of the experiment. These snacks were used later as options in the multiple-option decision

making task. In particular, in a computerized task, participants were presented pictures of the snacks one by one. For each snack, participants were required to indicate their willingness-to-pay (WTP) for each snack, using a visual analogue scale that ranged from HK$0 to HK$20. In other words, they had to indicate how much money they would be willing to spend to have the opportunity to consume the snack. Participants were encouraged to indicate WTP according to their own subjective preferences.

Five snacks chosen by the participant later during the decision making task were randomly selected after each experimental session. For each selected snack item, a random price ranging from HK$0 to HK$20 was drawn and compared to the WTP indicated by the participant. If the random price was lower than the WTP, the participant had to buy the snack at that random price. If the random price was higher than the WTP, the participant lost the chance to buy that snack. All purchased snacks had to be consumed before leaving the laboratory. All these procedures were explicitly explained to the participant. These procedures ensured that the WTP of each snack item was related to the participant's subjective value.

Decision making task

In the multiple-option decision making task, participants were required to choose repeatedly between snacks that they had rated during the BDM auction. The beginning of a trial was indicated by a fixation cross located at the centre of the screen, and participants' eye gaze had to fixate on the cross (Fig. 1A). Next, two, four or sixteen snack options were presented in random positions on the screen. All options were initially covered by black rectangles. When participants gazed at an option, the black rectangle on that option was removed and the snack item associated with that option was revealed. When the participant's gaze drifted away from that option, the option was covered by a black rectangle again. This ensured that in every moment, information could only be obtained from the option at the gaze position (i.e. central vision) recorded by an eye tracker, not from any other options in peripheral vision. Participants then chose their most preferred snack on

the trial by gazing at that option and then pressing a button. The chosen option would then be displayed at the centre of the screen. Participants had to confirm their choice by pressing a button or modify their choice by pressing another button, in which case an identical trial would be presented once again. Those trials that involved a change of choice were discarded in the analyses. In total, there were 20 two-option trials, 40 four-option trials and 60 sixteen-option trials presented randomly in the task.

High-definition transcranial direct current stimulation (HD-tDCS)

In each experimental session, we applied either sham or anodal HD-tDCS (Soterix tDCS stimulator with a 4 x 1 HD-tDCS adaptor) over participants' right dlPFC or right PPC. The HD-tDCS involved ring electrodes arranged in a 4 x 1 montage, i.e. an anode electrode was placed over the target region and surrounded by four reference electrodes 2.5 cm away from the anode. The position of the anode that targeted the right dlPFC region was determined by a meta-analysis of the neural activity associated with working memory (Owen et al. 2005) and targeted at the middle frontal gyrus (BA9/46). The position of the anode that targeted the PPC was placed over the human putative lateral intraparietal area (LIP) and medial intraparietal area (MIP) (Sereno et al. 2001; Mars et al. 2011). In an anodal session, a low-intensity direct current (2mA) stimulation was applied through a multichannel stimulator for 10 minutes. In a sham session, the current was only applied in the first 30 seconds and the last 30 seconds of the 10-minute period. Participants were asked to report any discomfort before, during and after the stimulation.

To estimate the current density distribution in the brain during HD-tDCS, simulation was conducted using SimNIBS 2.1 (Opitz et al. 2015). As in the actual experiment, a 4 x 1 electrode montage with ring shape electrodes was modelled. It simulated that a 2mA current was delivered though the anode and spread to the four cathode electrodes. Post-processing and visualisation of normalized current density were conducted using Gmsh (Geuzaine and Jean-Francois 2009) (Figs.

196 1B and 1C). The simulation confirmed that in both dlPFC and PPC participants, the electric current
197 density peaked in their respective target regions.

198

199 Eye tracking

200 During testing, participants sat in front of a Tobii eye tracker (Tobii TX300) with a 23-inch monitor
201 at 1920 x 1080 resolution. Time and position of eye gaze were recorded during the performance of
202 the decision making task at a sampling rate of 300 Hz. We analyzed the duration of the initial
203 fixation (i.e. the first fixation) of each option on each trial, because the nature of the subsequent re-
204 fixations were highly heterogeneous. They could be due to forgetting the snack behind a specific
205 location, forgetting the position of a previously seen snack, gathering additional information, or
206 confirming a choice. The heterogeneous nature of the re-fixation will inevitably add noise to the
207 data. Also, previous studies suggested that the duration of initial fixation is predictive of people's
208 subsequent choices (Krajbich et al. 2010; Voigt et al. 2019). For the interest of some readers, we
209 still repeat some key analyses using the re-fixation data (Supplementary Fig. 10 and 11). Not
210 surprisingly, we were not able to obtain the same results as the analyses using the initial fixation
211 data and, for the reasons above, these results using re-fixation data should be interpreted with
212 caution.

213 Data Acquisition and Analysis

214 Three types of behavioural data were collected from participants: WTP (relating to the subjective
215 preference) of the chosen option, reaction time and gaze pattern. The decision optimality of each
216 trial was defined by the equation below. The index ranged from 0 to 1, which indicates the WTP of
217 the chosen option relative to the best and worst options available on the same trial:

218 $$Decision\ optimality = \frac{WTP - \min(WTP)}{\max(WTP) - \min(WTP)}$$

Linear and logistic regression analyses were performed for every participant to predict their decision optimality (between 1 and 0) and chosen option location (contralateral or ipsilateral) using different general linear models (GLMs). The effect size of the regression coefficients across participants was tested by performing *t* tests (two-tailed; Figs. 4,5,6 and 8) or ANOVAs (Figs. 4,6 and 8).

GLM 1a examined the effects of fixating on better and poorer options on decision optimality:

Decision optimality = β0+ β1(fixation duration on the better options) +
β2(fixation duration on the poorer options) +

The better and poorer options refer to the rank 1 and rank 2 options on the two-option trials; the rank 1 and rank 2–4 options on the four-option trials; and the rank 1–4 and rank 5–16 options on the sixteen-option trials.

GLM 1b examined the effects of fixating on options of different ranks on the decision optimality on sixteen option trials:

Decision optimality = β0+ β1(fixation duration on rank 1-4 options) +
β2(fixation duration on rank 5-8 options) +
β3(fixation duration on rank 9-12 options) +
β4(fixation duration on rank 13-16 options)

GLM 1c examined the effects of early and late fixations on the decision optimality on the sixteen-option trials. It involved dividing each regressor in GLM 1b into two halves by considering whether each fixation occurred in the first or second half of a trial:

Decision optimality = β0+ β1(fixation duration on early-sampled rank 1-4 options) +
β2(fixation duration on early-sampled rank 5-8 options) +

β3(fixation duration on early-sampled rank 9-12 options) +

β4(fixation duration on early-sampled rank 13-16 options) +

β5(fixation duration on late-sampled rank 1-4 options) +

β6(fixation duration on late-sampled rank 5-8 options) +

β7(fixation duration on late-sampled rank 9-12 options) +

β8(fixation duration on late-sampled rank 13-16 options)

GLM 2 examined the effect of information side (contralateral or ipsilateral) on biasing the choice position. It involved splitting each regressor of GLM 1b into two halves by considering whether a fixation occurred contralateral or ipsilateral to the side of hemisphere that received HD-tDCS as well as a covariate that describes the value sum of all options:

Contralateral choice = β0+ β1(fixation duration on contralateral rank 1-4 options) +

β2(fixation duration on contralateral rank 5-8 options) +

β3(fixation duration on contralateral rank 9-12 options) +

β4(fixation duration on contralateral rank 13-16 options) +

β5(fixation duration on ipsilateral rank 1-4 options) +

β6(fixation duration on ipsilateral rank 5-8 options) +

β7(fixation duration on ipsilateral rank 9-12 options) +

β8(fixation duration on ipsilateral rank 13-16 options) +

β9(value sum of all options on the trial)

Data availability

Behavioural and eye movement data of all participants are available at:

https://osf.io/b9th3/?view_only=abf8cc5f64b74589bea4978235937dbc

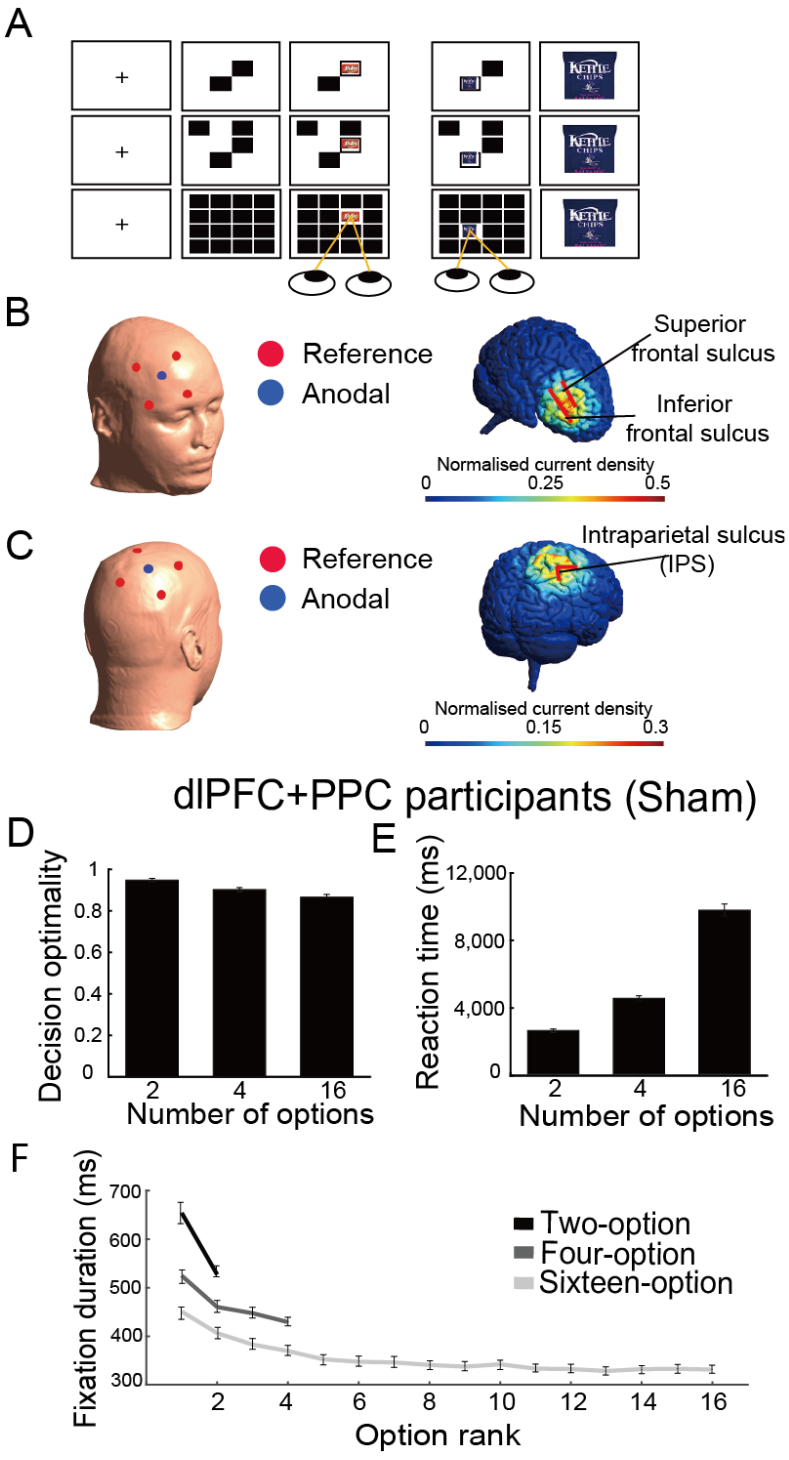
Code availability

The code associated with the results of this study is available from the corresponding authors upon reasonable request.

Results

The effects of option number and option rank on decision making and information sampling

We first tested the general effects of option number on decision optimality, reaction time (RT), and information sampling reflected by participants' duration of fixating on each option. Thus, we first focused on the data collected from the control, sham HD-tDCS session of both dlPFC and PPC participants. Decision optimality was defined as the WTP for the chosen option relative to the best and worst options present on the same trial (Methods: Data Acquisition and Analyses). Our results showed that when there were fewer options, participants were more likely to make more optimal decisions by choosing options with relatively higher WTP ($F_{2,134}$=25.171, p<0.001; Fig. 1D). In addition, participants' RTs were longer when there were more options ($F_{2,134}$=490.723, p<0.001; Fig. 1E). Similar patterns were found in dlPFC and PPC participants when their sham session data were analyzed separately (Supplementary Fig. 1). Finally, the eye tracking data also showed that fixation durations were longer as a function of poorer value ranks (i.e. the option with the highest WTP on a trial was assigned as the rank 1 option) of the options (Fig. 1F). Additional analysis suggested that when there were additional options available, less time was spent on sampling information (i.e. shorter fixation durations) from options of the same rank or similar WTP (Supplementary Fig. 2). These results showed that more time is spent on sampling information from individual options when they are better in value and when they are presented with fewer alternatives.



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295 **Fig 1. The decision making task and HD-tDCS current density simulation. (A)** In the task, every trial started with a
296 fixation cross presented at the centre of the screen. Then, two, four or sixteen options covered by black rectangles were
297 presented. The identity of each option was revealed transiently and only at the moment the participant fixated on it. The

participant was required to choose a favourite option from all given options. Finally, the chosen option was presented at the centre of the screen. Prior to the performance of the task, the participant received either sham or anodal HD-tDCS over **(B)** the right dlPFC or **(C)** right PPC using a 4 x 1 montage, in which the anode (red dots) that delivered the current was surrounded by 4 reference electrodes (blue dots). A simulation confirmed that the current density peaked at **(B, right)** BA9/46 in the dlPFC sessions and **(C, right)** the LIP and MIP areas in the PPC sessions. An analysis of the sham session data of both dlPFC and PPC participants showed that the presence of more options was associated with **(D)** greater decision optimality and **(E)** longer reaction times. **(F)** Fixation duration on each option increased as a function of higher rank (smaller rank number) of the option on two- (black line), four- (dark grey line) and sixteen-option (light grey line) trials. In addition, participants generally spent more time viewing each option when fewer options were offered on the same trial. Error bars denote standard error.

Next, we tested how the sampled information affected subsequent decisions. We applied general linear model (GLM) 1a to estimate the effect size of fixating on the better (higher rank) options and poorer (lower rank) options on decision optimality. In the sham session, we found that longer fixation on the better options was positively associated with decision optimality on two-option trials (i.e. rank 1 option; t_{67}=2.425, p=0.018), four-option trials (i.e. rank 1 option; t_{67}=9.494, p<0.001) and sixteen-option trials (i.e. rank 1-4 options; t_{67}=3.705, p<0.001; Fig. 2A). Figure 2B illustrates that when trials were binned according to the duration of fixation on the better options, trials with longer fixations also showed greater decision optimality. On the other hand, duration of fixation on the poorer options was negatively associated with decision optimality on two-option trials (i.e. rank 2 option; t_{67}=-3.972, p<0.001), four-option trials (i.e. rank 2-4 options; t_{67}=-5.040, p<0.001) and sixteen-option trials (i.e. rank 5-16 options; t_{67}=-8.641, p<0.001; Fig. 2A). Figure 2C illustrates that when trials were binned according to duration of fixation on the poorer options, those trials with longer fixations also showed poorer decision optimality. The results in Figures 2B and 2C were not confounded by the range and sum of option values on each trial, as similar results were obtained after these effects were partialled out from the decision optimality data (Supplementary Fig. 3). These results demonstrated the relationships between the sampled information and subsequent choices: more optimal decisions are made when the better options are viewed for longer and the poorer options are viewed for a shorter length of time.

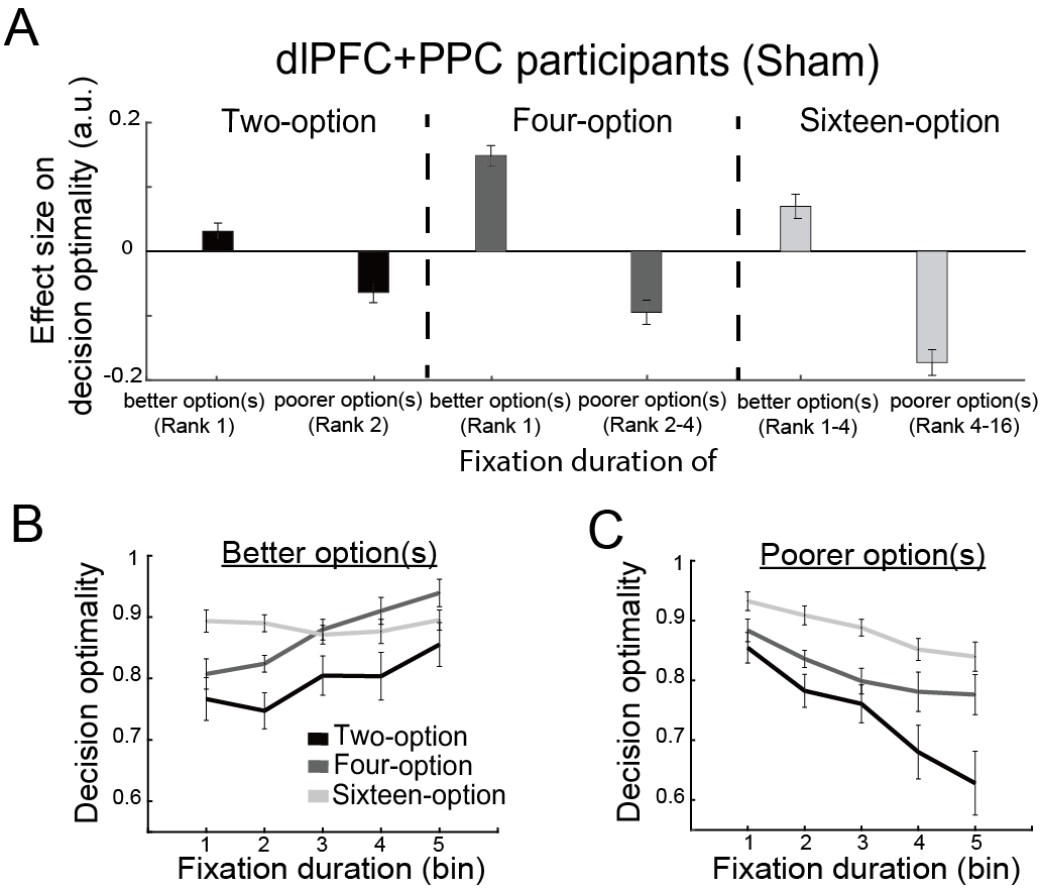


Fig 2. Relationship between fixation duration on better or poorer options and decision optimality. (A), The results of GLM 1a revealed that longer fixation durations on better options were related to greater decision optimality (positive effects) on two-, four- and sixteen-option trials. Conversely, shorter fixation durations on poorer options were related to higher decision optimality (negative effects) on two-, four- and sixteen-option trials. Trials were binned according to the duration of fixation on **(B)** better options or **(C)** poorer options. Trials with longer fixations on better options or shorter fixations on poorer options showed greater decision optimality. Error bars denote standard error.

Enhancing the dlPFC could reduce interference from irrelevant information from poor options

We then investigated the roles of dlPFC and PPC on multiple-option decision making by comparing participants' performance after receiving anodal (excitatory) or sham (control) HD-tDCS. A general analysis showed that neither anodal HD-tDCS over dlPFC nor PPC had an impact on general

decision optimality, RT and information sampling (Supplementary Figs. 4 and 5). We also investigated whether HD-tDCS affected the number of options viewed. We performed an ANOVA with Option Number and Stimulation as factors. There was no Option Number x Stimulation interaction effect in either dlPFC ($F_{2,64}$=0.967, p=0.386) or PPC participants ($F_{2,68}$=1.525, p=0.225). We did not obtain a significant main effect of Stimulation (dlPFC: $F_{1,32}$=0.971, p=0.332; PPC: $F_{1,34}$=1.465, p=0.234), but there was a significant Option Number main effect (dlPFC: $F_{2,34}$=2370.215, p<0.001; PPC: $F_{2,68}$=4342.957, p<0.001). This showed that more options were viewed when more options were available, demonstrating that HD-tDCS did not affect the number of options viewed. In other words, participants' overall choices, decision speed/patience, and information sampling strategy were not influenced by HD-tDCS over dlPFC or PPC. However, it is possible that more specific analysis is necessary to reveal precisely how decision making processes are modulated after applying anodal HD-tDCS. Our subsequent analysis suggested that anodal HD-tDCS over dlPFC and PPC had specific and dissociable effects on how information was used to guide decision making.

Previous studies suggested that dlPFC is particularly important for focusing on task-relevant information or filtering out task-irrelevant information. For example, the representation of task-relevant information in dlPFC neurons was attenuated when macaques had to remember too much information or when interfering information was presented (Watanabe and Funahashi 2014). During multiple-option decision making, it is important to focus on the information associated with the more preferred options and to ignore that from the less preferred options, especially when there are plenty of options. DlPFC could have a specific role in processing the information that was previously sampled for guiding decision making.

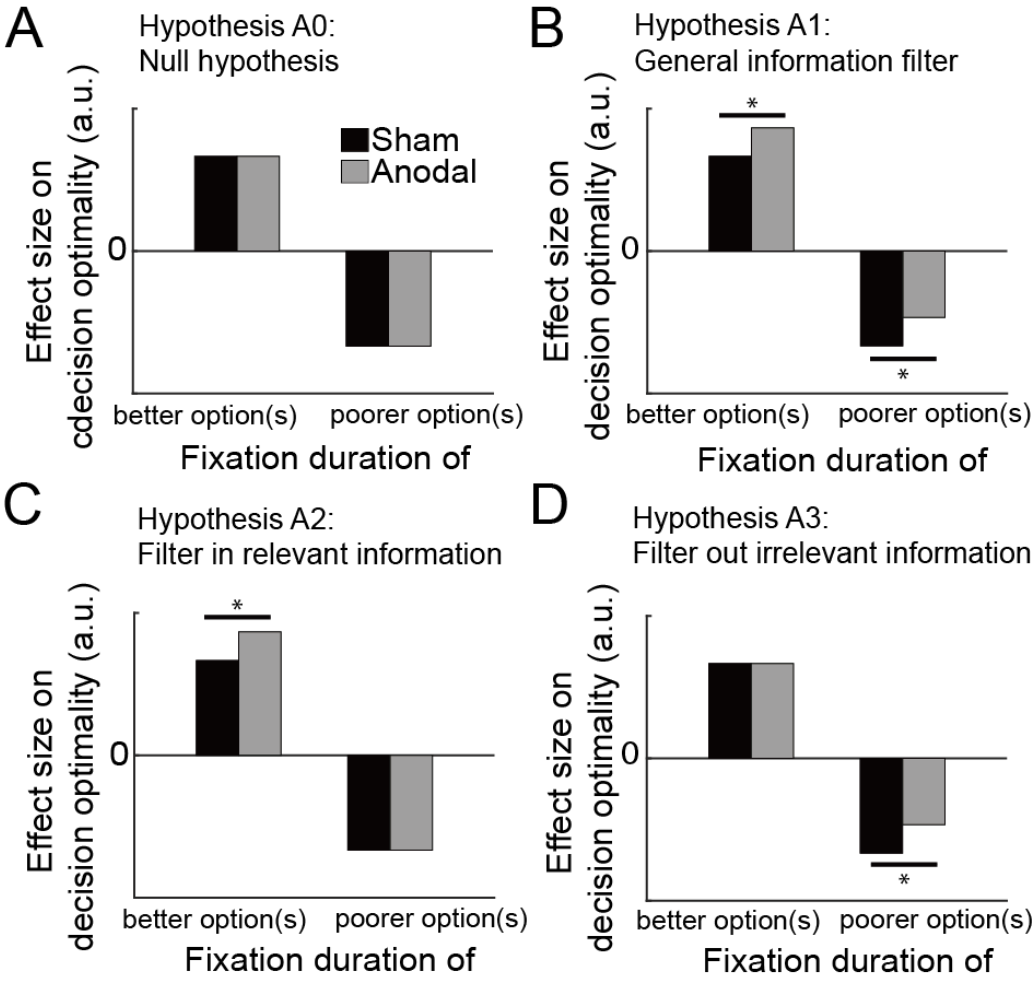


Fig 3. Four alternative hypotheses of the causal role of dlPFC/PPC in filtering choice information. (A) Longer duration of fixating on better options and shorter duration of fixating on poorer options should be related to greater decision optimality (black). If a region that is unrelated to information filtering (Hypothesis A0) is enhanced using anodal HD-tDCS, participants should show comparable effects of fixating on better and poorer options between the sham (black) and anodal (grey) sessions. **(B)** Hypothesis A1 suggests that the neural region is a general information filter. After anodal HD-tDCS (grey), the effect of fixating on better options should become more positive and that of fixating on poorer options should become less negative compared to the sham session (black). **(C)** Hypothesis A2 suggests that the neural region is a filter for including relevant information. After anodal HD-tDCS (grey), only the effect of fixating on better options should become more positive. **(D)** Hypothesis A3 suggests that the neural region is a filter for excluding irrelevant information. After anodal HD-tDCS (grey), only the effect of fixating on poorer options should become less negative. *=significantly different between anodal and sham sessions.

Next, we describe four alternative hypotheses about the role of dlPFC. In the sham session of all four hypotheses, as in Figure 2A, which also involves applying GLM 1a, longer fixations on better options and shorter fixations on poorer options should be related to higher decision optimality. In other words, fixating on better and poorer options should show positive and negative effects, respectively. If dlPFC is not involved in filtering information, these effects should be comparable between sham and anodal sessions (Fig. 3A, Hypothesis A0). Alternatively, Hypothesis A1 suggests that dlPFC is a general information filter. Since the better options involve choice-relevant information and the poorer options involve choice-irrelevant information, enhancing dlPFC in the anodal session results in more positive effect of fixating on better options and a less negative effect of fixating on poorer options (Fig. 3B). Hypothesis A2 suggests that dlPFC is a filter specific to choice-*relevant* information and the anodal session should only show a stronger positive effect of fixating on the better option, but the negative effect of fixating on the poorer option should remain comparable to that in the sham session (Fig. 3C). Finally, Hypothesis A3 suggests that dlPFC is a filter specific to choice-*irrelevant* information and the anodal session should only show a smaller negative effect of fixating on the poorer option (Fig. 3D).

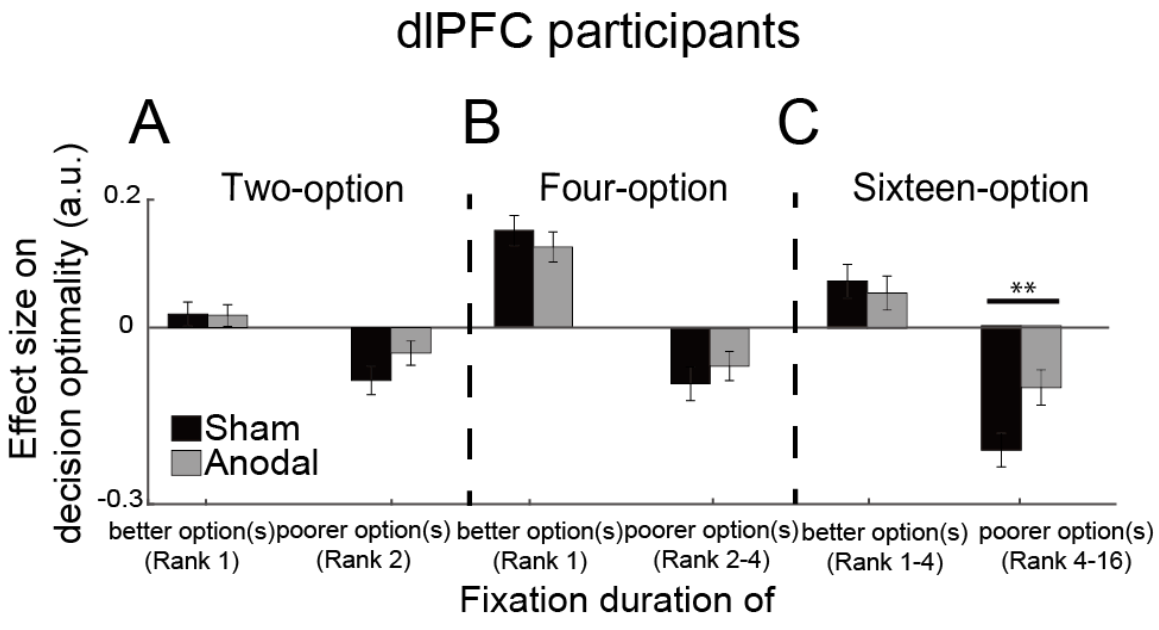


Fig 4. **Anodal HD-tDCS over dlPFC attenuated the negative impact of viewing poorer options on decision optimality on sixteen-option trials. (A)** On two-option trials, longer fixation on the better option (despite not reaching significance) and shorter fixation on the poorer option were associated with greater decision optimality. These effects were similar between sham (black) and anodal (grey) sessions. **(B)** A similar pattern was observed on four-option trials. **(C)** Interestingly, on sixteen-option trials, a significant reduction in the negative relationship between fixation duration on poorer options and decision optimality was found in the anodal session (grey) compared with the sham session (black). However, the positive effect of fixating on better options was comparable between anodal (grey) and sham (black) sessions.

The results from dlPFC participants support Hypothesis A3: dlPFC has a role in filtering out choice-irrelevant information from poorer options. We first analyzed the fixation effects estimated in GLM1a by applying a four-way ANOVA that included the following factors: Stimulation Site (dlPFC vs PPC), Stimulation (anodal vs sham), Option Rank (better vs poorer options) and Option Number (two-, four-, sixteen-option trials). Interestingly, the results showed a significant three-way Stimulation Site x Stimulation × Option Number interaction effect ($F_{2,126}$=5.143, p=0.007), suggesting that there was a Stimulation effect when anodal HD-tDCS was applied at a specific Stimulation Site and on options when there was a specific Option Number. In addition, the ANOVA also showed a marginally significant Stimulation Site x Stimulation × Option Rank effect ($F_{1,63}$=3.171, p=0.080) showed no significant four-way interaction effect ($F_{2,126}$=0.247, p=0.781) and other three way interaction effect ($F_{2,126}$<0.240, p>0.787). To further understand the critical Stimulation Site x Stimulation × Option Number interaction effect, we performed a post-hoc analysis to compare the data from dlPFC participants' anodal and sham sessions. This analysis was repeated using the data from PPC participants in a later section (see Fig. 6). Specifically, we found that the effects of fixating on the better options were comparable after anodal and sham HD-tDCS on two- (t_{32}=-0.015, p=0.988; Fig. 4A) four- (t_{32}=-0.752, p=0.457; Fig. 4B) and sixteen-option (t_{32}=-0.528, p=0.601; Fig. 4C) trials. Interestingly, for the poorer options, the negative impact of fixating these options on decision optimality was significantly reduced after anodal HD-tDCS, relative to sham, only on sixteen-option trials (t_{32}=3.093, p=0.004; Fig. 4C), but not on two- (t_{32}=1.440, p=0.160; Fig. 4A) and four-option (t_{32}=0.710, p=0.484; Fig. 4B) trials.

An additional analysis was performed to test whether the HD-tDCS effect persisted throughout the experiment. We median split the data by trial number and repeated the regression analysis of sixteen-option trials in Figure 4 for each half of the data. A three-way ANOVA using the factors of Stimulation, Option Rank and Persistence (i.e. first half or second half) revealed that there was no Stimulation x Option Rank x Persistence interaction ($F_{1,32}$=1.723, p= 0.199) or Stimulation x Persistence interaction ($F_{1,32}$=1.977, p=0.169). These results suggested that the HD-tDCS effect persisted throughout the experiment as it did not reduce significantly on later trials. Taken together, these results provide evidence supporting the causal role of dlPFC in filtering out choice-irrelevant information, particularly when there are many options.

The effects of HD-tDCS over dlPFC were most robust on the poorest options. When analyzing data from the sixteen-option trials, we arbitrarily defined the rank 1-4 options as better options and the rank 5-16 options as poorer options. To illustrate that the anodal HD-tDCS effect was not specific to how the 'poorer' options were defined, we gradually adjusted the boundary between better and poorer options, starting with a cutoff at rank 1.5 and moving gradually to rank 14.5; we calculated the effect of HD-tDCS (i.e. the difference in effect of fixating the poorer options between the anodal and sham sessions) at each cutoff. The results showed that regardless of where the cutoff was placed, the effect of fixating the poorer options on decision optimality was significantly reduced (i.e. positive difference in effect size) after anodal HD-tDCS was applied to dlPFC (cutoff ≥ rank 2.5: t_{32}>3.710, p<0.050; and marginally significant when cutoff = rank 1.5, t_{32}=2.020, p=0.052; Supplementary Fig. 6C). The effect of fixating the better options on decision optimality was insignificant in all cutoff levels (t_{32}<1.513, p>0.140, Supplementary Fig. 6A). Taken together, these results demonstrated that during multiple-option decision making dlPFC had a specific role in filtering out information from poorer options that were presumably irrelevant to the decisions rather than focusing on the better options.

The HD-tDCS effect over dlPFC was particularly robust on the most irrelevant options

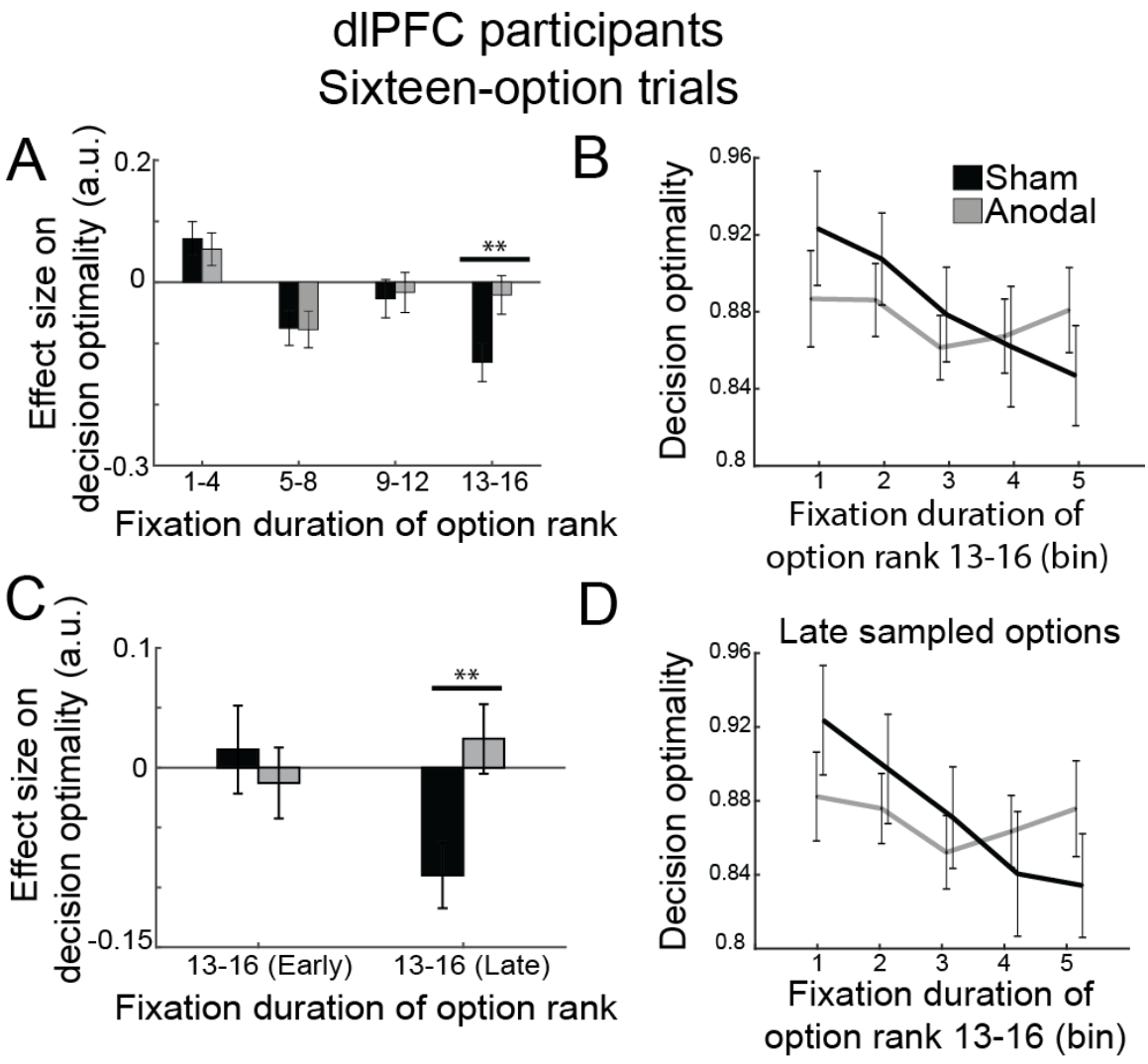


Fig 5. The effect of anodal HD-tDCS over dlPFC was most robust in the poorest options. (A) The options on the sixteen-option trials were divided into four smaller groups. The negative effect of fixation duration on decision optimality was attenuated (by comparing the black and gey bars) only in the poorest rank 13-16 options, but not in the other less poor options, after enhancing the dlPFC by anodal stimulation. **(B)** In sham sessions (black), trials with longer fixations on the poorest rank 13-16 options showed poorer decision optimality. However, this relationship was absent after participants received anodal HD-tDCS over dlPFC (grey). **(C)** The HD-tDCS effect over dlPFC was specific to information about the poorest options that was sampled late. When the effects of fixation duration on the poorest rank 13-16 options were estimated separately, the negative impact on decision optimality in sham sessions (black) was particularly strong when

these options were viewed before a decision was made. However, this negative impact was absent after participants received anodal HD-tDCS (grey). **(D)** Trials with longer late fixations on rank 13-16 options also showed poorer decision optimality in sham sessions (black) but not in anodal sessions (grey). ** $p<0.01$. Error bars denote standard error.

On sixteen-option trials, among the poorer options, arguably information about the worst snacks was the most irrelevant to participants' choices. To ascertain that the HD-tDCS effect was most robust on the worst options that were also the most irrelevant, we divided the poorer options on the sixteen-option trials into three bins: rank 5-8 options, rank 9-12 options, and rank 13-16 options. We applied GLM 1b to estimate the effect of fixation duration of each option bin on decision optimality then compared these effects between anodal and sham sessions. Consistent with our predictions, after anodal HD-tDCS over dlPFC a significant reduction in the negative effect of fixation duration on decision optimality was only present in the worst-ranked 13-16 options (t_{32}=3.093, p=0.004; Fig. 5A), but absent in the rank 5-8 and rank 9-12 options (t_{32}=-0.057, p=0.955 and t_{32}=0.232, p=0.818 respectively) that were less poor in value. Figure 5B shows that on trials where the poorest rank 13-16 options were fixated longer, decision optimality was only poorer in sham sessions (black) but not in anodal sessions (grey). Supplementary Fig. 7 shows a similar pattern in residual decision optimality after the effects of value range and sum of options were partialled out. Furthermore, similar results were obtained when a moving window analysis was applied. Instead of separating the options into discrete bins we set an analysis window of four options and moved this analysis window along the rank. When we first focused on the rank 1-4 options, the effects of fixating these options on decision optimality were comparable in both stimulation sessions (t_{32}=-0.528, p=0.601; Supplementary Fig. 6E). However, when we gradually moved this analysis window to the lower rank options, there was an increasing difference in the effect of fixation between anodal and sham stimulation sessions (r=0.921, p<0.001). The difference was strongest when the analysis window was placed at the poorest rank 13-16 options (t_{32}=3.264, p=0.003; Supplementary Fig. 6E).

In this task that involved sequential sampling of information, information about poorer options should be the most 'interfering' when it was sampled just before a decision was made. Hence, it is possible that information from the poorest options had a much stronger impact on impairing choices when sampled later (i.e. closer to the moment when a choice was made) than when sampled earlier (i.e. closer to the onset of a trial). In addition, enhancing the dlPFC using HD-tDCS could reduce the negative impact of such late information on decision optimality. To test this, we divided the regressors of GLM 1b in Figure 5A into two; one set of regressors describes the fixation duration that happened during the first half of each trial and another set of regressors describes those that happened during the second half of each trial (GLM 1c). Interestingly, the results showed exactly what was expected. In the sham HD-tDCS session the duration of late fixations on the poorest rank 13-16 options had a more negative relationship with decision optimality than the duration of early fixations (t_{32}=-3.030, p=0.005; Fig. 5C, black). This suggested that the poorest options only interfered with choices when viewed just before a choice was made (Fig. 5D, black). More importantly, this negative impact was attenuated after anodal HD-tDCS was applied over the dlPFC, because the effects of early and late fixations were comparable (t_{31}=2.963, p=0.006; Fig. 5C and 5D, grey). These effects of fixation duration on decision optimality were also compared by a three-way ANOVA that included factors of Stimulation (anodal vs sham), Sampling Time (early vs late) and Option Rank (rank1-4, rank 5-8, rank 9-12, rank 13-16). It revealed a significant three-way interaction effect ($F_{3,93}$=3.027, p=0.033). These results provided further evidence that enhancing the dlPFC could reduce interference from information related to poorer options.

Absence of interference reduction after stimulating the PPC

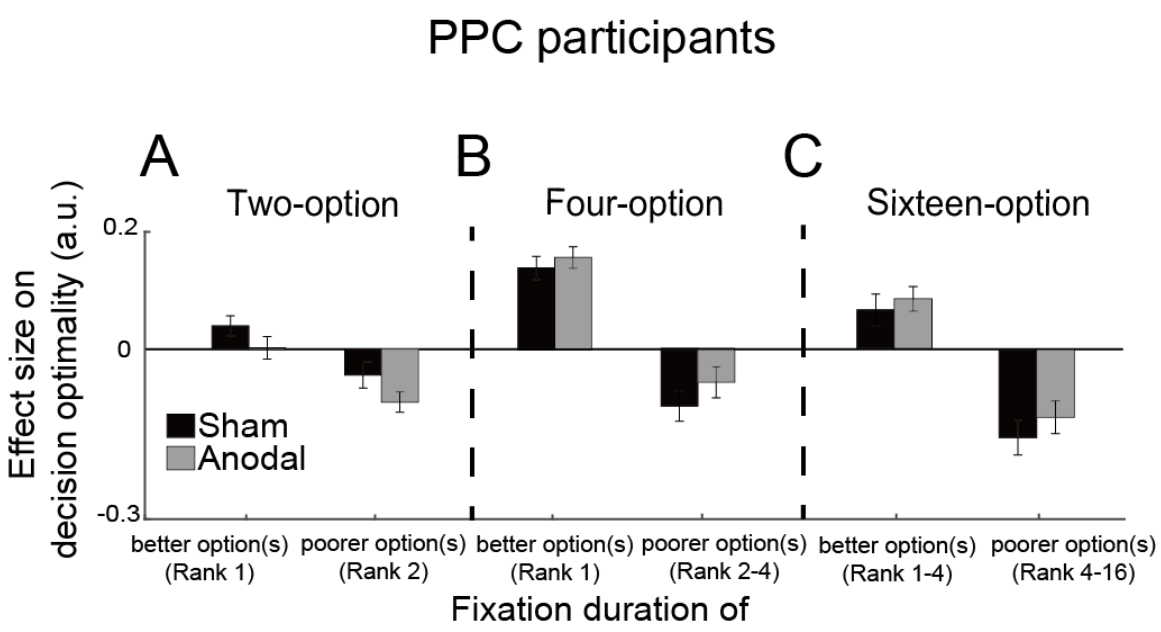


Fig 6. **After anodal HD-tDCS over PPC, unlike that over dlPFC, there was no impact on attenuating the effect of fixating the poorest options on decision optimality.** In PPC participants, the effects of fixating on better and poorer options in sham sessions (black) were comparable to those in anodal sessions (grey) on **(A)** two-option, **(B)** four-option and **(C)** sixteen-option trials.

To test whether the PPC has a role similar to the dlPFC in reducing interference, we repeated the analyses performed with the data of dlPFC participants with those of PPC participants. Interestingly, the PPC participants did not show any HD-tDCS effect in these analyses. In particular, as in Figure 4A, we applied GLM 1a to estimate the effects of fixating the better and poorer options on two-, four- and sixteen-option trials. We then compared the effects in anodal and sham sessions. Unlike the dlPFC participants, there was a lack of HD-tDCS effect on modulating the relationship between the duration of fixating different options and decision optimality on two-option trials (better option: t_{34}=-1.419, p=0.165; poorer option: t_{34}=-1.162, p=0.116; Fig. 6A), four-option trials (better option: t_{34}=1.241, p=0.223; poorer options: t_{34}=0.889, p=0.380; Fig. 6B) and sixteen-option trials (better options: t_{34}=0.490, p=0.630; poorer options: t_{34}=0.814, p=0.421; Fig. 6C). In addition, a moving window analysis (as in Supplementary Figs. 6A and C) showed that a HD-tDCS effect was

absent in PPC participants regardless of where the cutoff for dividing the options was placed (better option: t_{32}< 0.045, p>0.208; poorer option: t_{34}<0.951, p>0.348; Supplementary Figs. 6B and D). Finally, there was an absence of HD-tDCS effect in PPC participants even when the poorer options were divided into smaller bins (rank 5-8 options: t_{34}=0.629, p=0.534; rank 9-12 options: t_{34}=0.249, p=0.805; rank 13-16 options: t_{34}=0.197, p=0.845). Similarly, there was an absence of HD-tDCS effect in PPC participants across options of different ranks (Supplementary Fig. 6F). These results suggested that the role of reducing interference from irrelevant options was specific to the dlPFC.

The role of the PPC in value-based spatial selection

It is not yet clear whether and how the PPC is involved in multiple-option decision making. It is well-characterized that visuospatial topography can be found in various PPC regions (Gottlieb and Goldberg 1999). For instance, neurons in the LIP and MIP regions contain spatial information that makes reference to the retina and the hand respectively (Patel et al. 2010; Sereno and Huang 2014). Although it is widely accepted that the PPC contains signals that are spatially-related, the precise functions of these signals remain controversial. There is debate about whether the PPC is involved in value-based spatial coding (Platt and Glimcher 1999; Shadlen and Newsome 2001; Dorris and Glimcher 2004; Sugrue et al. 2004; Hanks et al. 2015; Zhou and Freedman 2019), salience-based spatial coding (Leathers and Olson 2012; Chen et al. 2020) or general spatial selection (Katz et al. 2016). Many of these findings were based on animal studies, with little human data contributing to the debate. Next, we ran a series of analyses to test these views using our human data.

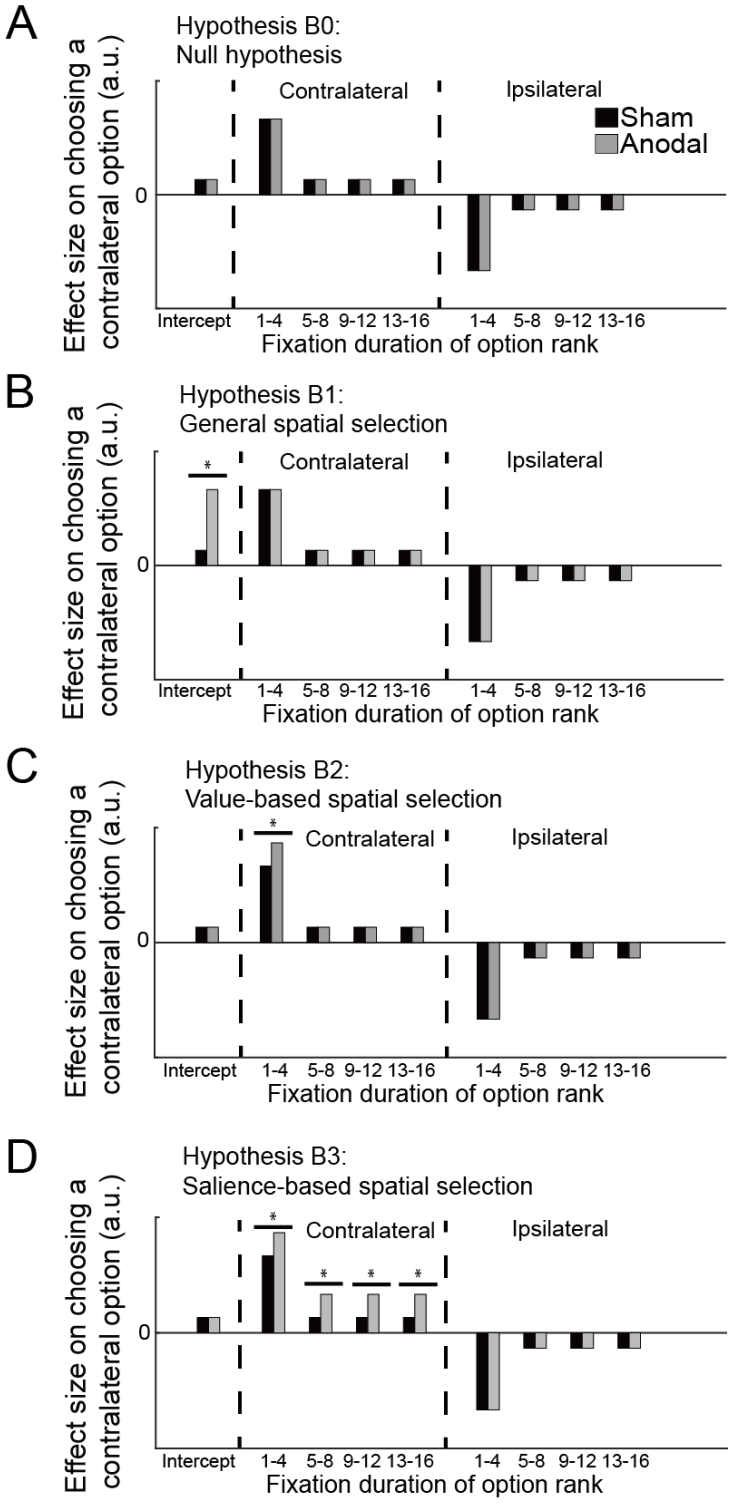


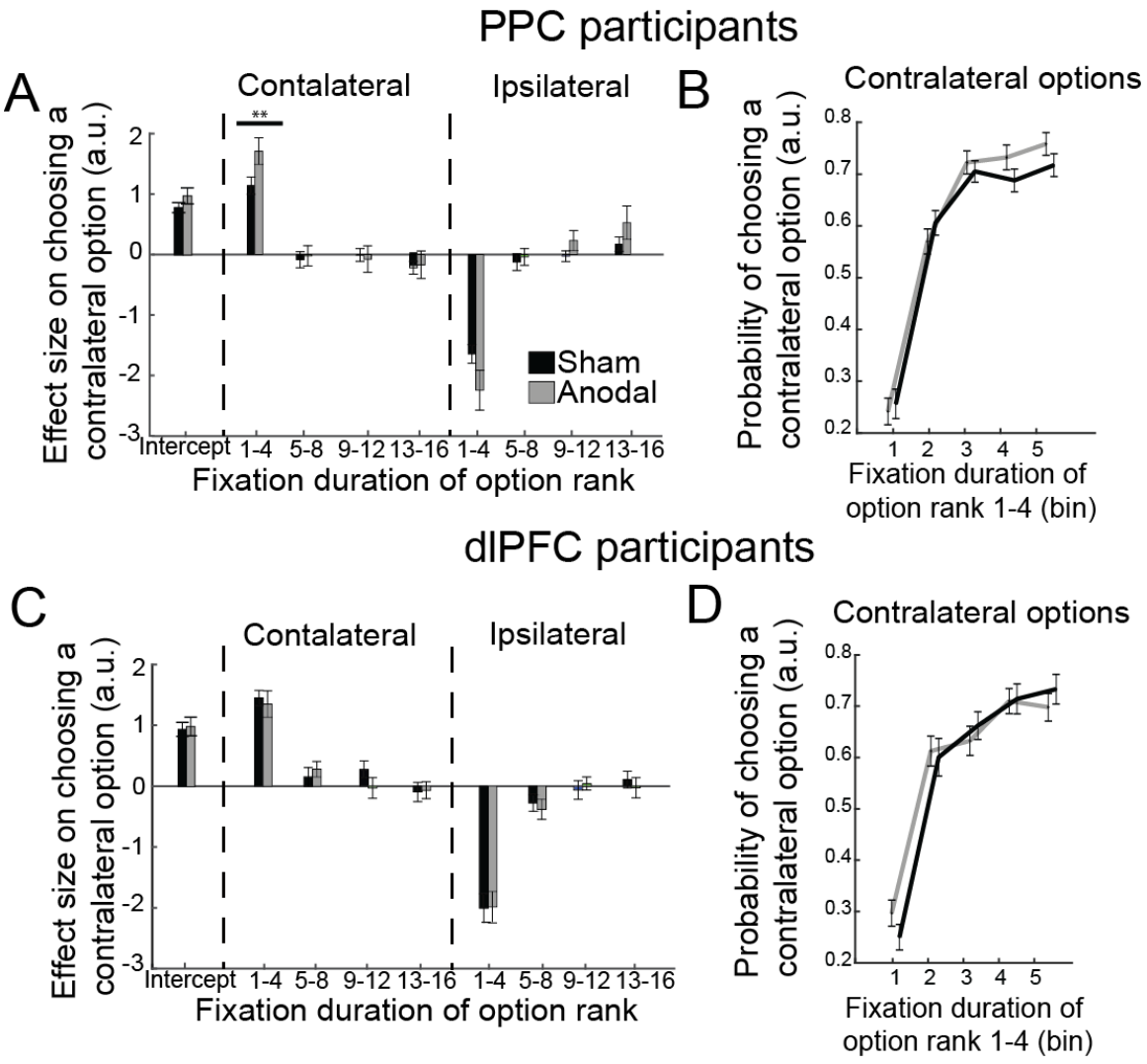
Fig 7. Four alternative hypotheses of the causal role of PPC/dlPFC in spatial selection. When GLM 2 was applied, in sham sessions (black bars in all panels) longer durations of fixating on the contralateral rank 1-4 options and shorter

durations of fixating on the ipsilateral rank 1-4 options should be related to more contralateral choices. The poorer rank 4-8, 9-12, and 13-16 options on the contralateral and ipsilateral sides should show a similar pattern but with smaller effect sizes (i.e. less positive contralaterally and less negative ipsilaterally). The intercept term is related to a general side bias and the effect is positive (i.e. a general left-side bias). **(A)** If a region that is unrelated to spatial selection (Hypothesis B0) is enhanced using anodal HD-tDCS, participants should show comparable effects between the sham (black) and anodal (grey) sessions in all terms. **(B)** Hypothesis B1 suggests that the neural region has a general role in spatial selection. After anodal HD-tDCS (grey), there should be an increase in the general tendency to select a contralateral option, and the intercept should become more positive compared to that of the sham session (black). **(C)** Hypothesis B2 suggests that the neural region encodes signals for value-based spatial selection. In other words, it encodes the value of an option located at a specific position. After anodal HD-tDCS (grey), the positive effect of fixating the best rank 1-4 options should become stronger, because the value of these important options is encoded more efficiently, and the remaining terms should remain comparable to those of the sham sessions. **(D)** Hypothesis B3 suggests that the neural region encodes signals for salience-based spatial selection. In general, options that are more salient (determined by a combination of value, physical qualities, etc.) should be fixated longer. When a salience code is enhanced and used for guiding decision making, all the terms relating to contralateral options should become more positive. *=significant difference between anodal and sham sessions.

To test the precise spatial function of the PPC, we took the advantage of the fact that there is a larger proportion of neurons with receptive fields located on the contralateral side than the ipsilateral side of the space. We carefully considered whether the information was presented contralaterally or ipsilaterally to the hemisphere to which HD-tDCS was applied and performed an analysis that tested whether the chosen option was presented on the ipsilateral or contralateral side (relative to the midline of the screen). We focused on analyzing the sixteen-option trials because, unlike the two- and four-option trials, these trials always had the same number of options on both contralateral and ipsilateral sides.

We first tested whether enhancing the PPC or dlPFC by HD-tDCS could modulate the spatial positions of the choices and fixations. We performed a three-way ANOVA to test the impact of Stimulation (anodal vs sham), Option Position (contralateral vs ipsilateral) and Option Rank (1-4, 5-8, 9-12) on percentage choices. To avoid rank deficiency, we excluded the percentage choices of rank 13-16 from the analysis. In PPC participants, there was an absence of Stimulation main

effect ($F_{1,34}$=1.260, p=0.269; Supplementary Fig. 8A), two-way Stimulation x Option Position interaction effect ($F_{1,34}$=0.936, p=0.340), and three-way Stimulation × Option Position × Option Rank interaction ($F_{2,68}$=0.846, p=0.434) on percentage choices. In addition, these effects were also insignificant on fixations (Stimulation: $F_{1,34}$=0.299, p=0.588; Stimulation x Option Position: $F_{1,34}$=0.066, p=0.799; Stimulation × Option Position × Option Rank: $F_{3,102}$=1.128, p=0.341; Supplementary Fig. 8B). Similarly, in dlPFC participants there was an absence of Stimulation main effect ($F_{1,32}$=2.976, p=0.094), two-way Stimulation x Option Position interaction effect (dlPFC: $F_{1,32}$=0.119, p=0.733), and three-way Stimulation × Option Position × Option Rank interaction ($F_{2,64}$=0.156, p=0.856, Supplementary Fig. 8C) on percentage choices. Finally, these effects were also insignificant on fixations (Stimulation: $F_{1,32}$=0.140, p=0.710; Stimulation x Option Position: $F_{1,32}$=0.963, p=0.334; Stimulation × Option Position × Option Rank: $F_{3,96}$=0.201, p=0.896; Supplementary Fig. 8D). These results suggested that anodal stimulation over either PPC or dlPFC had no impact on the spatial positions of choices and fixations.



586

587 **Fig 8. Anodal HD-tDCS over PPC, but not that over dlPFC, enhanced the spatial bias of choosing an option on the**
588 **contralateral side. (A)** In the sham session (black) of PPC participants, options on the contralateral side were chosen more
589 often as a function of longer fixations on the rank 1-4 options that appeared on the contralateral side. After the PPC was
590 stimulated using anodal HD-tDCS (grey), the positive effect of contralateral rank 1-4 options became even stronger. **(B)** In
591 general, trials with longer fixations on the contralateral rank 1-4 options were associated with more choices from options
592 located on the contralateral side. However, the positive effect was even stronger (steeper slope) in the anodal session (grey)
593 compared to the sham session. **(C)** In contrast, in dlPFC participants there was a lack of HD-tDCS effect on the choice of
594 contralateral options. **(D)** Despite a positive relationship between fixation duration of the rank 1-4 options and likelihood of
595 contralateral choices, the effects (i.e. the slopes) were comparable between the sham (black) and anodal (grey) sessions.
596 ** $p<0.01$. Error bars denote standard error

597

598 Next, we applied GLM 2 to predict whether an option was chosen from the contralateral or
599 ipsilateral side. As in GLM 1c, GLM 2 included separate regressors that describe the fixation
600 durations on options of different ranks (1-4, 5-8, 9-12, and 13-16). In addition, each regressor was
601 split into two according to whether the fixation occurred on the contralateral or ipsilateral side
602 relative to the hemisphere that received HD-tDCS. An additional covariate describing the total value
603 of options is included to avoid any confounding effects contributed by the subtle trial-by-trial
604 variance in option value. In the sham session (Fig. 7A, black bars), it is predicted that longer
605 fixations on the contralateral options and shorter fixations on the ipsilateral options are related to
606 higher chances of choosing options from the contralateral side (i.e. positive and negative effects of
607 fixating on contralateral and ipsilateral options respectively). In addition, the effects of the best rank
608 1-4 options, which are more choice-relevant, are stronger than those of the poorer rank 5-8, 9-12
609 and 13-16 options. Finally, there is a positive effect of intercept due to a bias of choosing options
610 from the contralateral side. Next, we describe how GLM 2 can be used to test four hypotheses
611 based on the recent debate of PPC functions.

612 In Hypothesis B0, the stimulated region has no spatial role and the effects in GLM 2 are
613 comparable between the sham and anodal sessions (Fig. 7A). Hypothesis B1 suggests that the
614 stimulated region is a post-decisional spatial selector, and more contralateral choices are made
615 after the region is enhanced using anodal HD-tDCS (Fig. 7B). This should be reflected by a stronger
616 positive effect of the intercept term in the anodal session than the sham session. Hypothesis B2
617 suggests that the stimulated region contains a value-based spatial signal (Fig. 7C). Unilateral HD-
618 tDCS, which enhances value signals in the region, should cause more positive effect of fixating on
619 the most valuable rank 1-4 options when they are presented on the contralateral side. Since the
620 choices are based mainly on the rank 1-4 options, enhancing this region should have no impact on
621 the effect of fixating on the less valuable rank 5-8, 9-12, and 13-16 options. The unilateral HD-tDCS
622 should also have no impact on the effect of fixating on the ipsilateral options and the intercept term.
623 Hypothesis B3 suggests that the stimulated region contains a salience-based spatial signal (Fig.
624 7D). As opposed to Hypothesis B2, unilateral HD-tDCS causes stronger positive effect of fixating

on all contralateral options, because any salient feature that captures fixation is amplified regardless of the option's value. Furthermore, two diagnostic tests should be run to test these hypotheses. First, a paired-sample t test should be performed to compare the effect of the intercept term between anodal and sham sessions. A significant difference in the intercept term between the anodal and sham sessions should be found only in Hypothesis B1. Second, a four-way ANOVA should be conducted, which includes factors of Stimulation Site (dlPFC vs PPC), Stimulation (anodal vs sham), Option Position (contralateral vs ipsilateral) and Option Rank (rank 1-4, rank 5-8, rank 9-12 and rank 13-16), to compare the remaining terms as well as the specificity of the dlPFC or PPC role. In Hypothesis B2 (value-based spatial selection) there should be a significant four-way Stimulation Site x Stimulation × Option Position× Option Rank interaction effect. In Hypothesis B3 (salience-based spatial selection) there should be a significant three-way Stimulation Site x Stimulation × Option Position interaction effect. Next, we applied these analyses to test our empirical data.

The two diagnostic tests above were performed after GLM 2 was applied to data from PPC participants. The results support Hypothesis B2, demonstrating that PPC has a role in value-based spatial selection. Two points are of particular relevance: first, the sizes of the intercept terms were comparable between the anodal and sham sessions (t_{33}=1.303, p=0.202; Fig. 8A), even though they were both positive in the sham (t_{34}=9.769, p<0.001) and anodal (t_{33}=6.225, p<0.001) sessions. Second, the ANOVA showed that there was a significant four-way Stimulation Site x Stimulation × Option Position× Option Rank interaction effect ($F_{3,183}$=3.237, p=0.023) and an absence of a three-way Stimulation Site x Stimulation × Option Position interaction effect ($F_{1,61}$=0.671, p=0.416).

Since there was a significant four-way Stimulation Site x Stimulation × Option Position × Option Rank interaction effect, follow-up analyses were performed to test whether the empirical data from PPC participants matched precisely with the predictions of Hypothesis B2. In both anodal and sham HD-tDCS sessions, PPC participants generally chose contralateral options more often when they fixated longer on the rank1-4 options presented on the contralateral side (anodal

651 t_{33}=7.629, p<0.001; sham t_{34}=7.977, p<0.001; Figs. 8A, 8B and Supplementary Fig. 9A) and *fixated*
652 *shorter* on the rank 1-4 options presented on the ipsilateral side (anodal: t_{33}=-6.733, p<0.001; sham:
653 t_{34}=-10.791, p<0.001). Critically, after the right PPC was stimulated using anodal HD-tDCS, the
654 impact of fixating the contralateral rank 1-4 option became significantly stronger than after
655 participants received sham HD-tDCS (t_{33}=2.302, p=0.028; Fig. 8A and 8B). In addition, a HD-tDCS
656 effect was absent in rank 5-8, 9-12 and 13-16 options (t_{33}<0.321, p>0.751). These results support
657 the view that PPC has a causal role in value-based spatial selection during decision making.

658 We performed the same analyses with the data from the dlPFC participants. The results
659 showed that the effect of the intercept term was comparable between anodal and sham sessions
660 (t_{28}=-0.963, p=0.343). Also, in the ANOVA there was an absence of a three-way Stimulation ×
661 Option Position × Option Rank interaction effect ($F_{3,84}$=1.079, p=0.363; Fig. 8C, 8D and
662 Supplementary Fig. 9B) and an absence of a two-way Stimulation × Option Position interaction
663 effect ($F_{1,28}$=0.499, p=0.486). Although, as in the PPC, a large proportion of neurons in the dlPFC
664 are spatially selective (Funahashi and Bruce 1989; Rainer et al. 1998), we found no evidence that
665 applying HD-tDCS could modulate spatial selection processes during decision making.

666

667 # Discussion

668

669 When there are plenty of options, limited cognitive capacity sometimes makes it impossible to
670 encode all individual options. For example, in the supermarket, choosing among hundreds of
671 grocery products, it is difficult to evaluate each option and make all possible pairwise
672 comparisons. Recent studies show that choice overload due to large sets of available options are
673 reflected in online signals in the dlPFC as well as in the dorsal striatum and anterior cingulate
674 (Reutskaja et al. 2018). Re-evaluation of options after choice overload is related to the signal in the
675 ventrolateral prefrontal cortex (Fujiwara et al. 2018). To overcome choice overload, this study

highlights that it is critical to filter choice information by filtering in information from relevant options (i.e. desired options) and filtering out information from irrelevant options (i.e. unwanted options). To ascertain the dissociable roles of dlPFC and PPC in multiple-option decision making, we investigated participants' choices after these regions were stimulated using HD-tDCS. Our findings provide evidence that dlPFC is important for filtering out choice-irrelevant information, especially when there were many options. Longer fixation on poor options could impair decision optimality; such impairment can be attenuated by enhancing the dlPFC using HD-tDCS (Figs. 4 and 5). In contrast, the PPC is important for value-based spatial selection. After unilateral PPC was enhanced, fixation on better options presented on the contralateral side became more influential in biasing the choices. These findings not only provide causal evidence of the dissociable cognitive functions of the dlPFC and PPC but also demonstrate that these functions can be enhanced non-invasively in humans using HD-tDCS.

It is important to consider what information is sampled (i.e. viewed) when predicting how choices are subsequently made (Krajbich et al. 2010; Lopez-Persem et al. 2016). Recent studies suggest that this is particularly important when there are plenty of options (Thomas et al. 2020). However, it is largely unclear how the sampled information is selected or filtered to guide decision making. In the dlPFC participants, the HD-tDCS effects were particularly robust when we focused on choice information that was particularly distracting, i.e. information from options that were poorest in value and sampled just before a choice was made (Fig. 5). However, stimulating the dlPFC had no impact on how information about better options guided decision making. These findings have important implications for the specific role of dlPFC in multiple-option decision making. In choices with a small set of options, information about all options is relevant to the decision and stimulating the dlPFC has little effect of on decision making (Fig. 4; see also Hämmerer et al. 2016). When the number of options increases, the proportion of information irrelevant to the decision also increases and the importance of the dlPFC in making these choices becomes more pronounced. These findings are also consistent with those from working memory literature. For example, when

703 monkeys had to memorise the locations of target stimuli, distraction by non-target stimuli was
704 associated with reduced neural representation of task-relevant information for the targets
705 (Watanabe and Funahashi 2014). Transient inactivation of or lesion in the dlPFC is also associated
706 with more distractions (Chao and Knight 1998; Suzuki and Gottlieb 2013). Our current results show
707 that these filtering mechanisms in the dlPFC can be applied not only to perceptual information,
708 such as in working memory experiments, but also to value-based information that relates to
709 subjective preferences during decision making.

710 Although it is widely accepted that PPC neurons involve spatial codes, the precise
711 functions of these codes remains highly controversial. Three main views suggest that PPC neurons
712 signal option value in space (Platt and Glimcher 1999; Shadlen and Newsome 2001; Dorris and
713 Glimcher 2004; Sugrue et al. 2004; Hanks et al. 2015; Zhou and Freedman 2019), stimulus salience
714 in space (Leathers and Olson 2012; Chen et al. 2020) or post-decisional spatial selection (Katz et
715 al. 2016). These views mainly involve data from neurophysiology or invasive stimulation
716 experiments conducted in animals, however; there is little causal evidence from human studies.
717 Previous studies using transcranial magnetic stimulation (TMS) in humans showed that transient
718 disruption of the PPC can result in longer RT during the performance of attention or decision making
719 tasks (Thut et al. 2005; Dambeck et al. 2006; Schindler et al. 2008; Gould et al. 2012). However, it
720 is unclear whether and how non-invasive stimulation over PPC can modulate actual choices. Our
721 findings support the view that the human PPC is involved in value-based spatial selection (Fig. 8).
722 In addition, applying non-invasive stimulation using HD-tDCS over the PPC can promote the use
723 of information presented on the contralateral side to bias whether or not to choose an option on the
724 same side.

725 Causal evidence is particularly important in the current debate about the specific function
726 of the PPC. Correlational data, for example from neurophysiology, suggest that signals from PPC
727 neurons can be related to decision making. For example, decision making is often described as a
728 diffusion process, in which a decision maker accumulates evidence that favours the choice of

729 each option. A decision is made once the evidence for one option surpasses a decision threshold.
730 Recordings of PPC neurons often show firing patterns that mimic the diffusion process. It is
731 possible that these diffusion-like signals are causally used for guiding decision making, but
732 another possibility is that these signals reflect post-decisional or non-decisional processes, such
733 as representing the spatial location of a chosen course of action. Hence, experiments that involve
734 brain stimulation or lesion, such as the current study that involved HD-tDCS, are important to test
735 the causal relationships between the PPC and decision making.

736 Although in the current study there was no data indicated directly whether the double-
737 blind design was successful, it is unlikely that the findings were artefacts of any failure of blinding.
738 There are several reasons for this. First, there was a double dissociation of the HD-tDCS effect in
739 the dlPFC and PPC sessions. Second, the control sessions involved a sham stimulation that
740 made it very difficult to guess the identity of the session. Third, the results concern how choices
741 were influenced by participants gazing at specific options, which is very difficult to be fabricated
742 due to any failure of blinding. Nevertheless, future HD-tDCS studies should provide more direct
743 evidence to support the success of blinding, such as by asking participants to guess whether they
744 received anodal or sham stimulation.

745 It was unclear in previous studies whether applying non-invasive stimulation over the PPC
746 in humans could modulate actual choices. For example, a number of studies showed that transient
747 disruption of the PPC using TMS could result in longer RT during the performance of attention or
748 decision making tasks (Thut et al. 2005; Dambeck et al. 2006; Schindler et al. 2008; Gould et al.
749 2012). However, it is less common for a study to report any qualitative changes in participants'
750 choices. One possible reason is that it could also be important to consider how participants sample
751 information in order to reveal any choice modulations after PPC stimulation. Recently it has been
752 suggested that some PPC neurons encode signals that guide information sampling during decision
753 making (Foley et al. 2017; Gottlieb and Oudeyer 2018; Horan et al. 2019). Horan and colleagues
754 had monkeys perform a perceptual decision making task in which they had to report the overall

motion direction of some random dots (Horan et al. 2019). They found that a subset of PPC neurons showed activity that reflected the degree to which information could be gained after spending time viewing the motion of the dots. Consideration of how information is sampled, such as by using an eye tracker, could be crucial to revealing how actual choices are modulated after the PPC is stimulated. Future studies should investigate the interactions between signals of information sampling and option value in the PPC during decision making.

In this study, participants' decision making were tested 15 minutes after receiving HD-tDCS. This procedure was adopted based on previous observations that the neuromodulation effect is strongest approximately 25 – 60 minutes after HD-tDCS is applied over the motor cortex (Kuo et al. 2013). However, due to anatomical variations across brain regions, it is unclear whether applying HD-tDCS over other brain regions would result in the same neuromodulation time course. Nevertheless, the current study showed that a neuromodulation effect can be observed when participants were tested in a window between 15 and 38 minutes after the HD-tDCS is applied over the dlPFC or PPC. Methodological studies should be conducted in the future to document the time course of HD-tDCS effect across different brain regions such that the testing window can be better determined to maximize the effectiveness of the experimental design.

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