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Decreasing propensity to mind-wander with transcranial direct current stimulation

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ABSTRACT

Mind wandering or task-unrelated thought (TUT) is associated with various impairments as well as with adaptive functions, indicating the importance of regulating this process. Although Axelrod et al. (2015) have shown that anodal/cathodal transcranial direct current stimulation (tDCS) of the left/right lateral prefrontal cortex (LPFC) could increase the propensity for mind wandering, it remains unclear whether a different tDCS protocol could have the reverse effect. The present study investigated whether and how simultaneous stimulation of the left LPFC and right inferior parietal lobule (IPL) could modulate TUTs. These areas may be crucial for regulating both TUTs and its neural underpinning (default mode network). We applied tDCS to the right IPL/left LPFC prior to a perceptually demanding flanker task and compared TUT propensity during the task among tDCS groups. We found that TUT propensity was reduced by anodal/cathodal tDCS of the right IPL/left LPFC compared with cathodal/anodal tDCS, and the results for the sham group were intermediate between these two groups. This is the first study to demonstrate that tDCS can decrease, as well as increase, TUT propensity.

1. Introduction

Mind wandering is the spontaneous transition of internal attention mainly to self-generated thoughts and occupies up to half of our waking hours (Axelrod et al., 2015). Mind wandering is related to adaptive functions such as planning, creativity, and a coherent sense of self (Andrews-Hanna et al., 2014). However, mind wandering, also referred to as task-unrelated thoughts (TUTs), causes intermittent shifts of attention from the task at hand and dampens sensory information processing (Baird et al., 2014; Barron et al., 2011), resulting in poor task performance (Kam et al., 2013; Kane and McVay, 2012), accidents (He et al., 2011), and maladaptation (e.g., poor lesson comprehension; Smallwood et al., 2007). Thus, regulating mind wandering propensity is quite important.

Transcranial direct current stimulation (tDCS) is a low-cost, portable, noninvasive neuromodulation technique that may be suited to external regulation of TUT propensity (Axelrod et al., 2015; Coffman et al., 2014). tDCS has been shown to enhance various cognitive functions such as attention, learning, and memory (Coffman et al., 2014) and the effects last up to 1 h following a 20-min session (Nitsche et al., 2003). Surprisingly and intriguingly, Axelrod et al. (2015) recently succeeded in increasing TUT propensity using tDCS. They applied the anodal electrode (generally increases neuronal excitability) to the left lateral prefrontal cortex (LPFC), which has been shown to be activated during mind wandering (Christoff et al., 2009), and the cathode (generally decreases neuronal excitability) to the right supraorbital area as a reference electrode. Stimulation that was applied during the first half of an attention task caused a clear increase in TUT propensity throughout the task. However, it remains unknown whether tDCS could decrease TUT propensity under different conditions.

We know of two possible methods for decreasing TUT propensity, which may be combinable. One is cathodal stimulation of the left LPFC (Coffman et al., 2014). The other is anodal stimulation of the right inferior parietal lobule (IPL). The IPL is a core region of the default mode network (DMN) (Buckner et al., 2008) that is strongly linked with mind wandering (Fox et al., 2015). Furthermore, the right IPL has been implicated as a crucial regulator of TUTs via its effect on the other regions of the DMN (Christoff et al., 2009; Di and Biswal, 2014; Hasenkamp et al., 2012; Mason et al., 2007). For example, Hasenkamp et al. (2012) examined neural activity related to mental experiences during meditation and reported that the IPL activates when attention shifts from mind wandering to breathing. In addition, dynamic causal modeling analysis of resting-state data has indicated that the right IPL causally affects activities in other core regions of the DMN (Di and Biswal, 2014). Collectively, the data suggest that the right IPL is important in regulating TUTs and thus tDCS of the right IPL/left

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LPFC, with IPL anodal, is an appropriate strategy for external downregulation of TUT propensity.

The present study explored whether tDCS of the right IPL/left LPFC can decrease TUT propensity. We hypothesized that the cathodal/anodal tDCS of the right IPL/left LPFC, which reproduces the anodal stimulation of the left LPFC implemented by Axelrod et al. (2015), would replicate the reported increasing effect of tDCS on TUT propensity. On the other hand, tDCS of the right IPL/left LPFC, with IPL anodal, is predicted to induce the opposite effect: a decrease in mind wandering. Since the IPL is involved in distractor filtering (Weiss and Lavidor, 2012) and response conflict resolution (Wendelken et al., 2009) as well as in DMN operations, we also made exploratory measurements to determine the effects of tDCS on such attention-related functions using a multi-condition, attention-demanding task.

2. Materials and methods

2.1. Participants

Eighty healthy participants with no history of neurological or psychiatric disease were paid to participate in this study (34 females; mean age=21.5 years, SD=2.4; only 1 participant, in the sham group, was left-handed). Participants were randomly allocated to three stimulation groups with different brain stimulation configurations (anode, cathode, and sham [control group]). Before conducting the data analyses, we excluded seven participants from further analyses: five participants were suspected to have made insincere responses because they selected the same thought probe category (see below) throughout at least one block, and two participants had trouble with the task program or the tDCS equipment. Ultimately, we included 24 participants in the anode group (14 males, mean age=21.4 ± 2.6 years), 24 in the sham group (13 males, mean age=21.0 ± 1.9 years), and 25 in the cathode group (14 males, mean age=21.9 ± 2.6 years). These sample sizes are more than two-fold greater than in previous between-subjects tDCS studies (Axelrod et al., 2015; Weiss and Lavidor, 2012). Participants provided written, informed consent before taking part in the study. The study was approved by the local institutional review board committee.

2.2. tDCS

Direct current was transferred by a saline-soaked pair of surface sponge electrodes (7×5 cm^2) and delivered by a battery-driven, constant-current stimulator (DC-stimulator, NeuroConn GmbH, Germany). The target electrode was placed over P4 according to the 10–20 International system for electroencephalographic electrode placement (Okamoto et al., 2004). The reference electrode was placed around AF7 over the LPFC (Bolognini et al., 2015; Nitsche et al., 2008). In the anode group, the anode and cathode were placed on P4 and around the AF7, respectively; these placements were reversed for the cathode group. Half of the participants in the sham group had the same electrode placement as the anode group, and the other half matched that of the cathode group. A constant 1.5-mA current was applied for 20 min. Participants felt the current as an itching sensation at both electrode contact points at the beginning of the stimulation. For sham stimulation, the stimulator was turned off after 30 s. Therefore, all participants felt the initial itching sensation but the sham group received no current for the rest of the stimulation period. This procedure enabled us to keep participants blind to their stimulation group.

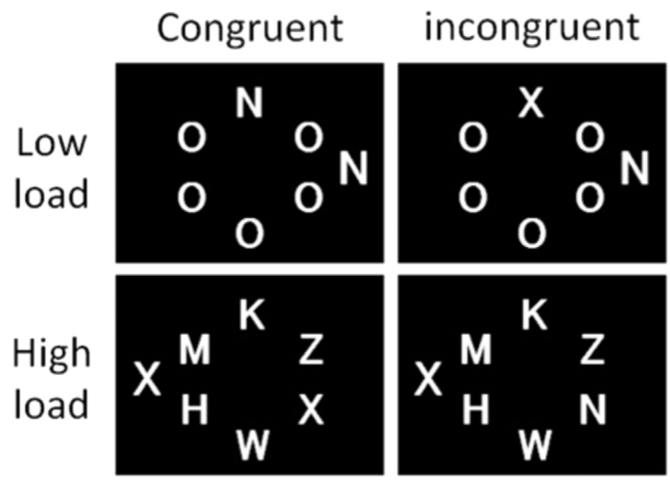

Fig. 1. Examples of the perceptual load task stimuli for each condition.

2.3. Perceptual load task

We used the perceptual load task (Lavie and Cox, 1997) which is known to induce sufficient TUTs (Forster and Lavie, 2009). Participants searched for two possible target letters (N or X) among central nontarget letters (see examples in Fig. 1). Participants responded by pressing a key to indicate which target letter was included in the stimulus. The task consists of two conditions: perceptual load and congruency. In the low-perceptual load condition, the circle included the target letter with five Os (low-competition condition). In the high-perceptual load condition, the circle contained the target letter and five additional competing letters (H, K, M, W, and Z; high-competition condition). In addition to the perceptual load, a flanker appeared to the right or left of the circle with equal probability. The flanker, which the participant was instructed to ignore, was X or N and could be congruent with or not congruent with the target letter (congruent condition and incongruent condition, respectively). The task was administered using Hot Soup Processor version 3.3 software (ONION software, Japan) on a 19-inch computer monitor (P190S, 1280×1024 pixels, refresh rate 75 Hz; Dell, USA). The distance between the participant and the monitor was about 57 cm. A fixation letter was displayed in the center of the monitor in a white 25-point Miriam font. The central and flanker letters were white in 31- and 37-point fonts, respectively. All letters were uppercase. Circle letters subtended 0.9° vertically and 0.6° horizontally. The flanker subtended 1.1° vertically and 0.9° horizontally. The distances from fixation to the central letters and the flanker subtended 2.1° and 4.3°, respectively. Target position, target letter, and distractor congruency were counterbalanced. Trial presentation was randomized within each session. Each experiment consisted of 3 sessions of 192 trials (48 trials for 4 conditions). Each trial began with a 500-ms fixation period before the stimulus was presented for 100 ms. A blank response screen was then presented until the response occurred or for 2000 ms. A response after 2000 ms was encoded as a miss. A blank screen was then presented for the intertrial interval of 2600 ms minus the response time (RT), or for an additional 600 ms in the case of a miss trial.

2.4. Thought probes

Thought probes that required the participants to classify the contents of their immediately preceding thoughts appeared during the perceptual load task. Participants responded based on their thought content just before the probe appeared. The thought probe categories were: "*1. Task contents*," "*2. Task performance*," "*3. A memory from the past*," "*4. Something in the future*," "*5. Current*