Neuropsychologia 85 (2016) 74–79

Contents lists available at ScienceDirect

Neuropsychologia

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

Electrical stimulation of the dorsolateral prefrontal cortex improves memory monitoring

Elizabeth F. Chua [a,b,*], Rifat Ahmed [a]

[a] Brooklyn College of the City University of New York, 2900 Bedford Ave, Brooklyn, NY 11210, United States
[b] The Graduate Center of the City University of New York, 365 5th Ave, New York, NY 10016, United States

ARTICLE INFO

Article history:
Received 17 December 2015
Received in revised form
6 March 2016
Accepted 7 March 2016
Available online 9 March 2016

Keywords:
tDCS
HD-tDCS
Prefrontal
Memory
Metamemory
Feeling-of-knowing

ABSTRACT

The ability to accurately monitor one's own memory is an important feature of normal memory function. Converging evidence from neuroimaging and lesion studies have implicated the dorsolateral prefrontal cortex (DLPFC) in memory monitoring. Here we used high definition transcranial direct stimulation (HD-tDCS), a non-invasive form of brain stimulation, to test whether the DLPFC has a causal role in memory monitoring, and the nature of that role. We used a metamemory monitoring task, in which participants first attempted to recall the answer to a general knowledge question, then gave a feeling-of-knowing (FOK) judgment, followed by a forced choice recognition task. When participants received DLPFC stimulation, their feeling-of-knowing judgments were better predictors of memory performance, i.e., they had better memory monitoring accuracy, compared to stimulation of a control site, the anterior temporal lobe (ATL). Effects of DLPFC stimulation were specific to monitoring accuracy, as there was no significant increase in memory performance, and if anything, there was poorer memory performance with DLPFC stimulation. Thus we have demonstrated a causal role for the DLPFC in memory monitoring, and showed that electrically stimulating the left DLPFC led people to more accurately monitor and judge their own memory.

1. Introduction

The ability to accurately monitor one's own memory, is one component of what is referred to as metamemory, and is an important feature of normal memory function (Nelson and Narens, 1990). For example, accurate memory monitoring can lead to better regulation of learning and memory, thereby improving overall performance (Thied et al., 2003). Furthermore, certain clinical populations have shown impairments in memory monitoring, independent of memory impairments (Stepanie Cosentino et al., 2007). Despite the critical role of monitoring in the effective use of memory, less is known about the neural mechanisms subserving memory monitoring accuracy, and whether it can be enhanced using non-invasive brain stimulation.

One common way to evaluate memory monitoring is by determining accuracy on metamemory tasks, such as the *feeling-of-knowing* (FOK) task (Nelson and Narens, 1990). Typical FOK tasks ask participants to recall a target piece of information, and when they fail to do so, they are asked to predict the likelihood that they will remember the answer later (i.e., to make a feeling-of-knowing judgment), followed by a recognition test for the target information (Hart, 1965; Kikyo and Miyashita, 2004; Maril et al., 2003; Metcalfe et al., 1993; Schwartz and Metcalfe, 1992). Monitoring accuracy, also referred to as metamemory accuracy, is then assessed by determining how well the individual's subjective FOK ratings relate to their objective memory performance (Benjamin and Diaz, 2008; Nelson, 1984; Pannu and Kaszniak, 2005).

Monitoring accuracy depends on how well the information used to make these metamemory judgments relates to memory accuracy (Chua et al., 2012). FOK judgments have been shown to be based on cue familiarity (Metcalfe et al., 1993; Reder, 1987), target accessibility (Koriat, 1993), and the combination of the two (Chua and Solinger, 2015; Koriat and Levy-Sadot, 2001). FOKs can be based on a rapid evaluation of the cue, with more familiar cues leading to higher FOKs (Metcalfe et al., 1993; Reder, 1987). Sufficient cue familiarity then leads to a memory retrieval search, and higher FOKs are given when more partial information accessed, regardless of whether this partial information is correct (Koriat, 1993). By this view, FOK accuracy (i.e., monitoring accuracy in the FOK task) depends on the quality of the memory processes, in that judgments are based on the outcomes of the search attempts for the target (Koriat, 1993).

Indeed, there is some evidence that FOK and memory may not

---

* Corresponding author at: Department of Psychology, Brooklyn College, CUNY, 2900 Bedford Avenue, Brooklyn, NY 11210, United States.
E-mail address: echua@brooklyn.cuny.edu (E.F. Chua).

http://dx.doi.org/10.1016/j.neuropsychologia.2016.03.008
0028-3932/© 2016 Elsevier Ltd. All rights reserved.

be completely independent processes. Memory impairments have been associated with reduced FOK accuracy (Bacon et al., 1998; Perrotin, et al., 2007). However, other studies have shown that impaired memory does not have to be associated with reduced FOK accuracy (Schacter, 1983; Shimamura and Squire, 1986). For example, comparisons of Korsakoff's patients and other amnesics, both of whom had reduced memory performance, showed that only Korsakoff's patients showed impaired FOK accuracy (Shimamura and Squire, 1986). This difference was attributed to the frontal lobe pathology seen in Korsakoff's patients, but not in the other amnesics.

The role of the prefrontal cortex in FOKs may be related to its role in executive functioning (Fernandez-Duque et al., 2000; Pannu and Kaszniak, 2005; Perrotin et al., 2008; Shimamura, 2000; Souchay et al., 2000). Recent work using neuropsychological testing showed that executive functioning contributed to FOK accuracy, and that this effect was much larger than the contribution of memory ability (Perrotin et al., 2008). Furthermore, several neuroimaging studies have shown that activity in the DLPFC increases with increasing demands on retrieval monitoring (Dobbins et al., 2002; Gallo et al., 2010), with monitoring being one of the executive functions.

Many fMRI studies have shown greater activation with increasing levels of FOKs in many PFC subregions (Chua et al., 2009; Elman et al., 2012; Kikyo, Ohki, and Miyashita, 2002; Maril et al., 2005), and this tends to be most consistent in left lateral prefrontal cortex (Chua et al., 2009; Kikyo and Miyashita, 2004; Kikyo et al., 2002; Maril et al., 2003). There are several possible explanations for why activity in the PFC modulates with FOK: 1) activity in the PFC may provide an index of the subjective feeling per se (Chua et al., 2009), 2) activity in the PFC increases with retrieval monitoring demands (Henson et al., 2000; Henson et al., 1999), and trials with higher FOKs tend to require weighing and monitoring of more information, or 3) the PFC may modulate based on the amount of target information accessed and higher levels of FOKs may be associated with increased target access and partial retrieval (Maril et al., 2005).

The role of the PFC in FOKs has yet to be tested using non-invasive brain stimulation, which has become a useful tool in cognitive neuroscience research and has potential use for development as an intervention (Berryhill et al., 2014; Sparing and Mottaghy, 2008). Transcranial direct current stimulation (tDCS) involves passing a low level of current between stimulation and reference electrodes placed on the scalp, with the stimulating electrode typically being placed over the targeted brain region (for review, see Nitsche et al., 2008). Stimulation using a positively charged electrode, typically referred to as anodal stimulation, has been shown to increase neural firing rates, with after effects that last beyond the stimulation duration. Conventional tDCS typically places large electrodes that are spaced relatively far apart on the scalp, thereby stimulating both the targeted brain region and surrounding and connected structures (Bai et al., 2014). More focal methods of tDCS have been developed, termed High Definition tDCS (HD-tDCS), which use a 4 × 1 ring electrode, and which better restricts the stimulation to the region of interest (Datta et al., 2009; Kuo et al., 2013).

In this study, we use HD-tDCS to test the whether or not the DLPFC has a causal role in the feeling-of-knowing using a general knowledge task, and to examine the nature of that role. We targeted the left DLPFC because it has modulated by level of FOK across multiple kinds of tasks (Reggev et al., 2011). Paralleling lesion studies that have compared patients with frontal and temporal lesions to examine metamemory versus memory contributions to FOK accuracy (Shimamura and Squire, 1986), we compared left DLPFC stimulation to left anterior temporal lobe (ATL) stimulation because the left ATL has been shown to be critical for semantic memory (Hodges et al., 1992; Mummery et al., 2000). If the role of the DLPFC in FOKs is to index the subjective feeling per se (Chua et al., 2009), excitation of the DLPFC should lead to higher FOKs compared to ATL and sham stimulation. In contrast, if the role of the DLPFC is in retrieval monitoring (Henson et al., 2000, 1999), then excitation of the DLPFC should lead to increased monitoring accuracy. Finally, if DLPFC activity relates to the amount of information accessed (Maril et al., 2005), then both DLPFC and ATL stimulation should lead to higher FOK ratings compared to sham, and potentially improved memory accuracy. In summary, the goals of this study were to use HD-tDCS to examine the role of the left DLPFC and left ATL in memory and metamemory for general knowledge questions.

2. Materials and methods

2.1. Participants

Thirty healthy, English speaking, right-handed, Brooklyn College students participated in this 3-session, research study for course credit (1 credit per hour) or for pay ($15/h). Three participants failed to return for all three visits, and the data from the 27 participants (13F/14M, ages 18-25, Mean ± SEM: 20.3 ± 0.31 years) who completed the study were analyzed. G*Power 3.1 (Faul et al., 2007) was used to determine that data from 27 subjects were needed for 80% power to detect a medium-sized effect (η^2=0.06) for a repeated measures ANOVA with 1 group and 3 measurements. Participants were screened before each experiment to ensure they were suitable to participate. Participants were free from neurologic and psychiatric illness, nor had any open wounds on the scalp and/or face. Each participant provided written consent in a manner approved by the Human Research Protection Program at the City University of New York (CUNY).

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

HD-tDCS was administered using the Soterix 4 × 1 adaptor for the Soterix 1 × 1 tDCS Low-Intensity Stimulator (Model 1224-B, Soterix Medical, New York, NY). For DLPFC and sham stimulation sessions, the anode was placed at the F3 position (using the 10-20 system) and 4 return electrodes were placed at positions AF3, F1, F5, and FC3. For ATL stimulation, the anode was placed at T7 and 4 return electrodes were placed at FT7, FT9, C5, and TP7. The stimulation electrodes were sintered Ag/AgCl ring electrodes (outer radius: 12 mm; inner radius 6 mm). The electrodes were fixed on an EEG cap with HD Electrode holders (Soterix Medical, New York, NY) and filled with Signa Gel to ensure electroconductivity to the scalp. In each montage, the anode was set to deliver a total current of 2 mA, and the return electrodes shared the same current intensity (0.5 mA each). These montages were chosen based on computational models that generated stimulated current maps using HDExplore (Soterix Medical, New York, NY) that showed good current flow in the left DLPFC and left ATL, respectively (Fig. 1). During active stimulation, participants received 2 mA of stimulation for 20 min, whereas during sham stimulation, the current ramped up to 2 mA and then back down during the first ~30 s, remained at 0.1 mA for 19 min, and then ramped up to 2 mA and down again at the end of the sham period for the last 30 s. Participants completed 3 sessions, approximately one week apart, and typically at the same time of day, with separate DLPFC, ATL, and sham HD-tDCS sessions; sessions were counterbalanced for stimulation and list order across subjects.

2.3. Stimuli and procedure

Stimuli consisted of 300 general knowledge questions that had previously been normed using a CUNY sample (Mangels et al., 2015), and were presented using Psychopy (Peirce, 2007). There were 4 additional practice questions used to familiarize participants with the task.

HD-tDCS began at the start of the general knowledge task. After the instructions, participants first viewed a general knowledge question on the screen and were asked to recall the answer and type it in. If they did not know the answer, they were instructed to type "idk" to indicate "I don't know." After 45 s, or a subject response, the trial advanced. This was followed by a FOK judgment, in which they had a maximum of 30 s to indicate the likelihood that they would recognize the correct answer on a 1–10 scale. This was then followed by a recognition judgment in which they had a maximum of 15 s to choose which among 4 answers was the correct answer to the general knowledge question. One of the answers was the correct answer, and the three incorrect answers were the most frequently given incorrect answers given by other CUNY students (Mangels et al., 2015). There were 100 questions per session, and the three sets of questions were matched on difficulty based on previous norming with CUNY students. Stimulation condition and