NEURAL MECHANISMS OF MULTIPLE CHOICE DEICIOSN MAKING

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Neural Mechanisms of Multiple Choice Decision Making

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CERTIFICATE OF ORIGINALITY

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_____ (Signed)

_____Woo Tsz Fung__ _____(Name of student)

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2 years ago, I was a fresh graduate from the occupational therapist program of PolyU. I was trained as a therapist instead of a researcher. On one hand, I realized that being a therapist is not I wanted to do for the rest of my life. On the other hand, being a therapist could bring me a stable and nice income. I hesitated a lot to walk out of my comfort zone at that time.

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Abstract

Studies in decision neuroscience have focused on examining the neural mechanisms of simple decisions where the size of the choice set is small. However, real life decision making often involves choices between many more options, such as shopping for a new laptop or deciding the destination for a honeymoon trip. However, it is broadly unclear whether those simple decision mechanisms are generalizable to decisions with large choice sets.

Despite being known as an important region to decision making, the dorsolateral prefrontal cortex (dlPFC) was only reported to be active in a subset of decision making experiments. However, the exact reason why the dlPFC is not involved in other decision making experiments is largely unclear. Apart from decision making, the dlPFC is also implicated in working memory. Hence, it is possible that the dlPFC is particularly important to decision when working memory is particularly demanding (for example when a large number of alternatives are available). Since decision neuroscience studies were largely focused on simple decisions, the role of the dlPFC in multiple choice decision is poorly understood. In addition, another region that is particularly important to both decision making and working memory is the posterior parietal cortex (PPC). The PPC seems to have a similar role to the dlPFC in working memory which makes it another potential candidate that is involved in multiple choice decision making. Hence, I have conducted two studies to examine the roles of dlPFC and PPC in multiple choice decision making.

In Study 1, I recruited human participants to perform a multiple choice decision making task, in which they chose between two, four or sixteen options. To test the causal role of dlPFC in multiple choice decision making, I applied either anodal or sham transcranial direct current stimulation (tDCS) over the right dlPFC, in a double-blinded crossover design. I found that in the control sham tDCS session, better decisions were made when there were longer fixations on the better options and also poorer decisions were made when there were longer fixations on the poorer options, regardless whether there were two, four or sixteen options. Interestingly, after the enhancement of dlPFC in the anodal tDCS session, the impact of fixating poorer options on choice accuracy was attenuated on sixteen-option trials, but not on two- and four-option trials. In addition, a follow-up analysis revealed that the impact was strongest on fixations that occurred early, rather than late, during the decision making process. These results suggested that the dlPFC could reduce the influence of the irrelevant information on our choice.

In Study 2, an experimental paradigm that was similar to that of Study 1 was adopted. Instead of applying stimulation over the dlPFC, I stimulated the right PPC to test its role in multiple choice decision making. In contrast to the stimulation over the dlPFC, anodal tDCS of the PPC did not alter the impact of fixating the better and poorer options on choice accuracy. However, after the anodal stimulation, the fixations on the options presented on the contralateral side of the stimulation became more influential to whether or not options on the same side were chosen. These results implied that the PPC has a role in processing the option information that is located on the contralateral spatial location.

Overall, my results suggested that the dlPFC and PPC have dissociable roles during multiple choice decision making. The dlPFC is related to the processing of decision-relevance of

option information. It is particularly important to the filtering of information from poorer options. In contrast, the PPC is related to the processing of spatial representation of decision information to bias decision making. My findings demonstrate that it is possible to enhance the filtering or spatial representation of choice information by using tDCS during multiple choice decision making.

Content

Chapter 1: Introduction

We make numerous decisions in our daily lives. For most of the time, we have to make a decision among plenty of options (i.e. multiple choice decision making). However, we have little understanding on the underlying processes as previous decision making studies mainly focused on understanding the neural mechanisms of decisions with less options, such as binary decision making. In this thesis, I have a major focus on the neural mechanisms of multiple choice decision making. To begin with, I review the general mechanisms of binary decision making (Chapter 1.1). After that I discuss the key brain regions that could be involved in multiple choice decision making, which are the dorsolateral prefrontal cortex (Chapter 1.2) and the posterior parietal cortex (Chapter 1.3). Finally, there is an overview of this thesis (Chapter 1.4).

1.1 Decision making

Binary choice decision making

Binary decisions, which involve choices between two options, has been the main focus of previous decision making studies.. These studies provided a simple but effective framework to describe how people make binary decisions. Such a framework of binary decision making generally involves a valuation process and a comparison process.

The valuation process refers to the process of understanding and interpreting the value, also known as the preference, of an option. If a region is involved in the valuation process, its activity should be related to the value of the option. The orbitofrontal cortex (OFC) was found to play an important role in the valuation process (Cai &Padoa-Schioppa, 2014; Padoa-Schioppa &Conen, 2017). Padoa-Schioppa and Conen (2017) found that the activity of OFC neurons of

primates correlated with the value of options. Since the OFC neurons activity is able to reflect the value of options, it is suggested to be involved in the valuation process (Padoa-Schioppa &Conen, 2017)

The comparison process refers to the comparison of the value of the two options during binary decision making. A brain region that performs the comparison process should reflect the value of the both options and signal which is the better option. The difference in value of the two options is a common measure for the comparison process as the sign (i.e. positive or negative) of it could signal the better option (Chau, Kolling, Hunt, Walton, &Rushworth, 2014; Hunt et al., 2012; Lopez-Persem, Domenech, &Pessiglione, 2016). For example, if the value difference between Options A and B (i.e. Option A value minus Option B value) is positive, it means that Option A is a better option. The ventromedial prefrontal cortex (vmPFC) was found to play an important role in the valuation process (Chau et al., 2014; Hunt et al., 2012; Strait, Blanchard, &Hayden, 2014). Functional Magnetic resonance imaging (fMRI) studies also ascertained vmPFC role in the comparison process as its activation is correlated with the difference of options' value (Jocham, Hunt, Near, &Behrens, 2012; Strait et al., 2014).

It is important to note that these two processes are not necessarily discrete, sequential processes, but instead it is possible that both processes could occur simultaneously (Wang, 2002). The mechanism behind the simultaneously occurrence of both process is discussed in the next section.

Decision making models

The underlying mechanism of the valuation and comparison process in binary decision are well-described by several simple but effective models. The drift diffusion model and the biophysical model are two of the widely used models since the neural data from fMRI study and animal single neuron activity matched with the features of these models.

Drift diffusion model (DDM)

The DDM is an influential model as it can predict the reaction time and accuracy of binary decisions. For example, during the process of binary decision making, the model describes that there is an evidence accumulation process on whether option A or option B could be a better option. In other words, if an individual prefers option A than B, there would be a net accumulation of evidence of option A. The accumulation process is terminated when the net evidence of option A reaches a "decision bound", which is a threshold that determines that there is sufficient amount of evidence for making a choice. The rate of the evidence accumulation is also affected by our preference. The accumulation rate would be low if we have similar preference for both options. As a result, it takes longer time for the evidence to reach the decision bound. In addition, the DDM describes the evidence accumulation process as a noisy process (Gold &Shadlen, 2007; Heekeren, Marrett, &Ungerleider, 2008), such that the evidence accumulated is incorporated with noise. When we have similar preference towards the options, the evidence accumulation process would be easily affect by the noise, thus the choice accuracy.

Moreover, Krajbich et al (2010) successfully adopted a modified DDM to explain the relationship between fixation and decision. The authors added an attentional attention component

to the DDM. In their modified DDM, the model accumulates the evidence of the attended option (i.e. the option that the participant is looking at) more rapidly than the unattended options. Krajbich et al (2010) found that the modified version of DDM could better account for the choice biases caused by fixation that are observed in human decision making. This finding provided a theoretical framework on how the fixation could affect the decision.

There is evidence from the neural data to support the DDM in describing the neural activity in a variety of situations. (A. C.Huk &Shadlen, 2005; Krajbich, Armel, &Rangel, 2010; Krajbich &Rangel, 2011; Palmer, Huk, &Shadlen, 2005). At the neuronal level, Roitman and Shadlen (2002) identified some parietal cortex neurons in rhesus monkeys behave in a way that is similar to the predictions made by the DDM while they were making decision based on perceptual information. The authors found that the activity of the parietal neurons fired more robustly when the task is simpler. This finding is in line with the DDM predictions that the rate of evidence accumulation is faster in simpler decision (i.e. one of the options is obviously better than the other one).

Biophysical model

The above studies provided evidence on the DDM in handling binary decision. However, One disadvantage is that the DDM does not offer any description about how decisions are made in a neuronal network. Another class of model, namely biophysical model, simulates how neurons are connected to each other as a network, how they receive choice information and then make a decision (Wang, 2002). This model was applied to describe the neural process of

decision making (Chau et al., 2014; Hämmerer, Bonaiuto, Klein-Flügge, Bikson, &Bestmann, 2016; Hunt et al., 2012).

In the paper by Wang (2002), he used a biophysical model to simulate the neural activity of binary decision. Their biophysical model comprises of two excitatory pyramidal neuron pools and an inhibitory interneuron pool. Each pool of excitatory neuron receive task-related input (i.e. option value) from one of the options. When the input (option value) is higher, the activity of the corresponding excitatory neuron pool will also be higher (i.e. the valuation process). Both excitatory neuron pools are self-connected by a recurrent excitatory connection so that the neuron pool can continuously excite itself in order to "memorize" the option value.

Apart from that, both excitatory neuron pools are connected to a common inhibitory neuron pool to conduct the comparison process. The inhibitory neuron pool mediates the activity of the excitatory neuron pools by exerting an inhibitory output back to themselves. For example, after the inhibitory neuron pool received an input from the excitatory neuron pool A, it will exert an inhibitory output to both excitatory neuron pools A and B. The neuron pool A could indirectly suppress the neuron pool B activity through the inhibitory neuron pool. In general, the neuron pool with higher activity (i.e. a pool encodes for a better option) will exert stronger input to the inhibitory pool which will be more effective in inhibiting another neuronal pool with lower input (i.e. a pool encodes for a poorer option). Since the excitatory neuron pools continuously encode the option's value and exert excitatory output to the inhibitory pool, the valuation and comparison process are also describe to be a simultaneous process. Eventually, there will only be one excitatory neuron pool ending up in a high firing rate state and the other pool will have a

particular low activity. The neuron pool with a high firing rate state is the ‘winning’ neuron pool and the high firing rate state is described as the ‘attractor state’ and will be chosen by the model. This model was proposed to be suitable to explain the behavior in both binary and multiple choice decision making by increasing the number of excitatory neuron pool (Chau et al., 2014; Furman &Wang, 2008; Wang, 2012).

Previous studies suggested that the biophysical models are able to predict both human choices and neural activity (Bonaiuto, DeBerker, &Bestmann, 2016; Chau, Kolling, Hunt, Walton, & Rushworth, 2014; Hämmerer, Bonaiuto, Klein-Flügge, Bikson, &Bestmann, 2016; Wang, 2002). Strait et al (2014) observed the neural activity in vmPFC that encodes the chosen option reached an ‘attractor state’ before decision. Azab and Hayden (2017) also observed the dorsal anterior cingulate cortex (dACC) exhibits the ‘attractor state’ pattern during decision process. These studies highlighted the decision making mechanism suggested by the biophysical model is similar to our brain activity.

Multiple choice decision making

Since most studies and models discussed above are only focused on binary decision making, there has been relatively little understanding on the multiple choice decision making. However, it is reasonable to assume that there are common mechanisms shared between multiple choice decision making and binary decision making. For example, similar to binary decision making, the vmPFC encodes the value difference signal for comparing the option value in multiple choice decision making (Boorman, Rushworth, &Behrens, 2013). However, it is not

reasonable to apply the same framework to the multiple choices decision as the increased number of irrelevant options can significantly influence the mechanism and the outcomes of a decision.

Early theories proposed that those irrelevant options should not cause any influence on our decisions (Luce, 1959). However, recent experimental findings revealed this might not be true. The observation of decoy effects is one example that suggests that our decisions are influenced by the presence of irrelevant options (Pettibone &Wedell, 2007; Slaughter, Sinar, &Highhouse, 1999; Wedell &Pettibone, 1996). Decoy effects describe a phenomenon that when there are three options even the worst option can still affect the preference of an individual towards the other two options. Imagine you are shopping for a new phone and there are only two available options. One has a 7 inch screen but with a 800 megapixel camera (option A) whereas the other one has a 6 inch screen but with a 1200 megapixel camera (option B). It is hard to make a decision between these two phones because both phones have its pros and cons. Decoy effects suggest that if we provide an additional option to you that is inferior to one of the options in both attributes, it increases the probability of you buying that option. For example, there is a third phone with an even smaller screen (5 inch) and a poorer camera (1000 megapixel) than option B. The presence of this additional option will increase your preference towards option B because option B looks better than the additional option in both attributes.

Apart from the decoy effects, recent decision making studies also demonstrated the impact of the irrelevant option on our choice (Boorman et al., 2013; Churchland, Kiani, &Shadlen, 2008; Insabato, Pannunzi, &Deco, 2017; Reutskaja, Lindner, Nagel, Andersen, &Camerer, 2018). Chau et al (2014) demonstrated the presence of a non-choosable, irrelevant

option would affect both our neural activity and choices. In the experiment, the authors asked their participant to make a choice between two options. On some of the trials, an additional third option was presented as a distractor (i.e. an irrelevant option). The results showed although the distractor was not an available option, its value would still have an impact on their choice. In particular, the presence of a higher-valued distractor would lead to a better decision. Chau et al (2014) proposed that when the value of the distractor option is high, it increased the overall inhibitory power of the neural network. As a result, the neuronal population that encodes the poorer option is more efficiently inhibited and the difference in activity between the neuronal populations related to the better and poorer options becomes more prominent. Hence, it reduces the impact of the poorer options on choices. The authors also observed this pattern from the vmPFC activity. The value difference signal encoded in the vmPFC was stronger on trials with a higher distractor values than trials with poorer distractor values. These results suggested that options that seemingly irrelevant and unimportant can still affect both our brain activity and behavior.

Although the biophysical model was proposed that it can model the neural activity of multiple choice condition by adding new neural pool to encode additional option, it did not account for the uniqueness in multiple choice decision making such as how the additional irrelevant information affects our choice. It is also not reasonable to increase the number of neural pool infinitely according to the option number since we have limited cognitive resource. Therefore, to study the neural mechanism of multiple choice decision making, the issue of handling additional irrelevant information under limited cognitive resources is important. This issue revealed the limitation of the current model. The dlPFC and the PPC are two possible

candidates that might help to resolve this issue in multiple choice decision making because both regions are actively involved in decision making and working memory. The role in encoding working memory is particularly important in multiple choice decision making as the ability of manipulating information is part of the working memory (Baddeley, 1992). A brain region that encodes working memory could able to manipulate the irrelevant option and reduce its impact on our choice. I will describe the role of the dlPFC and PPC in decision making and working memory in more detail below.

1.2 Dorsolateral prefrontal Cortex

Anatomy

The dlPFC consists of Brodmann areas (BAs) 9 and 46, it is dorsal to the inferior frontal sulcus. The dlPFC is well-connected to the anterior cingulate cortex (ACC) (Tik et al., 2017; Voloh, Valiante, Everling, &Womelsdorf, 2015) and posterior parietal cortex (Cieslik et al., 2013). Besides, Takada (2004) reported that the dlPFC is connected to motor areas such as the pre-supplementary motor area (pre-SMA) and rostral cingulate motor area (rCMA) via Premotor cortex (PMC). Such connection to the motor area might able to explain the role of dlPFC in decision making. This will be discussed below.

Decision making

Before discussing how the connection to the motor area would explain the features of the dlPFC activity, I will first describe the role of the dlPFC in multiple choice decision making. Recent studies illustrated the dlPFC encodes the subjective value of options (Jamali et al., 2019;

Lara, Kennerley, &Wallis, 2009). Jamali et al (2019) recorded the dlPFC activity of human participants with single-unit recording technique while they were required to judge subjectively whether the situation in a scene is safe or not. For example, participants were presented scenes with a jogger running next to a vehicle in different distances and asked to judge whether the jogger was safe or not. The authors found that the dlPFC activity could predict the judgement of that participant. If the dlPFC was responsible for encoding the objective "safety level", the dlPFC activity of all participant should be similar and predictable. However, they found that the dlPFC neurons varied across participants even they were judging the same scene. It means that, they could notuse activity of a participant to predict the judgement of another participant. Therefore, the authors suggested that the dlPFC encoded the subjective value of judgment instead of objective value for all participants.The authors also found that there was a great variability of subjective judgement of the 'safety level' in participants that with an intact dlPFC. However, less variability was observed in the participant with a dlPFC lesion. The authors argued that the judgement of the lesioned group was more objective because objective judgement generally has less variability than subjective judgement. This finding suggested that the dlPFC is able to encode the subjective value of an option.

Other than engaging in the valuation process, the dlPFC might also be important to the comparison process when the options share a similar value. Voigt et al (2019) used fMRI to examine the activation of the dlPFC while human participants were making binary decisions between snacks. On trials when the two options had similar subjective values, the dlPFC activity is particularly high. These results suggested that the dlPFC might be crucial in making hard decisions. It also implied that the dlPFC activity was correlated with the difficulty level.

In addition to the above, the dlPFC activity also contains the information of the choice (Cai &Padoa-Schioppa, 2014; Hunt, Behrens, Hosokawa, Wallis, &Kennerley, 2015; Tsutsui, Grabenhorst, Kobayashi, &Schultz, 2016). In the study by Hunt et al. (2015), monkeys were trained to choose between options of different values and costs. The monkeys indicated their choices by making a saccade to the desired option. The authors used neurophysiological recording to capture the signal from the dlPFC and observed an transformation of the dlPFC activity across time from encoding the option value at the early time of a trial to encode the chosen saccade at the later time of a trial. Cai and Padoa-Schioppa (2014) recorded activity of dlPFC neurons in monkeys and reported that most of the dlPFC neurons encode the option value while the options are presented. Later on, when the monkey was needed to make a choice, most of the dlPFC neurons then switch to encode the chosen target. Based on these results, Cai and Padoa-Schioppa suggested that the dlPFC could be an important region for connecting the decision making system and the motor system.

Working memory

Working memory is closely related to decision making especially in multiple choice decision making. When there are plenty of options, working memory is particularly important to hold option information and to manipulate the remembered information for making decisions. The dlPFC was found to be an important neural substrate of working memory (Bastos, Loonis, Kornblith, Lundqvist, &Miller, 2018; Clayton E.Curtis &D'Esposito, 2003; Jimura, Chushak, Westbrook, &Braver, 2017; Leavitt, Pieper, Sachs, &Martinez-Trujillo, 2017; Miller, Erickson, &Desimone, 1996). A delay-to-response task in which the subject had to recall the location of a

target after a delay was commonly used to assess whether a region is involved in working memory (Goldman & Galkin, 1978; Kesner, Bolland & Dakis, 1993; Kesner & Gilbert, 2006). The ability of storing the task-related information in this task determine whether the subject could make a correct response. Two types of task related information were necessarily to be maintained during the delay period: the spatial location of the target and the intended response. Studies showed that these two information were stored in different regions.

The dlPFC was found to store task related information when encoding working memory. Results of Goldman and Galkin (1978) showed that, after a surgical lesion in dlPFC, the accuracy of the delay-to-response task dropped nearly to the chance level. On the other hand, a later study by Passingham (1985) provided convergent evidence supporting the role of dlPFC in working memory. In this study, monkeys were trained to perform a similar experimental task as in Goldman and Galkin's study (1978). Again, after the dlPFC was damaged, animals performed poorly when they were recalling the locations of the targets after a delay. Critically, when the delay period was removed and working memory was no longer demanding, these animals showed intact performance in reporting the target locations. One explanation of this phenomenon is that the dlPFC stores the task related information, in this case, the spatial information of the target. Recent single-unit recording studies provided evidence for this argument. Donahue and Lee (2015) recorded the activities of dlPFC neurons when monkeys were performing a binary decision making task. Their results showed that after the options were presented to the monkeys, there were a significant proportion of dlPFC neurons started to encode the spatial information of the targeted option.

The other task-related information, the intended response, was found to be stored in the medial caudate nucleus(Kesner, Bolland, &Dakis, 1993; Kesner &Gilbert, 2006). Kesner and

Gilbert (2006) trained mice to perform a delay-to-response task in which the mice need to maintain the memory of the intended motor response instead of the target spatial location. The mice stayed inside a start box at the beginning of the experiment. The target and start box's spatial location would change after a delay. However, the relative location of the target to the start box would remain unchanged. For example, if the target was placed on the left side of the start box, it remained on the left side of the start box. Therefore, the mice would need to remember the motor response made before instead of the spatial location of the target and recall the same motor response after the delay. Interestingly, after a lesion in the medial caudate nucleus, the performance dropped to nearly chance level. This result showed that the intended motor response was stored in the medial caudate nucleus.

The causal role of the dlPFC in working memory was also revealed in humans by using non-invasive brain stimulation techniques, such as transcranial direct current stimulation (tDCS) and Transcranial magnetic stimulation (TMS), to either enhance or disrupt its activity transiently (Boggio et al., 2006; Fregni et al., 2005; Rossi et al., 2001; Zaehle, Sandmann, Thorne, Jancke, &Herrmann, 2011). In the study by Fregni et al. (2005), anodal tDCS was administered to enhance the dlPFC excitability and the behavior in stimulation session was compared with that in the control stimulation session. The N-back task was adopted to examine the working memory capacity in which the participant had to indicate if the current stimulus was the same as the stimulus presented in N trial(s) before (e.g. if N is 2, then the participant is needed to reported if the current stimulus is same as that two trials before). Therefore, the participant needed to memorize the previous stimulus and compare with the current stimulus. Results discovered that

there was a significant improvement after anodal stimulation at the dlPFC. This supports the causal role of the dlPFC in working memory capacity.

Consistent with the lesion and tDCS studies, single-cell recording studies also assessed the role of the dlPFC in working memory by providing a more in-depth view. Leavitt et al. (2017) measured monkeys' neuronal activities of the dlPFC in a delay-response task. During the task, some stimuli were presented randomly in one of the locations of a 4 times 4 grid. The monkeys had to indicate the location of the stimulus after a delay of 500 to 1500ms. They found that during the delay period, the dlPFC neurons that encoded the stimulus location demonstrated a sustained activity over time. This suggested that the memory was maintained in the form of sustained dlPFC neuronal activity.

In multiple choice decision making, there is a greater demand on working memory to hold plenty of irrelevant options. It is possible the dlPFC could play a role in processing the additional irrelevant information. Other than working memory, the dlPFC also has a role in executing cognitive control that might allow us to focus on the most relevant options.

Cognitive-control

The dlPFC has been reported to be involved in various types of cognitive control. For example, the dlPFC became more active when self-control is needed (Hare, Camerer, &Rangel, 2009). In general, people tend to choose to eat tasty food instead of healthy food. Since the tasty food is often unhealthy, we may need to control our desire on consuming excess unhealthy tasty food. In the study of Hare et al (2009), it found that when the participant chose a healthy but not

tasty food, the dlPFC activation was greater than choosing the tasty but not healthy food. Hare et al (2009) suggested the dlPFC could modulate the value representation towards the option in the vmPFC. In line with their hypothesis, they found that there is a functional connection from the dlPFC to vmPFC though the inferior frontal gyrus during self control.

The dlPFC is also important in exhibiting the cognitive control during intertemporal decisions (Figner et al., 2010; Peters &Büchel, 2011). An intertemporal decision often involves decisions between options that associated with either immediate but smaller reward or delayed but larger reward.. Figner et al (2010) asked their participant to make a binary choice intertemporal decision and they showed that an inactivation on the dlPFC would lead to a more frequent choice of the immediate reward.

Another evidence on the role of the dlPFC in self-control was provided from a cigarette craving study (Hayashi, Ko, Strafella, &Dagher, 2013). Hayashi et al (2013) combined both fMRI and TMS to investigate which neural substrate could inhibit the cigarette craving desire. The craving on the cigarette and intention to smoke were measured by a self-reported visual analog scale. They found that the participant received an active TMS on the dlPFC will have a reduction in craving cigarette as well as the intention to smoke index.

Taken together, these findings implicate the dlPFC in valuation component of decision making. Its activity can reflect the option value and might help in resolving hard decisions. The dlPFC might be particularly important in dealing with the additional irrelevant information in

multiple choice decision as it encodes working memory. Also, its role in cognitive control could direct our focus to the target without being distracted by the irrelevant information.

Other than the dlPFC, the PPC is another region that has a role in decision making and working memory. Since the PPC role seems to be similar to the dlPFC, it makes the PPC another potential candidate that is important in multiple choice decision making.

1.3 Posterior Parietal cortex

Anatomy

The PPC involves Brodmann's areas 5, 7, 39, and 40. The intraparietal sulcus (IPS) is an important landmark that divides the PPC into two parts: the superior parietal lobule (Brodmann's area 5 and 7) and inferior parietal lobule (Brodmann's area 39 and 40). The lateral intraparietal area (LIP), which is located in the inferior parietal lobule and lateral to the IPS, is a subregion of the PPC that has been widely studied in decision neuroscience literature. It receives input from various visual sensory areas, such as the occipital and parietal lobes (Ibos, Duhamel, &BenHamed, 2013; Lewis &VanEssen, 2000a). It is also connected to other regions related to eye-movement such as the frontal eye field (FEF) and the superior colliculus (Lewis &VanEssen, 2000a; M. N.Shadlen &Newsome, 2001).

The PPC is also connected the dlPFC to form the frontoparietal network (Domenech, Redouté, Koechlin, &Dreher, 2018; Duncan, 2010). Synchronization of both regions by using

transcranial alternating current stimulation enhances the performance in working memory tasks (Violante et al., 2017). A persistent activity was observed in both regions after the offset of visual stimuli when encoding working memory (Constantinidis &Procyk, 2004; Goldman-Rakic, 1995). The persistent activity in the PPC contains spatial information of the targeted visual stimuli. These results implied that PPC has a key role in encoding working memory

Decision making

Similar to the dlPFC, the PPC is involved in decision making such as encoding the option value. Platt and Glimcher (1999) demonstrated the engagement of the LIP neurons in encoding the value of options (the valuation process). In their experiment, the monkeys had to choose between two options that associate with different reward amount. They demonstrated that the LIP neuron activity is modulated by the value of the option that was placed inside the receptive field (RF) of the recorded neuron. RF refers to the particular physical location that elicits the greatest neural response of a particular neuron. Another evidence showing the PPC activity would be modulated by the option is from the study of Wu et al (2015). They used fMRI to capture the activation in the human PPC while the participant was making a choice between two lottery options. Each lottery option consisted of two pieces of information, the reward amount of the lottery and the probability of obtaining the reward. Their results showed that the PPC activation reflected the value of the lottery option (Wu, Delgado, &Maloney, 2015). It means that when the lottery has a higher reward amount and a higher probability of obtaining the reward, the PPC would have a greater activation. Huettel et al (2006) also found evidence on the risk preference (the probability of obtaining the reward) of the participants could predict the

activation in the PPC using fMRI. These results showed that the PPC has a similar role to the dlPFC in the valuation process.

However, unlike dlPFC, the option value encoded by the PPC is independent of the final choice (Bendiksby &Platt, 2006; Leathers &Olson, 2012). Leathers and Olson (2012) trained monkeys to decide between options associated with either different value or penalty. Results showed that the PPC would exhibit a higher activity when the option placed inside the RF was associated with high penalty even if the monkey chose the low penalty choice. This suggested that the PPC activity does not reflect the choice but the salience of the option.

The PPC was also found to be closely connected with the frontal eye field (FEF) (Chafee &Goldman-Rakic, 2000; Szczepanski, Konen, &Kastner, 2010). Although the FEF and dlPFC are anatomically close to each other, the FEF exhibited a significant role in saccade-related task. Similar to the PPC, FEF's activities were modulated by the stimuli inside their RF (Sato, Watanabe, Thompson, &Schall, 2003; Smith &Ratcliff, 2004). In contrast to the PPC, the FEF's activities were found to be closely related to the generation of saccades (Mirpour, Bolandnazar, &Bisley, 2018). Mirpour, Bolandnazara and Bisley (2018) found that when the targeted option was located in the fovea, the FEF would exhibit a low activity and when the fixation was maintained on the target. However, when a target was located outside the fovea, the FEF would become more active and guide a saccade towards the target. This feature of FEF is important to decision making in which helps us to stay focused on the targeted option during the information sampling process.

The PPC also helps in making decision based on perceptual sense (Swaminathan &Freedman, 2012; Zhong et al., 2019). Zhong et al (2019) tested the causal role of PPC of that using several techniques such as optogenetics to inactivate the PPC in mice. They trained mice to categorize auditory input into two categories, high tone and low tone. Their results suggested that the performance of categorizing well-learnt stimuli remains unchanged whereas the performance of categorizing newly learnt stimuli was significantly impaired after either silencing or inactivating the PPC. It implied that the PPC contributes to decision making when we are facing new stimuli. Moreover, they also tested whether the PPC could reduce the short-term history bias effect or not. The short-term history bias effect describes that our choice is easily biased by the most recent choice. For example, if we choose the left option in the last trial, our choice of the current trial would be biased to choose the left option. The authors also identified the role of the PPC in balancing this bias as the choices in the control group (with intact PPC) was not biased while the choices in the experimental group (i.e. silenced PPC) was biased to the choice of the last trial. The underlying mechanisms of how the PPC involved in history-bias could be accounted by its activities. A recent mice single-unit recording study showed that the activities of PPC neurons carry more information of the previous stimuli than the current stimuli (Akrami et al. 2018). These information about previous stimuli could counterbalance the response to avoid history bias.

There is also another type of history bias which the subjects would avoid repeating the previous response instead of repeating choosing the same response. Studies showed that the motor cortex activity before decision contributed to the alternation of responses (Pape & Siegel, 2016). The author claimed that the activity of motor cortex before decision carried the information of the previous response in which we utilized these information to counteracted the

history-bias. Hippocampus might also be involved in this situation. Wood et al (2000) recorded the neural activity of hippocampus while the mice was performing a spatial alternation task. The mice need to go to the direction (i.e. left or right) that is different from the previous trial to obtain a reward. The authors found that there are neurons in hippocampus selectively sensitive to the chosen direction (i.e. left or right) in the previous trial. These results showed that the hippocampus would be another key region contributes to counterbalance the history-bias.

Working memory

Like the dlPFC, the PPC also serves a key role in working memory. A persistent activity was observed from the PPC during the delay period (Gnadt &Anderson, 1988). However, compared to the dlPFC, the PPC engaged differently in working memory as its activity reflected the working memory capacity (Machizawa &Vogel, 2004; Todd, Marois, &Todd, 2004). Todd and Marois (2004) tested the role of the PPC in a working memory experiment in various levels of memory demand. The authors first showed a bundle of dots with different colors in different spatial locations to the participant and the number of dots varied across trials. The memory demand increases with the number of colored dots. After a delay period, a colored probe was shown and the participant had to indicate whether the probe matched with the previous colored dots were in the same position. They found that the PPC peak activation amplitude is correlated with the number of dots encoded (memory capacity) and exhibits a greater activity during both encoding (when the stimuli were presented on the screen) and maintaining (the delay period) period on the trial with greater working memory load.

Besides the PPC activity, the literature also show evidence that the collaboration of PPC and dlPFC would affect the working memory capacity. Edin et al (2009) proposed a top-down modulation model of the working memory capacity. In their model, the working memory capacity is determined by the activity of the PPC neurons and the amount of external input. A higher PPC activity and a greater external input to the PPC would increase the working memory capacity of the model. The dlPFC was proposed as a major source of external input to the parietal region (Edin et al., 2009). The model predicts that stronger connections between the dlPFC and PPC can boost working memory capacity, which is in line with previous findings (Palva, Monto, Kulashekhar, &Palva, 2010). Edin et al (2009) also conducted a human fMRI experiment on working memory and the results replicated the model prediction. The synchronization of the PPC and dlPFC activation increased when there was a high working memory load, suggesting that both regions are important on the trial that needed greater memory capacity. If the dlPFC is the source of external input to the PPC to boost the working memory capacity, the dlPFC should be better correlated to the performance on high load trials than low load trials because greater memory capacity is needed. The authors did observe the dlPFC activation has a stronger correlation with the performance on higher memory load trials than low load trials whereas the PPC activation has a similar correlation with the performance on all type of trial. Edin et al (2009) studies showed that the PPC activities correlated with the working memory capacity and the dlPFC would act as an external source to boost the working memory capacity.

Apart from the study of Edin et al (2009), the PPC and dlPFC were demonstrated to have a joint participation in working memory in various studies (Jacob, Hähnke, &Nieder, 2018; Palva

et al., 2010; Salazar, Dotson, Bressler, &Gray, 2012; Violante et al., 2017). The connectivity of the dlPFC and PPC was strengthened after having received training on working memory capacity (Constantinidis &Klingberg, 2016). Pavla et al (2010) combined MEG and Electroencephalography (EEG) to examine the degree of synchronization between parietal and frontal areas while encoding working memory. Their results suggested that during the delay period in a working memory task, the activity of the two regions becomes more synchronized and that the degree of this synchrony increased with the amount of information encoded (Palva et al., 2010; Salazar et al., 2012). The findings from these studies are in line with the model proposed by Edin et al (2009) that suggests that the collaboration of the dlPFC and PPC is important in working memory.

To summarize, the PPC is another neural substrate that participates in making decisions such as the valuation process. It also collaborates with the dlPFC to encode working memory. The collaborative role of dlPFC and PPC in working memory may favor them to deal with the irrelevant options in multiple choice decision making.

1.4 The current report

The current thesis aims to address the question of the specific roles of dlPFC and PPC in multiple choice decision making? In general, during decision making we should encode the value of the available options and make comparisons among them. Previous literature mainly

focused on studying the general mechanisms of decision making with a few choices, such as binary or trinary choices. However, models that describe the behavior and neural activity of these decisions may not be applicable when the option number increases. As there are more options, it is harder for us to remember the identity and value of all options and to manipulate the information gathered. In order to prevent the distractions from poor options, good manipulation of the registered information could keep us staying focused on the better option. Since there are key differences in the cognitive requirements between the well-studied binary decisions and multiple choice decisions, I performed an experiment to investigate the role of the dlPFC and PPC in multiple choice decision making.

In Chapter 2, I report an experiment that investigated the role of the dlPFC in multiple choice decision making. I designed a task with snack items and tested human participants. By using tDCS, I tested the role of the dlPFC in multiple choice decision by comparing the excitatory stimulation session and controlled session. I will provide evidence that reveal the role of dlPFC in information processing in multiple choice decision making.

In Chapter 3, I report an experiment that investigated the role of the PPC in multiple choice decision making. By adopting a similar experimental paradigm described in Chapter 2, I revealed the role of PPC in information processing and the distinct role of PPC and dlPFC in multiple choice decision.

Chapter 2: DlPFC in multiple choice decision making

2.1 Introduction

Despite a considerable amount being known about the neural mechanisms underlying decision making, such as the involvement of posterior parietal cortex (PPC) and ventromedial prefrontal cortex (vmPFC) (Chau et al., 2018; Hunt &Hayden, 2017; M. N. N.Shadlen &Shohamy, 2016), much of this knowledge was obtained from experiments where participants were offered a few choices only. However, the underlying mechanism of multiple choice decision making may differ from decision with few choices for important reasons. For example, the cognitive demand of decisions that involve larger numbers of options would be greater than decisions with fewer options. We need to handle and manipulate a greater amount of information from the options by shifting our focus onto a subset of information that facilitate us to make the best choice and filtering out information that are irrelevant and distracting at the same time. As we have limited cognitive resources and capacity (Cowan, 2010), making these decisions with a large number of options may involve an additional mechanism. I designed an experiment that aimed to study the neural mechanism of multiple choice decision making.

One candidate region that could be particularly important to multiple choice decision making is the dorsolateral prefrontal cortex (dlPFC) for two reasons. Firstly, the dlPFC was widely reported to be a key hub to encode working memory (Bilek et al., 2013; Chiang &Wallis, 2018; D'Ardenne et al., 2012; Leavitt et al., 2017; Violante et al., 2017). Numerous studies

observed a robust and persistent neural activity during the delay period of working memory task in animal experiments (Katsuki, Qi, et al., 2014; Katsuki, Saito, &Constantinidis, 2014) as well as in human fMRI experiments (C. E.Curtis, Rao, &D'Esposito, 2004; Sakai, Rowe, &Passingham, 2002; Sreenivasan, Curtis, &D'Esposito, 2014). For example, Sakai et al (2002) recorded the blood-oxygen-level-dependent (BOLD) signal from human participants while they were performing a working memory task. Participants were presented visual stimuli at different locations transiently and were asked to make responses about these locations after a delay. They found that the BOLD signal of the dlPFC remained strong when the participant needed to maintain the memory of the stimuli location during the delay period. Hence, during multiple choice decision with a large number of options, it is possible that the dlPFC is particularly important to hold as much relevant information as possible for effective decision making.

Secondly, apart from encoding relevant information, dlPFC also has an important role of filtering irrelevant information. This was demonstrated repeatedly in human fMRI (Clapp, Rubens, &Gazzaley, 2010; Dolcos, Miller, Kragel, Jha, &McCarthy, 2007; Feredoes, Heinen, Weiskopf, Ruff, &Driver, 2011; Postle, 2005), monkey single cell recording (Suzuki &Gottlieb, 2013) and computational modeling (Murray, Jaramillo, &Wang, 2017) studies. For example, both Feredoes et al (2011) and Dolcos et al (2007) observed a greater activation in dlPFC during the delay period on trials with irrelevant and distracting information than trials with no irrelevant and distracting information in human fMRI experiments. Similarly, Suzuki and Gottlieb (2013) trained monkey to perform a working memory task and found that dlPFC neurons encoded the spatial information of both the target stimulus and irrelevant stimuli (a distractor). Interestingly, on the correct trials where the location of the target was successfully recalled, the representation

of the correct stimulus location in the dlPFC is stronger than the distractor location. In contrast, on error trials, the representation of the distractor stimulus became stronger than that of the correct stimulus. This result illustrated the role of the dlPFC in filtering and suppressing the neural representation of the distractor. If the dlPFC could suppress the distractor representation successfully, it would be much easier for us to recall a correct answer or to make an adaptive decision. In the current study, I tested whether the dlPFC also has a role in filtering out irrelevant information in multiple choice decision making.

The dlPFC is sometimes implicated in decision making studies and this is particularly true in those decisions where it is important to focus on a subset of relevant information and to ignore another subset of irrelevant information. For example, it is often tempting to choose a food that is tasty rather than healthy. However, when people are asked to choose healthier food, the dlPFC activity is strongly related to the value of the healthy, as opposed to another situation when people are freely choosing some unhealthy but tasty food (Hare et al., 2009; Hare, Schultz, Camerer, O'Doherty, &Rangel, 2011). In addition, the causal role of the dlPFC in decision with irrelevant information could be illustrated by lesion studies. Vaidya and Fellows (2016) found that patients with dlPFC lesions are more easily distracted by the visual stimuli that are irrelevant to their choices and prone to misuse information they obtained to guide their decisions. However, most of these studies focused on the role of dlPFC in dealing with a small quantity of irrelevant information. We have very little understanding on the role of dlPFC in dealing with a large number of irrelevant information, especially during multiple choice decision making. During multiple choice decision making, it is important to focus on information related to the best option available and to ignore information related to the poorer options. Thus, it is possible that the

dlPFC is particularly important to guide individuals to focus on the most important option during multiple choice decision making.

In the current study, I examined the role of dlPFC in multiple choice decision making using high definition transcranial direct current stimulation (tDCS). Participants were tested in two experimental sessions in which either excitatory anodal tDCS or control sham tDCS was applied in a double-blinded design. After receiving tDCS, participants performed a decision making task in which they were presented with food choices in sets of two, four or sixteen on each trial. Eye movement was recorded concurrently in order to understand how participants sampled information and how the information was used to guide decision making. Our results provided causal evidence suggesting that the dlPFC plays a role in filtering information from options that are particularly poor in terms of value and especially when these poor options are sampled just before a decision is made.

2.2 Methods

Participant

Thirty-three healthy right-handed young adults were recruited in this study by convenience sampling (aged 18-30 years, 17 females). Since I investigated the general neural mechanisms of multiple choice decision making, thus I tested normal healthy participants. Convenience sampling is an easy and cost effective way to recruit healthy participants, which is commonly employed in decision neuroscience experiments. All participants had no current, or history of, neurological / psychiatric conditions and had normal or corrected-to-normal vision. They were also required to pass the safety screening of tDCS using the Transcranial Magnetic Stimulation Adult Safety Screen before the experiment. Written informed consent was obtained from each participant before the test. This study is approved by the Human Subjects Ethics Committee of The Hong Kong Polytechnic University.

Procedure

The experiment adopted a double-blinded cross-over HD-tDCS design, in which the participant was tested in two experimental sessions separated at least one week apart. To ensure the participant was motivated to select between snacks, they were requested not to consume any food at least two hours before the experiment. Each session started with a Becker–DeGroot–Marschak (BDM) auction procedure to assess participants' subjective preference to each snack and then participants received either anodal or sham HD-tDCS. The order of anodal/sham stimulation was randomized across sessions and double-blinded to the participant and experimenter. The identity of the stimulation of each session was decided by a second experimenter and was revealed only after the end of the whole experiment. Since the effect of the

stimulation is strongest approximately 30 to 60 minutes after stimulation (Kuo et al., 2013), the participant rested for fifteen minutes after receiving tDCS and then performed a multiple-choice decision making task.

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, DeGroot, &Marschak, 1964). These snacks would be used later in the multiple choice decision making task. In particular, the participant was presented with pictures of snacks and required to indicate his/her willingness-to-pay (WTP) for each snack, using a visual analog scale of HK$0 to HK$20. In other words, they had to indicate how much money they are willing to spend to have the opportunity to consume the snack. The participant was encouraged to indicate the WTP according to their subjective preference.

Five snacks chosen by the participant later during the decision making task were randomly selected after each session of the experiment. For each selected snack item, a random price ranged 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 according to that random price. If the random number was higher than the WTP, the participant lost the chance to buy that snack. All the snacks that were bought had to be consumed before leaving the laboratory and this encouraged participant to perform the task according to their subjective preferences.

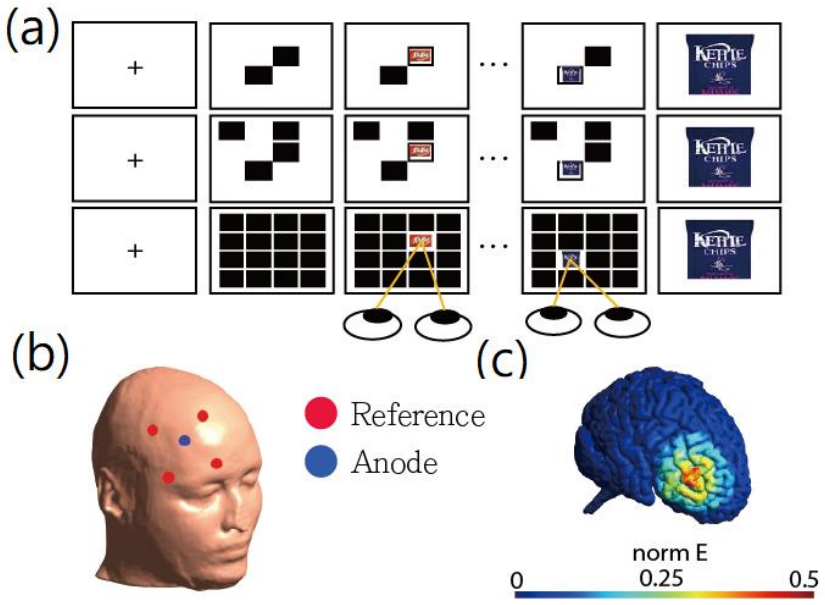

Figure 1. The decision making task and current density simulation of HD-tDCS. (a) Every trial started with a fixation cross presented at the center of the screen. Then, two, four or sixteen options that were covered by black rectangles were presented. The identity of each option was revealed transiently only when the participant fixated on it. The participant was required to choose the favorite option among all given options. Finally, the chosen option was presented at the center of the screen. (b) HD-tDCS was applied using a 4 x 1 montage over the right dlPFC. The anode (red dot) which delivery the current was surrounded by 4 reference electrodes (blue dots). (c) A simulation confirmed that the current density was strongest in the dlPFC.

Decision making task

In the multiple-choice decision making task, the participant was required to choose repeatedly between different snacks that had been rated earlier in the BDM auction (Figure 1a). The beginning of a trial was indicated by a fixation cross located at the center of the screen and

the participant's eye gaze had to fixate on the cross for one second. Next, two, four or sixteen snack options were presented at the random positions on the screen. Each option was initially covered by a black rectangle. When the participant gazed at an option, the black rectangle covering that option was then removed and a picture of the snack 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 option information could only be obtained from the gaze position (i.e. central vision), but not from the peripheral vision. Participants were allowed to self-pace their sampling process by sampling a new option or re-sampling a previously sampled option. They could make their choices without sampling all the options. All the options presented were randomly assigned from all 64 options for all the trials. Participants then chose their most preferred snack on the trial by gazing at that option and then left clicking the mouse. The chosen option would then be displayed at the center of the screen. The participant had to confirm their choice by left clicking again or to modify their choice by right clicking the mouse, in case an identical trial would then be presented once again. In total, there were 120 trials with 20 two-option trials, 40 four-option trials and 60 sixteen-option trials presented randomly during the task. The number of trials was limited to 120 such that participants would be able to complete the task within 30 minutes, while the HD-tDCS effect was the most robust. In addition, since I wanted to test the role of dlPFC in multiple choice decision making, therefore I had the greatest number of sixteen-option trials.

Throughout the task a Tobii eye tracker was used to monitor the time and position of eye gaze at a sampling rate of 300 Hz. The gaze position data allowed us to measure the amount of time spent on gazing at each option.

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

On each experimental session, I applied either the sham or the anodal HD-tDCS (Soterix tDCS stimulator with a Soterix 4 x 1 HD-tDCS adaptor) over the participant's right dlPFC. The HD-tDCS involved ring shape electrodes arranged in a 4 x 1 montage, i.e. an anodal electrode was placed on the target region and surrounded by 4 reference electrodes located 2.5 cm away from the anode (Figure 1b). The position of the anode that targeted at the right dlPFC region (at MNI coordinates 40, 32, 30) was determined by a meta-analysis of the neural activity associated with working memory (Owen, McMillan, Laird, &Bullmore, 2005). 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 same current was only applied in the first 30 seconds and the last 30 seconds of the 10-minute period. Participant was asked to report any discomfort before, during and after the stimulation.

To confirm that the HD-tDCS was targeted at the right dlPFC, a current density simulation was modeled by SimNIBS (Figure 1c). The current density is at peak on the middle frontal gyrus (MFG) of the dlPFC.

Data Acquisition and Analyses

Three types of behavioral data were collected from the participant: the WTP (that was related to the subjective preference) of the chosen option, reaction time and gaze pattern. The choice accuracy of each trial is defined by the equation below, which indicates the WTP of the chosen option *relative* to the best and worst options available on the same trial:

$$accuracy = \frac{chosen\ WTP - \min(WTP)}{\max(WTP) - \min(WTP)}$$

Linear and logistic regression analyzes were performed for every participant to predict their choice accuracy and chosen option location from different general linear models (GLMs). The beta (β) weight of each regressor in the GLM was calculated.

GLM 1: information processing in dlPFC

$$Choice\ accuracy$$
$$= \beta 0 + \beta 1(\text{duration of fixation on the better option})$$
$$+ \beta 2(\text{duration of fixation on the poorer option})$$

GLM 2: information processing in dlPFC

$Choice\ accuracy\ (16\ option\ trial)$

$$= \beta 0 + \beta 1(\text{duration of fixation on option ranked 1st to 4th})$$
$$+ \beta 2(\text{duration of fixation on option ranked 5th to 8th})$$
$$+ \beta 3(\text{duration of fixation on option ranked 9th to 12th})$$
$$+ \beta 4(\text{duration of fixation on option ranked 13th to 16th})$$

GLM 1 aimed at exploring the relationship between fixation duration and choice accuracy on different trial types. I divided the options into better and poorer options. These refer to the rank 1 option and rank 2 option on the two-option trials respectively; the rank 1 option and rank 2-4 options on the four-option trials respectively; and the rank 1-4 options and rank 5-16 options on the sixteen-option trials respectively. I applied the logistic regression analysis on the two-option trials since the choice accuracy was binary (Figure 5a). A multiple linear regression was applied to examine the data on four- and sixteen option trials (Figure 5b & c).

After testing the relationships between fixation duration and choice accuracy, we further analyzed the beta weights using a three-way ANOVA analysis. The three independent variables were Stimulation Session (anodal or sham session), Trial Type (two-, four- or sixteen-option) and Option Rank (better or poorer option). Furthermore, since we identified a significant effect from the sixteen-option trial between anodal and sham session (Figure 5c), we constructed GLM 2 by dividing options in 16-option trial into 4 smaller groups. GLM 2 allows us to test whether the significant effect in Figure 5c was more robust in options that were poorest.

GLM 3: order effect in dlPFC

$$\begin{aligned} Choice\ accuracy \\ = \beta 0 + \beta 1(\text{duration of fixation on early sampled option ranked 1st to 4th}) \\ + \beta 2(\text{duration of fixation on early sampled option ranked 5th to 8th}) \\ + \beta 3(\text{duration of fixation onearly sampled option ranked 9th to 12th}) \\ + \beta 4(\text{duration of fixation onearly sampled option ranked 13th to 16th}) \\ + \beta 5(\text{duration of fixation onlate sampled option ranked 1st to 4th}) \\ + \beta 6(\text{duration of fixation onlate sampled option ranked 5th to 8th}) \\ + \beta 7(\text{duration of fixation onlate sampled option ranked 9th to 12th}) \\ + \beta 8(\text{duration of fixation onlate sampled option ranked 13th to 16th}) \end{aligned}$$

To further test how the sampling order of the irrelevant option influenced choice accuracy, in GLM3 we split all the regressors in GLM2 according to whether the fixation occurred before or after halfway of the reaction time. The first sampled half is regarded as early fixations whereas the remaining half is regarded as the late fixations.

GLM 4: moving window analysis

$$Choice\ accuracy = \beta 0 + \beta 1(\text{fixation duration on targeted option}) + \beta 2(\text{fixation duration on remaining option})$$

To study the impact of the irrelevant option on choice after anodal stimulation, we used GLM 4 to perform a moving window analysis. The window started at rank 1 to 4 option and moved one step away from the starting point (i.e. rank 1+x to 4+x option in which x ranging from 0 to 12).

2.3 Results

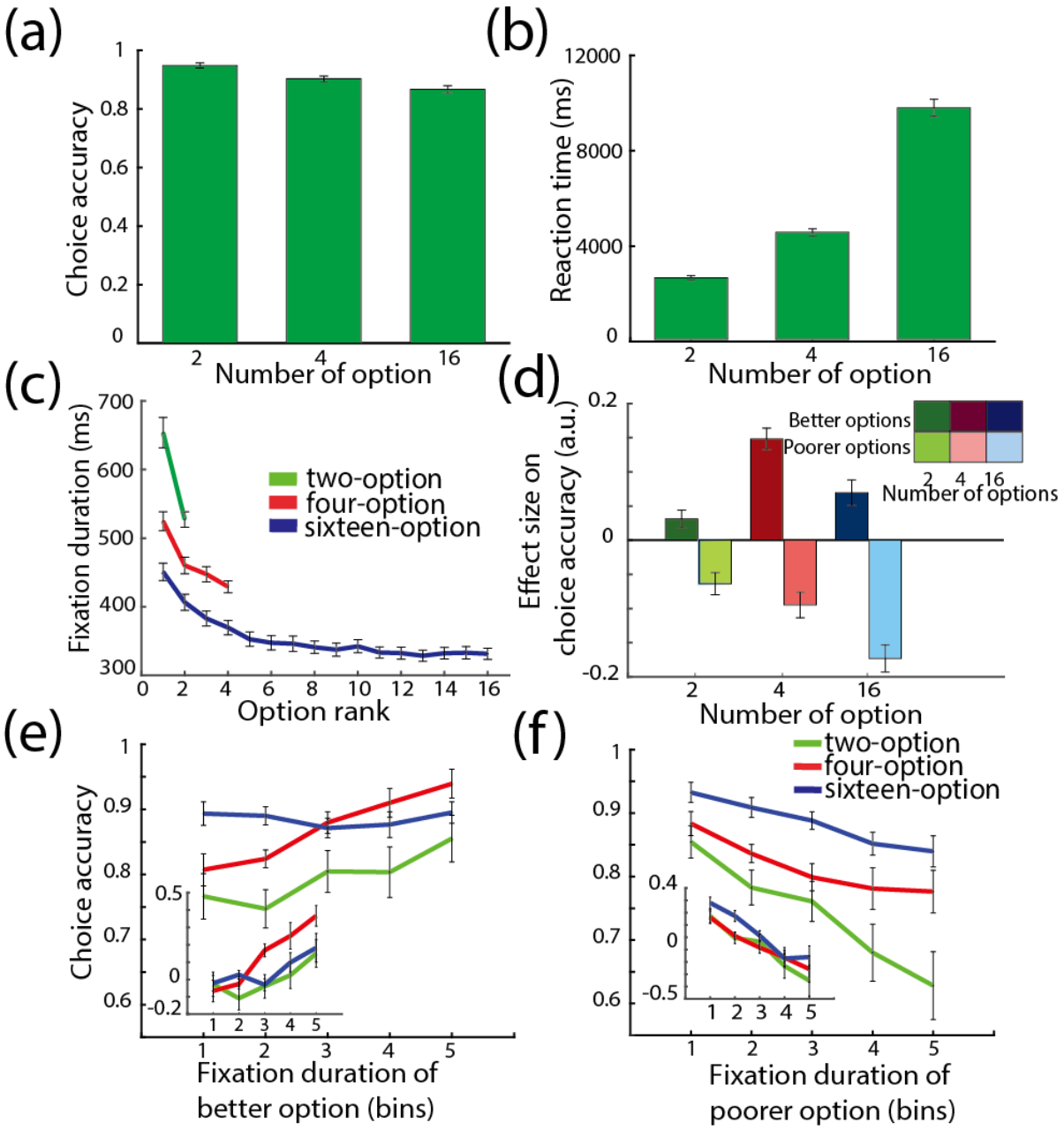
(a)
Choice accuracy
Number of option
(b)
Reaction time (ms)
Number of option
(c)
Fixation duration (ms)
two-option
four-option
sixteen-option
Option rank
(d)
Effect size on choice accuracy (a.u.)
Better options
Poorer options
Number of options
Number of option
(e)
Choice accuracy
Fixation duration of better option (bins)
(f)
two-option
four-option
sixteen-option
Fixation duration of poorer option (bins)

Figure 2. Behavioral analysis of the sham session data. (a) The choice accuracy was negatively associated with the option number. (b) Reaction time was positively associated with the option number. (c) Initial fixation duration sorted as a function of value rank on two-, four- and sixteen-option trial. A higher rank option (e.g. rank 1) refers to options associated with a higher WTP index (i.e. better option). Participants spent more time on options with higher ranking. Also, generally, participants spent more time on viewing options on trials with less options. (d) A linear regression analysis was performed to test the relationship of initial fixation duration and choice accuracy. The results showed that higher choice accuracies were associated with longer fixation durations on better options (darker color bars) and shorter fixation durations on poorer options (lighter color bars) on two-, four- and sixteen-option trials. When trials were binned according to the duration of fixation, higher choice accuracies were shown in (e) bins with longer fixations on the better options and (f) bins with shorter fixations on the poorer options. Insets of (e) and (f) show similar results when the residual choice accuracy, after the effect of the range and sum of option's value were partialled out, was plotted. Error bars denote standard error.

The effects of option number on decision making

First, I tested the effect of option number on choice accuracy, reaction time and information sampling (reflected by participant's fixation duration) by analyzing the data from the sham sessions. The results showed that when there were additional options, participants were more likely to make less accurate decisions by choosing their most preferred option on a trial ($F_{2,134}$=25.171, $p<0.001$; Figure 2a), as well as to make slower decisions ($F_{2, 134}$= 490.723, $p<0.001$; Figure 2b) by a one-way ANOVA analysis with the Trial Type be the sole factor.

The options information sampling process change with the option number

Although slower decisions were associated with larger set of options, it is unclear how time was allocated to sample information of each individual option. It is possible that an uneven amount of time was spent on the additional options presented on those trials with larger choice set. Hence, we analyzed participant's eye-tracking data by investigating the fixation duration at individual options. We focused on the duration of the initial fixation of each option because previous studies suggested that this is more predictive of people's choices compared to other fixation indices (Krajbich et al., 2010; Voigt, Murawski, Speer, &Bode, 2019). Also, as there were various reasons to re-fixate on an option, such as forgetting the location of the options and gathering additional option information, we were not able to distinguish the purpose of each re-fixation in this study. Therefore, only the initial fixation duration were investigated in this study, rather than the re-fixation duration. Figure 2c illustrates the fixation duration at all options sorted as a function of their value rank (i.e. the option with the highest WTP on a trial was assigned as the rank 1 option).

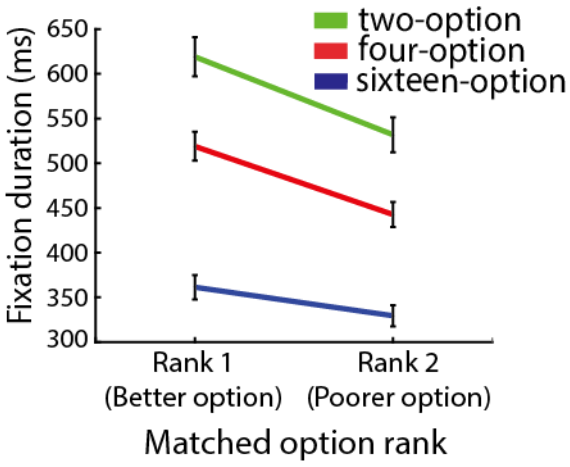

Figure 3. A pair of options with matched WTP (i.e. similar value) between two-, four- and sixteen-option trials was selected from each trial type. The fixation duration of the matched option was plotted against the matched rank option. Similar results were obtained compared to Figure 2C. More time were spent on better options among all trial types. Also, generally, participants spent more time on viewing options on less options trials. *Error bars denote standard error.*

We compared the fixation duration of the best two options on the two-, four- and sixteen option trials using a two-way ANOVA analysis with Trial Type and Option Rank as the factors, to test how information was sampled differently on trials with more options. Firstly, even though the RTs were generally longer on trials with more options, the fixation duration at the best two options were shorter on trials with more options ($F_{2, 64}$= 59.082, p<0.001; Figure 2c). Not surprisingly, the fixation durations at rank 2 options are also shorter than those at rank 1 options as a main effect of Option Rank was observed ($F_{1, 32}$= 65.571, p<0.001). An interaction of Trial Type and Option Rank was not found ($F_{2, 64}$= 0.703, p=0.499). It is possible that these results could be confounded by the fact that the best two options on the trials with more options generally consist of more high WTP options than trials with less options. To rule out this possibility, I repeated the two-way ANOVA analysis similar to the above, so that I could compare how the snack items on the four- and sixteen-option trials with matched WTP with the two-option trials option were sampled differently. Similar main effects of Trial type ($F_{2,64}$=159.390, p<0.001) and Option Rank ($F_{1,32}$=45.860, p<0.001) were observed. In addition to that, an interaction effect was obtained and reported in Figure 3 ($F_{2,64}$=4.077, p=0.022). Taken together, these results suggest that the time spent on each option decreased with option number.

Options with different ranking have opposite impact on decisions

After I identified the distinct information sampling process across trial type, we then moved one step forward to test how the sampled information affected the decisions across trial type. I ran a regression analysis to test the sham session data to investigate the influence of better options (i.e. high ranking options) and poorer options (i.e. low ranking options) on decision making (GLM1). I found that longer fixation durations on the better options on two-option trials (i.e. rank 1 option), four-option trials (i.e. rank 1 option) and sixteen-option trials (i.e. rank 1-4 options) were associated with greater choice accuracy (two-option: t_{67}=2.423, p=0.018; four-option: t_{67}=9.494, p<0.001; sixteen-option: t_{67}=3.705, p<0.001; Figure 2d & e). Conversely, shorter fixation durations on the poorer options on the two-option trials (i.e. rank 2 option), four-option trials (i.e. rank 2-4 option) and sixteen-option trials (i.e. rank 5-16 options) were associated with better choice accuracy (two-option: t_{67}=-3.972, p<0.001; four-option: t_{67}=-5.040, p<0.001; sixteen-option: t_{67}=-8.641, p<0.001; Figure 2d & f).

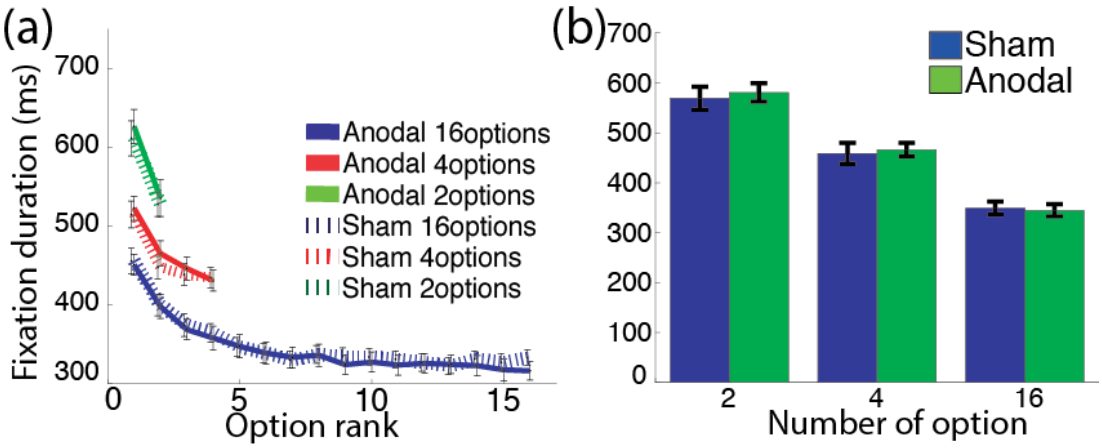

Figure 4. (a) A similar plot as Figure 2c, but with data from the anodal session was also plotted together. Fixation duration on each option decreased as a function of option rank in both anodal (solid line) and sham (dotted line) stimulation sessions. (b) The average fixation duration of different trial type in anodal (green bar) and sham (blue bar) stimulation session. Error bars denote standard error.

The tDCS effect on participant behavior

Next, I investigated the role of the dlPFC on multiple choice decision making by comparing participant's performance on the anodal (excitatory) and sham (control) tDCS sessions. I first ran a two-way ANOVA to test the effects of Stimulation Session (anodal vs sham) and Trial Type on choice accuracy and reaction time. The results showed that there was no interaction between Stimulation Session × Trial Type on choice accuracy ($F_{2, 64} = 0.800$, $p=0.454$) and reaction time ($F_{2, 132}= 0.486$, $p=0.617$). Also, a main effect of Stimulation Session was absent for both choice accuracy ($F_{1, 32} = 0.035$, $p=0.852$) and reaction time ($F_{1, 32} = 1.599$, $p=0.215$). However, there were main effects of Trial Type on choice accuracy ($F_{2, 64} = 24.297$, $p<0.001$) and reaction time ($F_{2, 64} = 316.305$, $p<0.001$). This suggested that the only the option number, but not the stimulation of dlPFC, affected the choice accuracy and reaction time.

I also tested whether the dlPFC has a role in guiding how information was sampled by comparing participants' fixation duration between the anodal and sham stimulation sessions by a two-way ANOVA analysis with Stimulation Session and Option Rank as the factors. Figure 4a & b demonstrate a similar fixation duration pattern in both stimulation sessions as the main

effect of Stimulation Session and the Stimulation Session x Option Rank interaction were not significant on two- (Stimulation Session: $F_{1, 32}$= 0.238, p=0.629; interaction: $F_{1, 32}$= 0.068, p=0.795), four- (Stimulation Session: $F_{1, 32}$= 0.184, p=0.671; interaction: $F_{3, 96}$= 0.664, p=0.576) and sixteen-option trials (Stimulation Session: $F_{1, 32}$= 0.111, p=0.741; interaction: $F_{15, 480}$= 0.575, p=0.895).The main effect of the Option Rank was significant on two- ($F_{1, 32}$= 22.756, p<0.001), four- ($F_{3, 96}$= 55.393, p<0.001) and sixteen- ($F_{1, 32}$= 76.208, p<0.001) trials. These results suggested that anodal tDCS over the dlPFC did not affect the time spent on gazing the options.

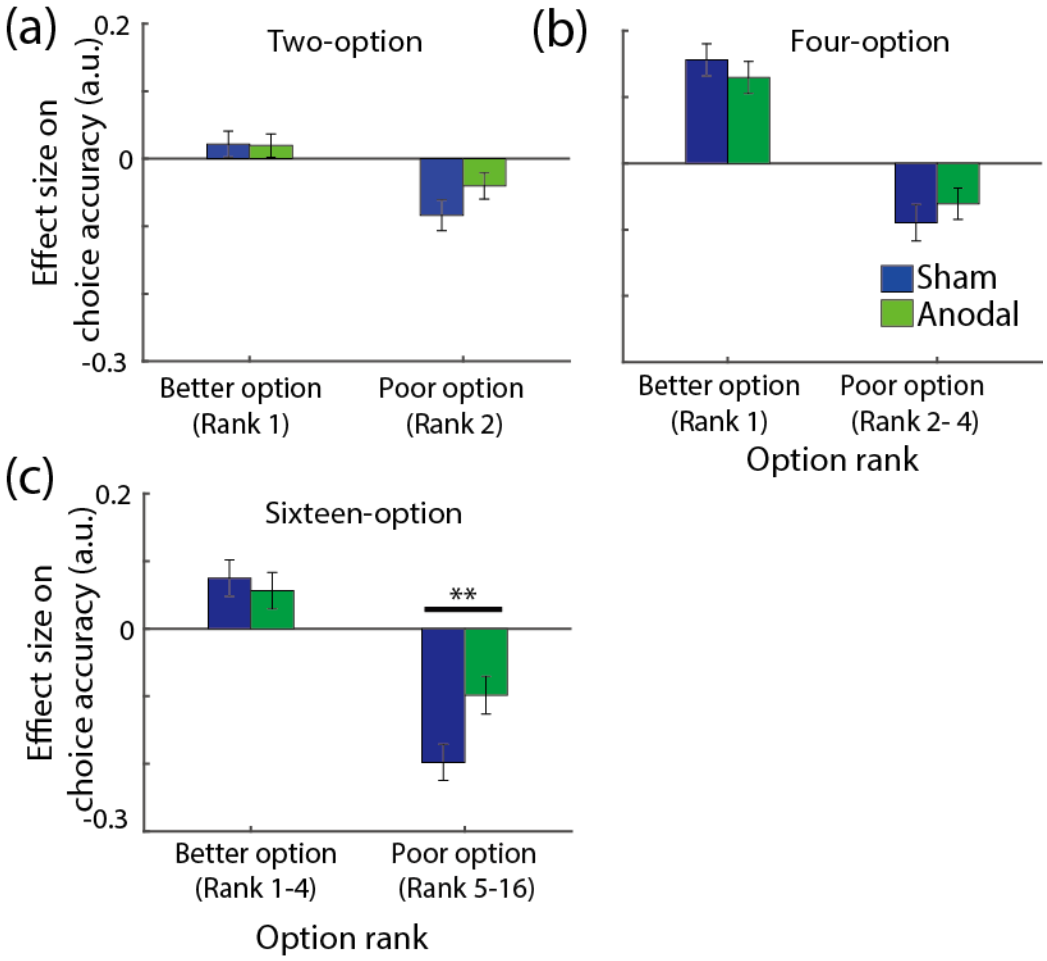

*Figure 5. Linear regression analyses that were similar to figure 2d were conducted on all trial types. Similar effect sizes of fixating better and poorer options on choice accuracy between sham (blue bars) and anodal (green bars) sessions were found on (a) two-option and (b) four-option trials. However, a significant reduction in the negative relationship between fixation duration on poorer options and choice accuracy on sixteen-option trials was observed. **= $p<0.01$. Error bars denote standard error.*

The role of dlPFC in information processing

Previous studies suggested that the dlPFC is particularly important for focusing on the task-relevant information and filtering out the task-irrelevant information. For example, one previous study involved macaque monkeys performing a dual task, while single-neuron activity in dlPFC was recorded (Watanabe &Funahashi, 2014). The results showed that the representation of task-relevant information by these neurons was attenuated when macaques had to remember information beyond their cognitive capacity or when interfering information was presented. Similar to the performance of a dual task, during multiple choice decision making, it is important to focus on the information associated with the more preferred options and to ignore those from the less preferred options, especially when there are plenty of options. Hence, DlPFC may have a specific role in processing the information that was sampled, possibly reducing the influence of task irrelevant information.

Hence, I ran a fine-grained analysis to test whether the fixation duration (time spent) at the better and poorer options have different influences on choice accuracy (see Methods GLM 1).

I conducted a linear regression analysis to reveal the relationship between fixation duration on options and choice accuracy (Figure 5). A positive bar in figure 5 denoted a positive relationship between fixation duration on options and choice accuracy. A negative bar denoted a negative relationship. On two-option trials, longer fixations on the better options did not affect the choice accuracy (anodal t_{32} = 1.180, p=0.247; sham t_{32} = 1.081, p=0.288; Figure.5a) while they were associated with greater choice accuracies on four-option trials (anodal t_{32} =5.321, p<0.001; sham t_{32} =6.431, p<0.001; Figure.5b) and sixteen-option trials options (anodal t_{32}=2.075, p=0.046; sham t_{32}=2.781, p=0.009; Figure.5c). Shorter fixations on the poorer snacks on the two- and four-option trials were also associated with higher choice accuracy on two-option trials (anodal t_{32} = -2.025, p=0.051; sham t_{32} = -3.596, p=0.001; Fig.4a), four-option trials (anodal t_{32} = -2.565, p=0.015; sham t_{32} = -3.262 p=0.003; Fig.4b) and sixteen-option trials (anodal t_{32}=-3.510, p=0.001; sham t_{32}=-7.361, p<0.001; Fig.4c).

Next, I compared these effects of fixating on the better and poorer options on choice accuracy between the anodal and sham dlPFC stimulation sessions. I found that the effects of fixating the better options were comparable after anodal and sham stimulation on two- (t_{32} = -0.015, p=0.988) four- (t_{32} = -0.752, p=0.457) and sixteen-option (t_{32}=-0.528, p=0.601) trials. Interestingly, when I focused on the poorer options, the negative impact of fixating on these options on choice accuracy was significantly reduced after anodal tDCS, relative to sham, only on sixteen-option trials (t_{32}=3.093, p=0.004), but not on two- (t_{32}=1.440, p=0.160) and four-option (t_{32}=0.710, p=0.484) trials. This suggested that when there were more options the impact of fixating on poorer options on choices was attenuated by anodal tDCS on dlPFC.

On the sixteen-option trials, I arbitrarily defined the rank 1-4 options as the better options and the rank 5-16 options as the poorer options. To illustrate that the anodal HD-tDCS effect was not specific to how the "poorer" options were defined, I gradually adjusted the boundary between the better and poorer options, starting with a cutoff at rank 1.5 and eventually at rank 14.5 and then calculated the difference in effect of fixating the poorer options between the sham and anodal tDCS sessions. The results showed that regardless of where the cutoff was placed, the effect of fixating the poorer options on choice accuracy was significantly reduced after anodal tDCS was applied to dlPFC ($t_{32}<3.710$, $p>0.050$; note that it was marginally significant when poorer options was defined as rank 2-16 options, $t_{32}=2.020$, $p=0.052$; Figure.6).

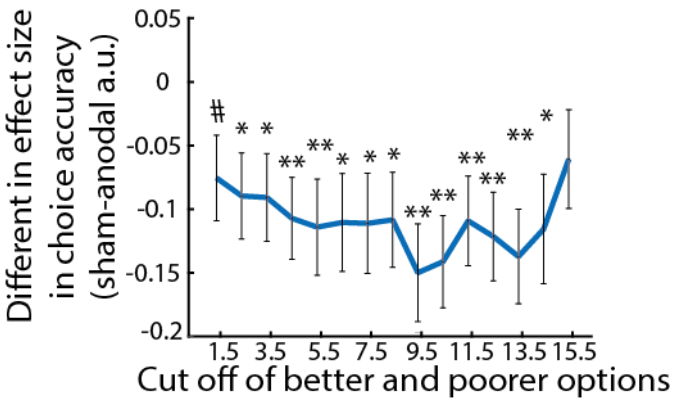

Figure 6. To ensure the significant reduction in the negative relationship between fixation duration on poorer options and choice accuracy after anodal stimulation on dlPFC (see Figure 5c) was not biased by the definition of better and poorer option, we performed the same analysis with all the possible definition of better and poorer options. By moving the cut off of better and poorer options, the result shows that after anodal tDCS, the influence of fixating on the poorer

option on the choice accuracy reduced regardless of the cut off ranking for defining "poorer options". Error bars denote standard error.

Taken together, these results demonstrated that dlPFC has a specific role in filtering out information from poor options that were presumably irrelevant to the decisions. This was confirmed by a three-way ANOVA with factors of Stimulation Session, Option Rank and Trial Type. The analysis showed a significant two-way Stimulation Session×Option Rank interaction effect ($F_{1, 32}$=7.7210, p=0.009), although there was no significant three-way interaction ($F_{2, 64}$=0.163, p=0.850). Although this combination of a presence of Stimulation Session×Option Rank interaction effect and an absence of three-way interaction effect suggested the reduced influence of poorer options on decision was general to all trial types, the fine-grained analysis revealed that this effect was the most robust on the trials with the greatest number of options (Fig.4,5). Finally, the main effects of Trial Type ($F_{2, 64}$=9.476, p=<0.001) and Option Rank ($F_{1, 32}$=75.966, p<0.001) were significant but not the Stimulation Session ($F_{1, 32}$=2.804, p=0.104). Since the tDCS effect is the most robust on affecting the relationship of poorer option and choice, I then further tested this effect by dividing the poorer option group on the sixteen-option trial into smaller groups.

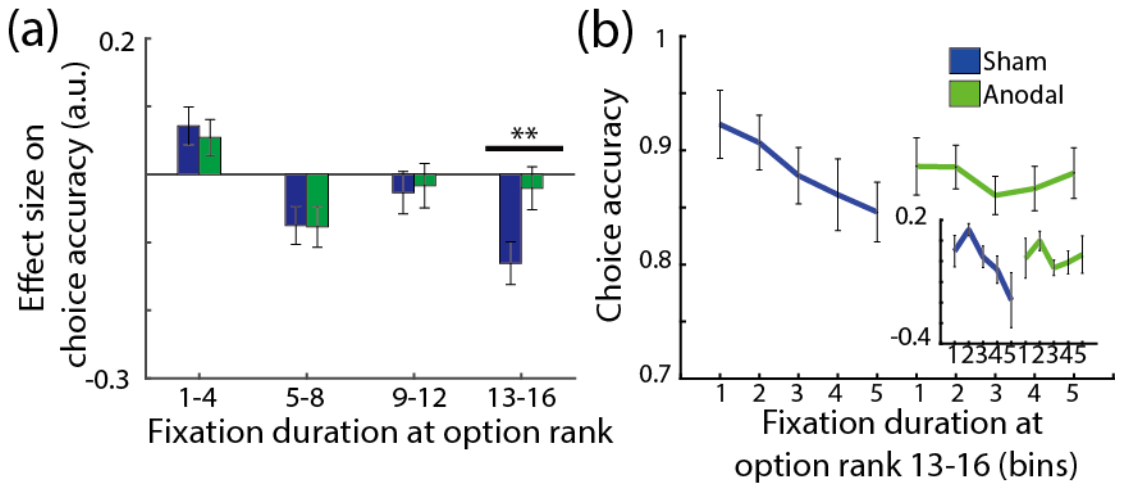

*Figure 7 (a) Similar regression analysis as in Figure 5, except all the options were divided into four smaller groups. The negative effect of fixating on the poorest options (rank 13-16) and choice accuracy in the sham session was attenuated after anodal stimulation. (b) Plot of choice accuracy against the fixation duration on the lowest rank option group. Inset: Residual choice accuracy was plotted instead of the choice accuracy. In the sham session, longer fixation on the poorest group option would lead to a lower choice accuracy. However in the anodal session, fixation duration on the poorest option would not affect the choice accuracy. **= $p<0.01$. Error bars denote standard error.*

On sixteen-option trials, arguably the information from the worst snacks among the poor options is the most irrelevant. It is hypothesized that the impact of tDCS over the dlPFC should be the most robust when we focus on the effect of fixating at the worst snacks on choice accuracy. Hence, we further divided the poor options into three smaller groups – rank 5-8 snacks, rank 9-12 snacks and rank 13-16 snacks (see Methods GLM 2). Consistent to our hypothesis, after anodal tDCS over the dlPFC, there was a significant reduction in the negative effect of

fixation duration on choice accuracy only with the worst rank 13-16 snacks (t_{32}=3.093, p=0.004; Figure 7a & b). The tDCS effect was insignificant with those of the less poor rank 5-8 and rank 9-12 options (t_{32}=-0.057, p=0.955; t_{32}=0.232, p=0.818; Figure 7a).

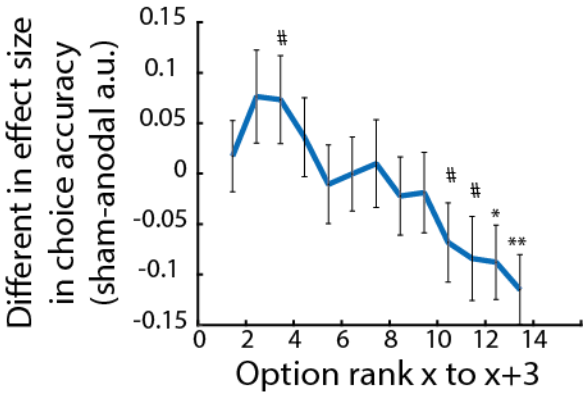

*Figure 8. Unlike the analysis in Figure 7a, a moving window analysis did not have four discrete groups of options. Instead, I set the window to be consisted of four options. I moved this window with rank 1-4 options at the beginning gradually to rank 13-16 options at the end. This analyses estimated the effect size of fixating duration on different options on choice accuracy and compared them between the sham and anodal tDCS sessions. The effects of the anodal tDCS were stronger on options with lower ranks. * = p<0.05; **= p<0.01; # =p<0.1. Error bar denoted standard error.*

In the analysis of Figure 7a, we found that the dlPFC has a role in filtering out the most irreverent options (i.e. the fourth groups of options). Next, to further confirm the role of dlPFC in filtering out the most irrelevant options, I performed a moving window analysis (GLM 4). One advantage of having a moving window analysis is that there would not be any discrete groups of option, unlike Figure 7a, there were 4 discrete groups of options. In this moving window analysis, a window would consist of four options. When I first set an analysis window of four options on

the rank 1-4 options, the effect of fixating on these options on choice accuracy were comparable between the stimulation sessions (t_{32}=-0.528, p=0.601; Figure 6b). However, when I gradually move this analysis window to the lower rank options, there was an increasing difference in the effect of fixation between anodal and sham stimulation sessions. The difference was strongest when the window was placed at the poorest rank 13-16 options (t_{32}=3.264, p<0.003; Fig.5b).

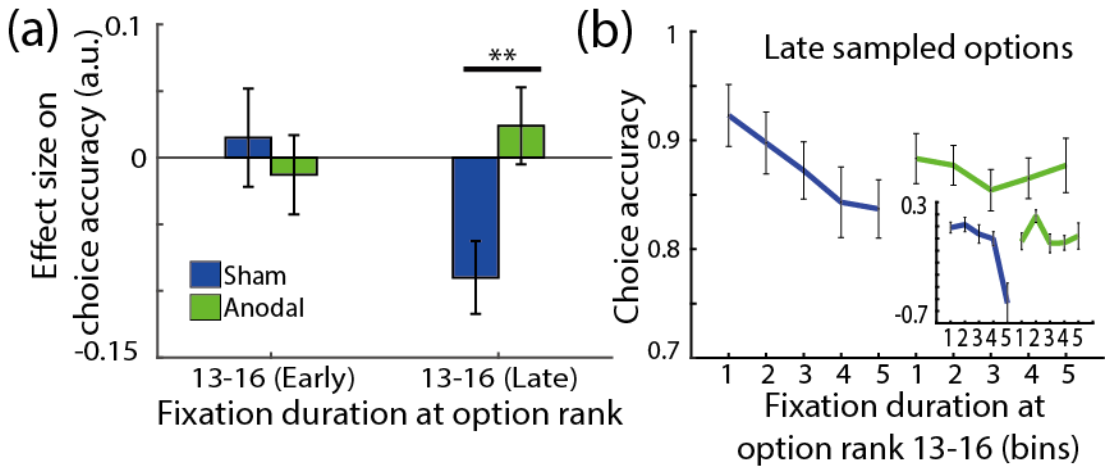

*Figure 9. The relationship of fixation duration at early and late sampled poorest option and choice accuracy on the sixteen-option trials. (a) There was a negative correlation between fixation duration of the late sampled poorest option and choice accuracy in the sham session. Such negative correlation was not observed in the anodal session (t_{31}=2.963, p=0.006). (b) The choice accuracy was plotted against the fixation duration of late sampled poorest option that was partitioned into bins. A negative correlation between the fixation duration of late sampled option and choice accuracy was shown in sham session (decrease trend of the blue line). Insect: Residual choice accuracy was plotted instead of the choice accuracy. **= p<0.01. Error bars denote standard error.*

In the current task that involved sequential sampling of information, the information of the poorer options should be the most "interfering" when it was sampled just before a decision was made. Hence, it is possible that, first, information from the poorest options has a much stronger impact on impairing choices when it is sampled later (i.e. closer to the moment when a choice was made) compared to the same information that is sampled earlier (i.e. closer to the beginning of a trial). Second, enhancing the dlPFC using tDCS could reduce the negative impact of such late sampled information on choice accuracy. To test these, I divided the regressors that describe the fixation duration on each set of options into two – one set of regressors that describes fixation duration that happened before half of the RT on each trial and another set of regressors that describes fixation duration that happened after half of the RT on each trial (see Methods GLM3). Interestingly, the results showed exactly what have been hypothesized. On the sham tDCS session, the duration of the late fixation on the poorest rank 13-16 options had a more negative relationship with choice accuracy than the duration of the early fixation. More importantly, the negative impact of the duration of these late fixations on choice accuracy was much weaker after anodal tDCS was applied over the dlPFC (t_{31}=2.963, p=0.006; Figure.9a & b). A three-way ANOVA testing the effects of fixation duration on the rank 13-16 snacks on choice accuracy also revealed a significant Stimulation × Sampling Time x Option Rank; $F_{3,93}$=3.027, p=0.033). These results provided further evidence that the dlPFC is important to represent information related to the better options, especially when this information is strongly interfered by information related to poorer options.

2.4 Discussion

During multiple choice decision making, it is critical to filter in a subset of information that is useful and to filter out another subset of information that is irrelevant in order to make adaptive decisions. This is particularly the case when there is an increasing number of options and the information load is beyond our cognitive capacity. Due to the well-understood function of dlPFC in filtering working memory, the current study investigate the causal roles of dlPFC in multiple choice decision making using HD-tDCS. This study revealed that when there is a large number of options, the influence of the low rank options on choice accuracy is reduced the dlPFC is enhanced using anodal tDCS.

Information sampling and processing in dlPFC

The fixation duration on options decreases with an increase in the option number. The fixation durations of the best two options decrease with the option number and the best option received the longest fixation duration (Figure 1c). By spending more time on high rank options, participants had more effective use of time and reduce the inference from the distracting option. Also, the average fixation duration of all given options decreased with the option number. Our results showed that the dlPFC does not involve in information sampling because the strategy used for information sampling is similar in both stimulation session (Figure 2). The fixation duration distribution to each option is similar between anodal and sham session that indicated an analogous sampling strategy was adopted. On the 16-option trial of the sham session, our result revealed that a longer fixation duration on the poorest option group is associated with lower choice accuracy (Figure 5). On the other hand, a longer fixation on those options does not affect

the choice accuracy after the dlPFC was enhanced. By comparing these results, it suggested that the fixation on the poorest option is no longer affecting the decision process after enhancement in the dlPFC.

Filter out distracting information during decision making

Our results showed that the impact of irrelevant information in multiple choice decision is attenuated after excitation of dlPFC. This is consistent with the notion that dlPFC is involved in filtering out irrelevant information (Anticevic, Repovs, Krystal, &Barch, 2012; Chao &Knight, 1998; Dolcos et al., 2007; Suzuki &Gottlieb, 2013; Thompson-schill et al., 2002). A previous study of Chao and Knight (1998) demonstrated a lesion in the dlPFC would cause more error in a delay-response task with distractors presented during the delay period compared to those with intact dlPFC.

A recently proposed mechanism of working memory might able to account for dlPFC's role in reducing the impact of irrelevant information after the anodal tDCS session. When we are trying to keep certain information in our mind, some components of the information can be recalled more easily than others. For example, when you are shopping in the supermarket and a list of shopping items have been kept in your mind, it is very often that you can recall some of the items easily but forget the others. A variable precision (VP) model of working memory was introduced to explain this phenomenon(van denBerg, Shin, Chou, George, &Ma, 2012). The VP model proposes that the cognitive resources can be distributed to all options in a flexible manner (Fougnie, Suchow, &Alvarez, 2012; Ma, Husain, &Bays, 2014). The fraction of the cognitive

resource distributed to each option varies randomly. An option that receives more cognitive resource will be encoded in a more precise manner. Therefore, some of the items will be remembered better than the others, even when these options have a similar value. This model provides an explanation of why we sometimes recall several items more easily than others.

In my study, the VP model could be used to explain the behavioral changes after the enhancement of dlPFC on the sixteen-option trials. When there are only a few options (such as on the 2 and 4-option trial), our cognitive resources are sufficiently distributed to every option with good precision. However, when the number of options is too great and exceeds the capacity of working memory, the distribution of cognitive resources becomes a major determinant of how precisely an option is remembered. One possible account of the tDCS effect on the poorest options is that the enhancement of the dlPFC is associated with better allocation of cognitive resources to those options with higher value. When a more efficient distribution of cognitive resources is achieved, fewer neurons will be assigned to encode the option with low value. Those neurons' activity will be easily suppressed by other high value option encoding neurons. Thus, the effect of the low value option on decision making will be minimized. Therefore, the longer fixation time on those low-ranking options will not trigger any behavioral change.

The current study extended our understanding on the role of the dlPFC from working memory to decision making. In addition, it provided insight in the development of the decision model. One direction would be combining the Biophysical model (Chapter1) and the VP model. It might help to better model of the neural response under multiple choice option situation. The dlPFC is not only involved in filtering distracting information when encoding working memory,

it is also involved in multiple choice decision making to reduce the influence of poor options that are distracting. Apart from the dlPFC, the PPC is another potential area that could be involved in multiple choice decision making as the PPC is also a key candidate that encodes working memory just like the dlPFC. For example, the PPC activity has a higher degree of synchronization with the dlPFC when maintaining working memory. Human fMRI studies also revealed that there is a co-activation of both regions in working memory task that required spatial attention (Buschman &Miller, 2007; Chafee &Goldman-Rakic, 2000; Munk et al., 2002; Raye, Johnson, Mitchell, Reeder, &Greene, 2002) In the next chapter, I will talk about another experiment that used to test the dissociable roles of dlPFC and PPC in in multiple choice decision making.

Chapter 3: PPC in multiple choice decision making

3.1 Introduction

In Study 1 (Chapter 2), I found that the dorsolateral prefrontal cortex (dlPFC) has a role in filtering out irrelevant and distracting information from poor options and to promote more accurate choices. These findings are in line with the working memory literature that suggested the dlPFC has a role in filtering irrelevant information while encoding working memory (Li et al., 2017; Sarma, Masse, Wang, &Freedman, 2015; Suzuki &Gottlieb, 2013). As in the dlPFC, the posterior parietal cortex (PPC) is another region that is often reported to be engaged in both decision making and working memory (Brodt et al., 2016; Harvey, Coen, &Tank, 2012; Jones &Berryhill, 2012; Raposo, Kaufman, &Churchland, 2014; Ratcliff, Smith, Brown, &McKoon, 2016). However, it is important to note that there are important functional differences between the PPC and dlPFC in both decision making and working memory.

During decision making, the activity of PPC neurons reflects the value of an option that is located inside their own receptive fields and its activity is independent from the choice (Bendiksby &Platt, 2006; Leathers &Olson, 2012). As opposed to the activity of PPC, the activity in the dlPFC consists of the choice information. There is a transformation of the dlPFC activity from encoding the option value to chosen option during the decision process (see Chapter 1 for more details)(Hunt et al., 2015). The difference between these two areas could be accounted by their connection profiles. Since the dlPFC is well connected to the motor cortex (Cai &Padoa-Schioppa, 2014; Takada et al., 2004), it is not surprising that it's activity can also reflect the choice that guides the motor cortex to execute an action of choosing the option. In

contrast, the PPC is closely connected to visual areas but not the motor cortex (Ibos et al., 2013; Lewis &VanEssen, 2000b). Therefore, choice information encoded in the PPC follows a spatial reference frame in which the activity of these neurons is particularly sensitive to the stimuli presented within its receptive field. These results demonstrated the distinct engagement of the PPC in decision making that the PPC is involved in the valuation process of the option located in its receptive field.

Other than decision making, the PPC is also involved in working memory in a different way to the dlPFC. A frontoparietal network model was proposed to describe how these two regions contribute to working memory differently but collaborately to encode memory (Ciavarro et al., 2013; Harding, Yücel, Harrison, Pantelis, &Breakspear, 2015; Murray et al., 2017; Palva et al., 2010). The model proposed by Murray et al (2017) consisted of two modules, a PPC module and a prefrontal cortex (PFC) module, with each module comprised of two excitatory neuron pools that are selective to distinct input stimuli. The PPC module receives sensory input and passes it to PFC via long range connections. This model is able to simulate the persistent neuronal activity (an attractor state of the neuronal pool) during the delay period in both regions while encoding working memory. Murray et al (2017) proposed that the PPC module encodes all the information presented, including both relevant and irrelevant information, whereas the PFC module is able to modulate the activity in the PPC module to inhibit the irrelevant information representation in the PPC module. The PPC module in this model has a weaker ‘attractor state’ (i.e. a weaker persistence high firing rate state) than that of the PFC module while encoding working memory so that its activity can be easily modulated by the feedback from PFC module via long connections. This model proposes that the role of the PPC in working memory is to

encode all given information regardless of the relevance of the information whereas the role of the dlPFC is to filter out the encoding irrelevant information in the PPC module. This model provides a theoretical framework that describes how these two regions collaborate to encode working memory.

Consistent to the model prediction, the PPC and dlPFC were shown to collaborate in working memory (Palva et al., 2010; Suzuki &Gottlieb, 2013; Violante et al., 2017). A stronger connection between the dlPFC and PPC is associated with greater accuracy in encoding working memory (Palva et al., 2010; Violante et al., 2017). In the study by Violante et al (2017), they used tACS to synchronize the activity of the dlPFC and PPC and captured the activation of both regions using fMRI. Their results showed that the task-related signals of both regions are significantly greater after synchronizing the dlPFC and PPC activity and people also show better working memory. Apart from the collaboration of the two regions, the PPC was also revealed to encode the information presented on its corresponding receptive field regardless of the relevance of the option. Suzuki and Gottlieb (2013) found that an inactivation over the PPC would lead to more errors in a working memory task if the target was located at the receptive field of the PPC.

Taken these findings together, it is possible for the PPC to have a different role in multiple choice decision making compared to the dlPFC. To dissociate the role of dlPFC and PPC, I used the same type of brain stimulation technique, tDCS, to investigate the behavioral change after enhancing PPC excitability. I also adopted the same experimental paradigm and procedure as in Study 1 (Chapter 2) to compare the roles of dlPFC and PPC in multiple choice decision making process. It is possible that, the PPC is particularly important in processing the

options that were presented contralaterally to stimulation. In Study 1, the impact of the irrelevant option on choices in multiple choice decision making was attenuated after anodal tDCS over the dlPFC. Although I did not observe such effect after anodal tDCS over the PPC, a role for the PPC in processing information presented contralaterally to the side of stimulation was revealed in this experiment.

3.2 Method

Participant

The current study involved thirty-five participants recruited by convenience sampling who received stimulation of the right PPC (18-26 years; 19 females). In addition, data from thirty-three participants that were involved in Study 1 that received stimulation on the right dlPFC were also included in the analysis of this study. All participants had no current, or history of, neurological / psychiatric conditions and had normal or corrected-to-normal vision. They were all required to pass the safety screening of tDCS using the Transcranial Magnetic Stimulation Adult Safety Screen before commencing to experiment. 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.

Procedure

The experimental procedure was the same as that in Study 1 (Chapter 2)

Decision making task

The computerized decision making task used was identical to that in Study 1 (Chapter 2)

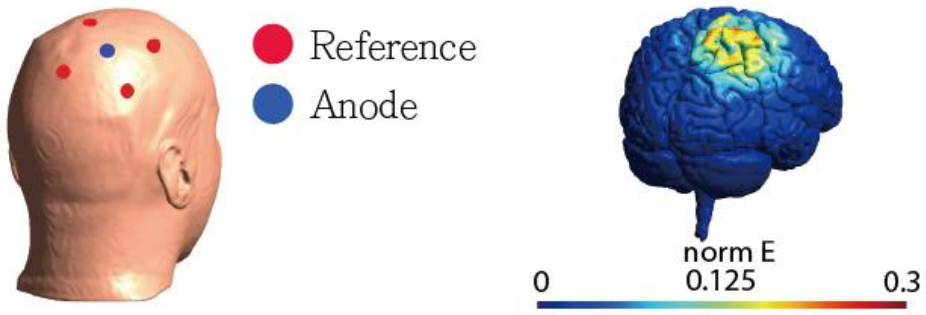

Figure 10. (a) HD-tDCS was applied using a 4 x 1 montage over the right PPC. The anode electrode (blue) that delivery the current was surrounded by 4 reference electrodes (red). (b) A simulation confirmed that the current density was strongest in the MIP and LIP of PPC.

Transcranial direct current stimulation

I adopted a stimulation protocol that was similar to that in Study 1 (Chapter 2), except that the electrodes were placed over the right PPC. On each experimental session, I applied either sham or anodal HD-tDCS (Soterix tDCS stimulator with a Soterix 4 x 1 HD-tDCS adaptor) over the participant's right PPC. The position of the anode targeted the putative human lateral intraparietal area (LIP) and medial intraparietal area (MIP) of the right PPC (Mars, 2011; at MNI coordinates 28, -55, 55). 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. The participant was asked to report any discomfort before, during and after the stimulation.

To confirm that the HD-tDCS was targeted at the right PPC, a current density simulation was modeled by SimNIBS (Figure 10). The current density is at peak over the putative human LIP and MIP area.

Behavioral analysis

Three types of behavioral data were collected from the participant: the WTP (that was related to the subjective preference) of the chosen option, reaction time and gaze pattern. The choice accuracy of each trial is defined by the equation below, which indicates the WTP of the chosen option *relative* to the best and worst option available on the same trial:

$$accuracy = \frac{chosen\ WTP - \min(WTP)}{\max(WTP) - \min(WTP)}$$

Linear and logistic regression analyzes were performed for every participant to predict their choice accuracy and chosen option location from different general linear models (GLMs). The beta (β) weight of each regressor in the GLM was calculated.

GLM 1: information processing in PPC

$$Choice\ accuracy = \beta 0 + \beta 1(\text{duration of fixation on the better option}) + \beta 2(\text{duration of fixation on the poorer option})$$

GLM 2: information processing in PPC

$$Choice\ accuracy\ (16\ option\ trial) = \beta 0 + \beta 1(\text{duration of fixation on option ranked 1st to 4th}) + \beta 2(\text{duration of fixation on option ranked 5th to 8th}) + \beta 3(\text{duration of fixation on option ranked 9th to 12th}) + \beta 4(\text{duration of fixation on option ranked 13th to 16th})$$

GLM 1 aimed at exploring the relationship between the fixation duration and the choice accuracy on different trial type. Like Study 1, I divided the options into two groups, better options and poorer options. These refer to the rank 1 option and rank 2 option on the two-option trials respectively; the rank 1 option and rank 2-4 options on the four-option trials respectively; and the rank 1-4 options and rank 5-16 options on the sixteen-option trials respectively. I applied logistic regression analysis on the two-option trials since the choice accuracy was binary (Figure 14). A multiple linear regression was applied to examine the data on four- and sixteen option trials (Figure 14). After testing the relationships between fixation duration and choice accuracy, we further tested this beta-weight using a three-way ANOVA analysis. The three independent variables were Stimulation Session (i.e. anodal or sham session), Trial Type and Option Rank (i.e. better or poorer option). I also constructed GLM 2 by dividing options on 16-option trials into 4 smaller groups.

GLM 3: spatial bias in PPC and dlPFC

$$Chosen\ option\ position$$

$$= \beta0 + \beta1(\text{duration of fixation of option ranked 1st to 4th on contralateral side})$$

$$+ \beta2(\text{duration of fixation of option ranked5th to 8th on contralateral side})$$

$$+ \beta3(\text{duration of fixation of option ranked9th to 12th on contralateral side})$$

$$+ \beta4(\text{duration of fixation of option ranked13th to 16th on contralateral side})$$

$$+ \beta5(\text{duration of fixation of option ranked1st to 4th on ipsilateral side})$$

$$+ \beta6(\text{duration of fixation of option ranked5th to 8th on ipsilateral side})$$

$$+ \beta7(\text{duration of fixation of option ranked9th to 12th on ipsilateral side})$$

$$+ \beta8(\text{duration of fixation of option ranked13th to 16th on ipsilateral side})$$

GLM 3 was used to examine the spatial role of PPC. I classified the regressors in GLM 2 in two groups by the spatial location of the option and tested their relationship with the chosen option position (i.e. contralateral or ipsilateral to the stimulation side). The location was determined by the midline of the screen. After testing the relationships between fixation duration and the chosen option position, we further tested this beta-weight using a three-way ANOVA analysis. The three independent variables are Stimulation Session (i.e. anodal or sham session), Option Position and Option Rank (i.e. better or poorer option).

GLM 4: moving window analysis

$$Choice\ accuracy$$

$$= \beta0 + \beta1(\text{duration of fixation on targeted option})$$

$$+ \beta2(\text{duration of fixation on remaining option})$$

To study the impact of the irrelevant option on choice after anodal stimulation, I used GLM 4 to perform a moving window analysis. The window started at rank 1 to 4 option and moved one step away from the starting point (i.e. rank 1+x to 4+x option in which x ranging from 0 to 12).

3.3 Results

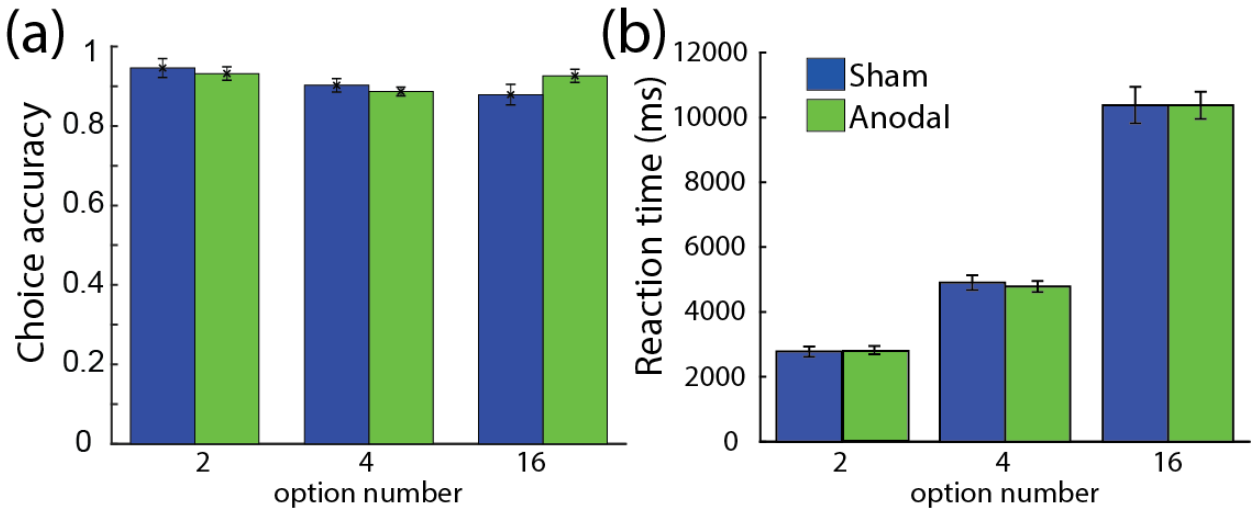

Figure 12 Comparison of the (a) choice accuracy and (b) reaction time between sham and anodal session. No significant difference was observed after enhancing the PPC activity. Error bars denote standard error.

The tDCS effect on participants behavior

As in Study 1, I investigated the role of the PPC on multiple choice decision making by comparing participants' performance on the anodal (excitatory) and sham (control) tDCS sessions. A two-way ANOVA analysis was used to test the effect of the Stimulation Session (anodal vs sham) and Trial Type on both the choice accuracy and reaction time. There was no significant interaction between Stimulation Session × Trial Type on choice accuracy ($F_{2, 68}$ = 0.610, p=0.547; Figure 12) and reaction time ($F_{2, 68}$= 0.071, p=0.931; Figure 12). In addition, there was no significant main effect of Stimulation Session on both choice accuracy ($F_{1, 34}$ = 1.907, p=0.176) and reaction time ($F_{1, 32}$ = 0.007, p=0.936). The main effect of the Trial Type was significant on choice accuracy ($F_{2, 68}$ = 16.934, p<0.001) and reaction time ($F_{2, 68}$ = 554.251,

p<0.001). These results implied that tDCS over the PPC did not affect overall choice accuracy and reaction time.

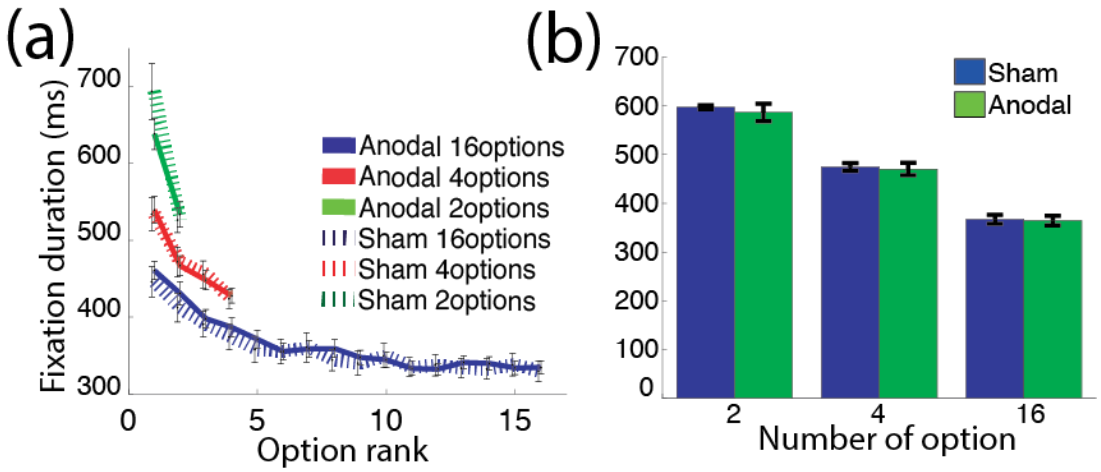

Figure 13. Comparison of fixation pattern in different tDCS session. Fixation duration was sorted as a function of option rank in anodal (solid line) and sham stimulation session (dotted line). The data from anodal session was similar to that of sham session. Implying that, participants shared similar information sampling process in both stimulation sessions. (b) showed the average fixation duration of different trial type in anodal (green bar) and sham (blue bar) stimulation session. Error bars denote standard error.

The information sampling process of both stimulation sessions was shown in Figure 13a and b. A two-way ANOVA analysis with factors of Stimulation Session and Option Rank was conducted to test the fixation duration pattern on both stimulation sessions. A two-way interaction was found on two-option trials ($F_{1, 34}$= 4.939, p=0.033) but not four- ($F_{3, 102}$= 0.436, p=0.728) and sixteen-option trials ($F_{15, 510}$= 1.113, p=0.330). The main effect of the Stimulation Session was absent on two- ($F_{1, 34}$= 0.746, p=0.394), four- ($F_{1, 34}$= 0.002, p=0.967) and sixteen -option ($F_{1, 34}$= 0.165, p=0.687) trials. The main effect of the Option Rank was significant on two-

($F_{1, 32}$= 57.428, p<0.001), four- ($F_{3, 102}$= 62.300, p<0.001) and sixteen- ($F_{15, 510}$= 75.914, p<0.001) trials.

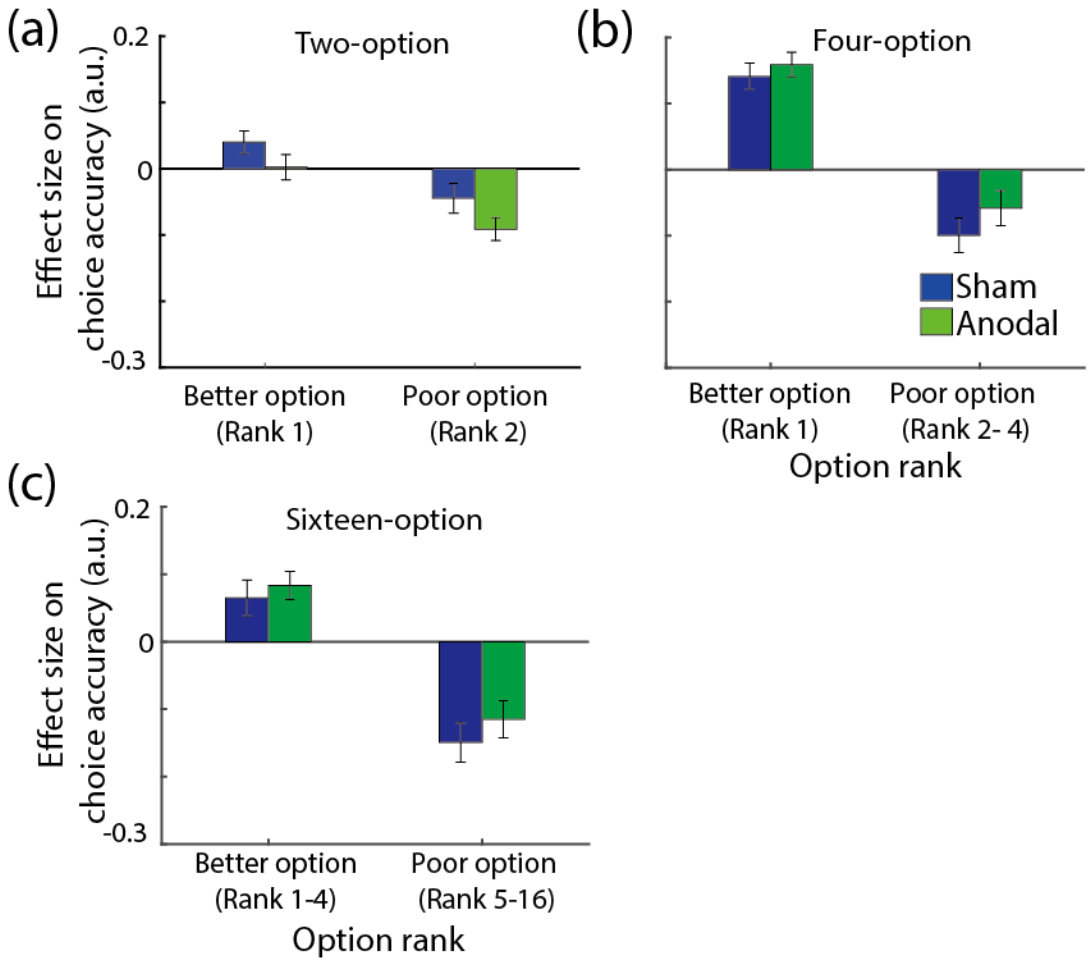

Figure 14. Linear regression analyses that were similar to figure 5 were conducted with the PPC participants' data. Comparison of the relationship of fixation duration and choice accuracy in anodal and sham stimulation session. A positive bar indicates a positive correlation of fixation duration and choice accuracy while a negative bar indicates a negative correlation. No significant difference was observed by comparing the data of anodal and sham stimulation sessions. Error bars denote standard error.

The role of PPC in information processing

A fine-grained analysis was conducted to test the role of the PPC in information processing (see Methods GLM 1). I applied a paired-sample t-test to examine whether there was a change in the impact of option fixation and choice accuracy after anodal tDCS, by comparing the beta-weights obtained from the regression analyses of the sham and anodal sessions. Unlike applying anodal stimulation on dlPFC, there was a lack of tDCS effect on modulating the relationship between the duration of fixating different options and choice accuracy on the two-option trials (better option: t_{34}=-1.419 p=0.165; poorer option: t_{34}=-1.162, p=0.116; Figure 14a), four-option trials (better option: t_{34}=1.241, p=0.223; poorer option: t_{34}=0.889, p=0.380; Figure 14b) and sixteen-option trials (better option: t_{34}=0.490, p=0.630; t_{34}=0.814, p=0.421; Figure 14c). A two-way interaction effect of Stimulation Session×TrialType was identified ($F_{2,68}$=3.655, p=0.031) from a three-way ANOVA analysis that included factors of Stimulation Session, Option Rank and Trial Type. There was a presence of main effects of Option Rank ($F_{1,34}$=179.429, p<0.001) and Trial Type ($F_{2,68}$=13.354, p<0.001) but an absence of Stimulation Session main effect ($F_{1,34}$=0.125, p=0.726). The absence of the Stimulation Session main effect might probably due to the reversed trend of the tDCS effect on the two-option trials. The relationship between fixation duration and choice became more negative on the two-option trials whereas on the four- and sixteen- option trials, that became more positive. Although a two-way interaction between Stimulation Session and Trial Type was found ($F_{2,68}$=3.655, p=0.031), there earlier pair-wise comparisons did not show any significant tDCS effect on these beta-weights on the two-, four- and sixteen-option trials (Figure 14)

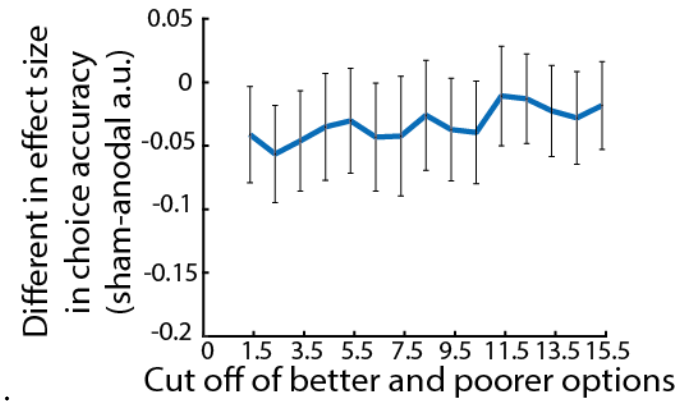

Figure 15. A similar analysis as figure 6. By moving the cut off of better and poorer options, the results showed that after anodal tDCS, the influence of fixating on the poorer option on the choice accuracy was unaffected. Error bars denote standard error.

To ensure the definition of better and poorer options did not bias the result, similar to figure 6, I repeated the same analysis with different cut off of better and poorer options. We did not observed any impact of enhancing the PPC on the relationship between fixation duration on options and choice accuracy (Figure 15).

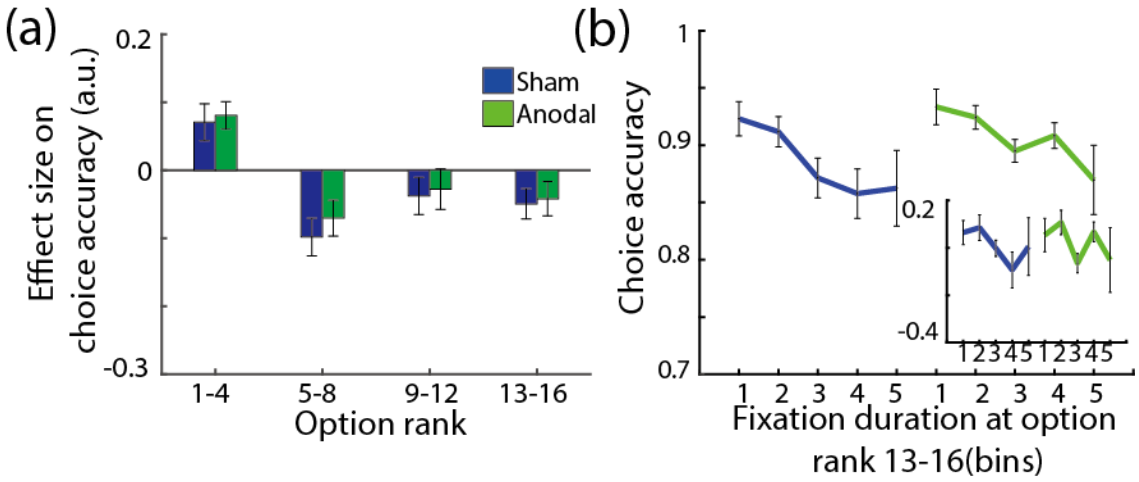

Figure 16. (a) Similar regression analysis as in Figure 14, except all the options were divided into four smaller groups. The effects of fixating on options with different ranks on choice accuracy were comparable in both stimulation sessions (b) A plot of choice accuracy against fixation duration on the lowest rank options. Inset: Residual choice accuracy was plotted instead of the choice accuracy. In both stimulation sessions, longer fixations on the lowest rank options were related to poorer choice accuracies. Error bars denote standard error.

Similar to Study 2, I divided the poorer options in to smaller subgroups (i.e. option rank 5-8, 9-12 and 13-16) to further examine the influence of poorer option on decision. Similar to the result reported in Figure 14, the relationship between fixating duration on various subgroups and the choice accuracy was comparable in both sessions (Figure 16). In addition, I performed a moving window analysis, which was similar to that in figure 8, that tested how the duration of fixating options at different ranks affected the choices. When the window was focused on the best four options, the beta weight of the duration of fixating these options on choice accuracy was similar in both stimulation sessions (t_{34}=0.490, p=0.630). In the moving window analysis, I gradually moved this window to the lower rank options. Again, I also did not find any tDCS effect from this analysis (t<0.951, p>0.348; Figure 17).

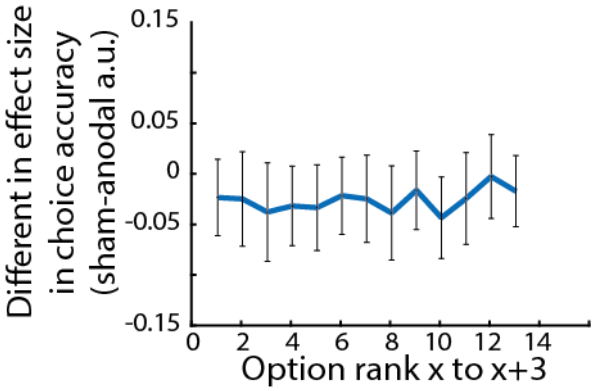

Figure 17. A moving window analysis that was similar to figure 8 was conducted. By comparing the data from anodal and sham session, the influence of fixation duration on choice accuracy was similar regardless of the stimulation session as well as the location of the window. Error bar denoted standard error.

Spatial role of PPC in information processing

So far, it is not yet clear whether and how the PPC is involved in multiple choice decision making. It is well-characterized that retinotopic maps are found in various PPC sub-regions, for instance the LIP and MIP regions (Patel et al., 2010; Sereno &Huang, 2014). In particular, many of these PPC neurons have receptive fields that response selectively to information presented on a subset of the visual field (Gottlieb &Goldberg, 1999; Leathers &Olson, 2012). Since the receptive field of these neurons lies within a subset of the visual field, therefore, the receptive field of these neurons changes according to eye movement. Apart from retinotopic maps, somatotopic maps are also found in the PPC (Sereno & Huang, 2014). The neurons within the somatotopic maps are selectively sensitive to the stimuli presented on a particular body part. Since the receptive field of these neurons is on a particular part of body, therefore, the receptive field of this map would not be affected by eye movement. For both maps, there is a larger proportion of these neurons whose receptive fields are located on the contralateral than the ipsilateral side. Thus, to test the precise functions of PPC during multiple choice decision making using tDCS, it is critical to carefully consider the spatial location of the stimuli.

As such, I performed an analysis that considered whether an option was presented ipsilaterally or contralaterally to the stimulation site and investigated their impact on decision

making (see Methods GLM 3). I took the midline of the screen as a reference to consider laterality. This should be justifiable if PPC subregions that encode somatotopic maps (e.g. MIP that encodes a map of hand and arm position) is considered. Although the receptive field PPC subregions that encodes retinotopic maps (e.g. LIP) would be affected by the eye movement, the options located on the left side of the screen were on the contralateral side of the visual field for most of the time in the experiment (Figure 18).

I focused on analyzing the sixteen-option trials because, unlike the two- and four-option trials, these trials always have the same number of options on the contralateral and ipsilateral sides. In the two- and four-option trials, the options were arbitrarily placed on the contralateral and ipsilateral sides. As a result, there could be an uneven number of options on each side. As in the previous analysis, I included separate regressors that describe the fixation duration on options of different ranks (1-4, 5-8, 9-12, and 13-16). We split each regressor into two, according to whether the fixation occurred on the contralateral or ipsilateral side relative to the right hemisphere that received tDCS.

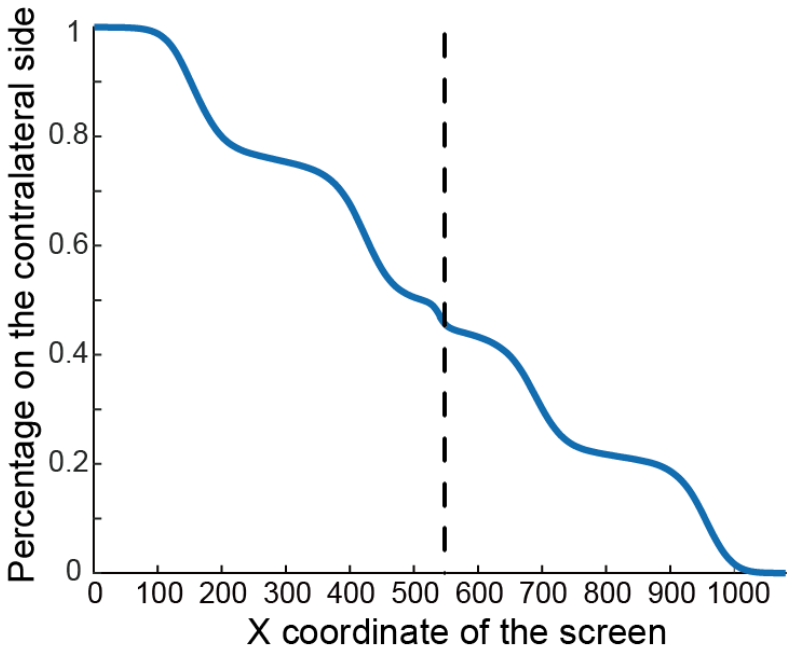

Figure 18 A plot showing that the percentage time that the particular x coordinate was located contralaterally to the simulation site. This figure illustrated that although eye movement would affect the number of the options located on the contralateral side of the retinotopic map, the options located on the left side of the screen were located in the contralateral visual field. Black dotted line: midline of the screen.

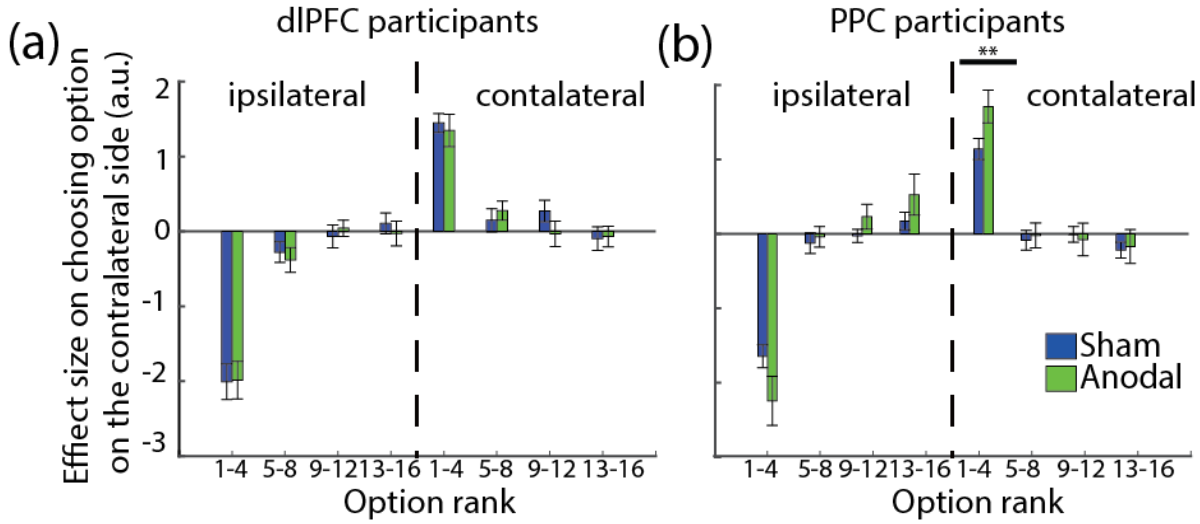

Figure 19 Logistic regression on the relationship between chosen locations (i.e. contralateral vs. ipsilateral) and fixation duration on options at different ranks. (a) The data from Study 1 (Chapter 2) showed no bias on spatial processing of options at different rank. (b) The data from the current study showed after the right PPC was enhanced using tDCS there was a bias in processing the best options presented on side contralateral to the PPC stimulated. Error bars denote standard error.

In addition, instead of testing how these factors influenced choice accuracy, we now investigate how they bias the choice of options presented on the contralateral side (as opposed to the ipsilateral side). The results showed that in both the anodal and sham tDCS sessions, PPC participant was more biased to choose a contralateral option when they fixated longer on the rank1-4 options presented on the contralateral side (anodal t_{33}=7.629, p<0.001; sham t_{34}=7.977, p<0.001; Figure 19) and fixated shorter on the rank 1-4 options presented on the ipsilateral side (anodal: t_{33}= -6.733, p<0.001; sham: t_{34}= -10.791, p<0.001). Critically, after the right PPC was stimulated using anodal tDCS, the impact of fixating the contralateral rank1-4 snacks became significantly stronger than that after they received sham tDCS (t_{33}= 2.302, p=0.028). In a three-way ANOVA, a significant main effect of Option Position ($F_{1,33}$=28.974, p<0.001) was observed whereas the main effects of Stimulation Session ($F_{1,33}$=2.988, p=0.093) and Option Rank ($F_{3,99}$=2.463, p=0.067) were not significant. However, I also identified a significant Stimulation Session× Option Position × Option Rank interaction effect ($F_{3,99}$ = 4.926, p=0.003). In contrast, when a similar analysis was repeated using the data of the dlPFC participant, there was an absence of a Stimulation Session× Option Position × Option Rank interaction effect ($F_{3,84}$ = 1.079, p=0.363; Figure 19) and main effect of Stimulation Session ($F_{1,28}$ = 1.025, p=0.320). The main effects of Option Position ($F_{1,28}$ = 58.622, p<0.001) and Option Rank ($F_{3,84}$ = 3.703, p=0.015) were significant. These results suggested that enhancing unilateral PPC could cause a bias in processing the better options presented on the contralateral side.

3.4 Discussion

In the current study, the role of the PPC in multiple choice decision making was tested. The results showed that the PPC is mainly involved in biasing the processing of the contralateral options. Unlike the dlPFC, enhancing the PPC using tDCS did not result in better filtering of decision irrelevant information sampled from poorer options. My results demonstrated that the dlPFC and PPC process information in different dimensions. DlPFC is involved in decision-relevance processing of choice information, whereas PPC is involved in spatial processing of choice information.

The bias in the information processing of the contralateral option during decision making is consistent with previous studies. First, literature often reported that the PPC neurons are responsive to contralateral stimuli (Alexander C.Huk, Katz, &Yates, 2017; Husain &Nachev, 2007; Silver &Kastner, 2009), which is consistent with my result. For example, the PPC neurons were found to be particularly sensitive to the information displayed on the contralateral sides (Patel et al., 2010; Sereno &Huang, 2014). In monkey fMRI study, the PPC activates only when the stimuli were presented on the contralateral side (Patel et al., 2010). A lesion on the PPC could cause a contralateral spatial neglect which means that people with lesioned PPC would tend to ignore the object on the contralateral side (Husain &Rorden, 2003; Vallar, 1998). In a previous tDCS study, participants who received anodal tDCS on the PPC also had a higher accuracy on detecting stimuli on the contralateral side (Sparing et al., 2009). These studies reported similar results to the current experiment that the PPC has an important role in processing the stimuli presented on the contralateral side. Second, the PPC was also largely

reported to be involved in decision making, such as determining the directions of motions (Sarma et al., 2015), classifying auditory tones into different categories (Zhong et al., 2019) and encoding value of option within the receptive field (Bendiksby &Platt, 2006). Platt and Glimcher (2009) observed that the PPC activity is modulated by the value of option such that greater value options would be able to induce a greater activity in the PPC. This study illustrated the role of the PPC in the valuation process during decision making. Combining these findings, the PPC is sensitive to contralateral information during decision making.

In contrast to information processing, the information sampling was unaffected after stimulating the PPC. Although the PPC was well-described to be involved in decisions that required eye-movement (Katz, Yates, Pillow, &Huk, 2016; M. N.Shadlen &Newsome, 2001; Sugrue, Corrado, &Newsome, 2005), I did not observed any significant change in the information sampling process after we excited the PPC. It could be accounted for the sampling strategy used in information sampling. In this experiment, the participant had to actively sample information from the options one by one, rather than passively gaze at the options that are visually salient. This implied a top-down sampling strategy was adopted. According to the previous work of studying top-down and bottom-up attention in the frontal and parietal area, the PPC should be involved in bottom-up attention while the frontal eye field area (FEF) is responsible for top-down control of attention (Buschman &Miller, 2007). Therefore, in order to change the information sampling in multiple choice decision, FEF would be a potential candidate region to focus on.

In this experiment, the results did not only show that the PPC was engaged in biasing information from the contralateral visual field, they also suggested that the PPC has a distinct role from the dlPFC in multiple choice decision making. By adopting the same experiment protocol, I compared the roles of the PPC and dlPFC. Unlike dlPFC, the anodal stimulation on the PPC did not alter the information processing of the poorer options. This is consistent with the previous work on dissociating the dlPFC and PPC roles in working memory (Everling, Tinsley, Gaffan, &Duncan, 2002) in which the dlPFC was found to be able to suppress the distracting and irrelevant information. Everling et al (2002) found that compare to the present of a targeted option the dlPFC would become less active when a non-target option was presented, even when the macaque monkey was attending to the non-target option. Also, another monkey single cell recording study provided evidence of how the dlPFC could reduce the impact of the distracting information on our behavior (Parthasarathy et al., 2017). It showed that the dlPFC activity is able to morph when a distractor information was present and the morphed activity in the dlPFC is still able to keep most of the information of the target option. They also recorded the activity from an adjacent region of dlPFC, the FEF, and they noticed that only the dlPFC neurons are able to morph its activity to keep most of the target information. The activity of the FEF becomes unstable after the presentation of distracting information, and loses most of the information about the target. However, the role of PPC in filtering distracting information (i.e. poorer option) has rarely been reported, therefore we cannot see the diminished relationship between fixation duration on poorer option and choice in this experiment.

Chapter 4: General Discussion

To investigate the neural mechanisms of multiple choice decision making, I applied transcranial direct current stimulation (tDCS) on the dorsolateral prefrontal cortex (dlPFC) (Chapter 2) and posterior parietal cortex (PPC; Chapter 3), which are important candidate regions. Two major findings were reported in this thesis. First, the dlPFC is involved in reducing the influence of the irrelevant option on decisions. Second, the PPC is involved in the processing of the contralateral option.

4.1 Reducing the impact of irrelevant option on decisions in dlPFC

In Study 1, to test the role of the dlPFC in multiple choice decision making, I applied tDCS over the dlPFC of the participant and tested their behavior by comparing the anodal and sham session. After applying anodal tDCS on the dlPFC, I found that the choice was less affected by the duration of fixating the poor option compared to the sham session. The results from Study 1 revealed that the dlPFC is involved in filtering out the impact of irrelevant options (poor options) on choices (Figure 5), although the overall choice accuracy was unaffected. The overall choice accuracy was comparable in both stimulation sessions might due to the ceiling effect. Since the choice accuracy was high in both session (~85%), there is limited room for improvement. The role of dlPFC observed in this study is consistent with the previous findings in the working memory literature. The dlPFC has been found to be involved in filtering out irrelevant information (i.e. the non-target stimuli) while encoding working memory (Parthasarathy et al., 2017; Sakai et al., 2002; Suzuki &Gottlieb, 2013)**.** For example, the dlPFC can reduce the influence of non-target stimuli by inhibiting its neural representation (Suzuki

&Gottlieb, 2013). The importance of the dlPFC in reducing the effect of irrelevant information was also revealed by a lesion study (Chao &Knight, 1998). The authors found that if there is a lesion on the dlPFC, more errors will be detected on trials with the presence of distracting information (i.e. non-target)**.** In Study 1, the results suggested that other than reducing the impact of the distracting information when encoding working memory, the dlPFC also helps to reduce the influence of the irrelevant option during multiple choice decision making.

A recent working memory model, the variable-precision (VP) model, could explain the underlying mechanism of how the dlPFC could keep our choice unaffected by the irrelevant option (van denBerg et al., 2012). The VP model proposes that our cognitive resource can be flexibly allocated to encoding different stimuli. This means that some of the stimuli will receive more cognitive resources, so that we have a better memory on that. Our results in Study 1 showed that the poorer option has less impact on the choice after stimulating the dlPFC. Based on the framework postulated by the VP model, after the dlPFC was enhanced by anodal tDCS, there could be a more efficient allocation of the cognitive resources. Hence, the relevant option (i.e. the better option) would receive more cognitive resources and the irrelevant option (i.e. the poorer option) would receive less cognitive resources. It means that even when we put more attention (i.e. longer fixation) to the irrelevant option, a more efficient allocation of cognitive resource reduced its impact on our choices.

Since the role of the dlPFC in working memory makes it particularly important in multiple choice decision making, I then tested another region that is highly involved in working

memory, which is the PPC. I tested the role of the PPC by adopting a similar paradigm of multiple choice decision making task.

4.2 Enhancing the impact of the contralateral options in PPC

In Study 2, similar to Study 1, I applied tDCS over the PPC to test its role in multiple choice decision making. The results showed that the PPC is not involved in filtering irrelevant options as the choices were affected by the duration of fixation on the poor option to the same extent in both anodal and sham sessions. After anodal tDCS, however, the contralateral option was chosen even more frequently when people fixated longer on the contralateral options. These results suggested the role of the PPC in processing the option on the contralateral side in decision making.

These results are in line with the previous literature. The PPC was reported to have an important role in processing the stimuli on the contralateral sides rather than dealing with the irrelevant stimuli (Ikkai &Curtis, 2011; Roy, Sparing, Fink, &Hesse, 2015; Saalmann, Pigarev, &Vidyasagar, 2007; Schindler, Ellison, &Milner, 2008). For example, a previous tDCS study also reported an increase in the ability of detecting the contralateral stimuli after applying anodal stimulation on the PPC (Sparing et al., 2009). At the same time, the ability of detecting the ipsilateral stimuli was not affected after tDCS. In addition, a TMS study by Schindler et al (2008) showed that after disrupting the PPC activity, the participant's reaction time on searching the correct target on the contralateral side significantly increased on a visual searching task. These studies demonstrated a causal role of the PPC in processing the contralateral stimuli in a non-decision making situation. Taken together, the current study provides evidence supporting the

notion that the PPC has a role in processing contralateral options in multiple choice decision making.

4.3 The frontoparietal network in multiple choice decision making

The results of Studies 1 and 2 together suggested that the dlPFC and PPC have distinct roles in multiple choice decision making. Since the dlPFC and PPC are strongly connected anatomically, these two regions should work collaboratively rather than independently during the multiple choice decision making. The dlPFC and PPC form a frontoparietal network and work together to encode working memory (Palva et al., 2010; Salazar et al., 2012). Frequency-specific neural synchrony of the dlPFC and PPC was found to encode distinct task related information (Jacob et al., 2018; Roux &Uhlhaas, 2014). Jacob, Hahnke and Nieder (2018) trained monkeys to perform a working memory task in which the monkeys needed to remember the number of stimuli presented and ignore the distracting stimuli presented subsequently. Their results showed that the neural synchronization of the alpha band is important for protecting the memory from the distractor. A review study from Roux and Uhlhaas (2014) also revealed that the alpha band activity is modulated by the number of distracting stimuli. A loss of the alpha band synchrony would lead to an incorrect response (Jacob et al., 2018). The beta band synchrony in these two regions peaked during the presentation of stimuli and distracting stimuli regardless of the relevance of the stimuli. The theta band synchrony of the frontoparietal network stored the information of relevant and distracting stimuli in a orthogonal manner (Jacob et al., 2018). The degree of the synchronization within the frontoparietal network is able to predict reaction time as well as the performance (Violante et al., 2017).

The frontoparietal role in encoding working memory is also described by a model by Murray et al (2017). This model proposes that the PPC in the frontoparietal network has a role in encoding the stimuli displayed on the contralateral side while the dlPFC has a role in allocating more resources to encode the most relevant information by modulating the PPC activity. In line with the model, previous findings showed that inactivation in the dlPFC would lead to a higher error rate than inactivating the PPC because its activity is closely linked to the irrelevant information (Suzuki &Gottlieb, 2013). An inactivation over the PPC only impaired performance when the target was on the contralateral side of the inactivation regardless of the presence of any irrelevant information (Suzuki &Gottlieb, 2013).These studies revealed the significant contribution of the frontoparietal in encoding and processing the irrelevant information in a working memory task. It is possible that, the frontoparietal network would be particularly important in multiple choice decision making, since there is plenty of irrelevant information.

4.4 Future directions

By combining the results from Study 1 and Study 2, the distinct roles of the dlPFC and PPC in processing information during multiple choice decision making was revealed. However, sampling information was not shown to be related to either the dlPFC or PPC. My results showed that the average time spent on each option was significantly reduced on trials with more options (Figure 2c). This implies that a distinct or additional process is involved in the multiple choice decision making. Previous studies reported that the anterior cingulate cortex (ACC) is important for information sampling in binary decision as its activity reflected the value of searching (Kolling, Behrens, Mars, &Rushworth, 2012; Kolling, Scholl, Chekroud, Trier,

&Rushworth, 2018). When the value of the options to be explored is greater, the ACC would be more active.

The results mentioned above show the importance of the ACC in the information sampling process of binary decision. In addition, my results implied that the information sampling process in multiple choice decision making is possibly different from that in binary decision. Therefore, in the future, I suggest that an fMRI experiment should be performed to investigate the neural mechanism of information sampling process in multiple choice decision making. Analysis could be performed to investigate whether information sampling in binary and multiple choice decision making would involve different brain regions. Moreover, my results showed that people spend less time on viewing the option in multiple choice decision making. Therefore, another possible analysis could be conducted to identify the brain region or regions whose activity is related to fixation time on the options.

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