COMMENTARY

Stimulating minds to wander

James M. Broadway[1], Claire M. Zedelius, Benjamin W. Mooneyham, Michael D. Mrazek, and Jonathan W. Schooler
Department of Psychological and Brain Sciences, University of California, Santa Barbara, CA 93105

Springing from memory and imagination, mind wandering is a mental state occupying as much as half of our waking life, involving a shift of attention away from the external environment and toward task-unrelated concerns (1). Although mind wandering may play an important role in planning and creativity (2, 3), it is also widely associated with negative mood and degraded performance on measures of vigilance, working memory, fluid intelligence, and reading comprehension (4, 5). The intrinsically subjective and spontaneous nature of mind wandering has made it difficult to investigate with direct experimental manipulations (6). Researchers have used various approaches to do so indirectly, by altering related factors such as mood, motivation, the amount of time spent on a task, or cognitive load (7, 8). However, these factors may influence various cognitive processes besides mind wandering. Moreover, these approaches do not directly implicate underlying neural mechanisms of mind wandering. In contrast, Axelrod et al. (9) demonstrate that mind wandering can be increased by direct experimental manipulation of brain activity using transcranial direct current stimulation (tDCS) to the prefrontal cortex (PFC). The article by Axelrod et al. thus marks a new era for research into mind wandering and previews some of the insights that continued methodological advances will likely make possible.

Axelrod et al. used tDCS to stimulate the frontal lobes for 20 min by placing a positively charged electrode (anode) over the left dorsolateral prefrontal cortex (DLPFC) and a negatively charged electrode (cathode) on the ridge over the right eye. This technique transmits a low-voltage electric current through the skull to stimulate populations of neurons in the underlying cortex. This is thought to alter the excitability of those neurons, thus increasing the likelihood of firing spontaneously or in response to events. Poststimulation effects, lasting perhaps up to 20 min, are thought to be due to more sustained changes in cortex similar to long-term potentiation (10). In the experiments by Axelrod et al., participants performed a vigilance task during and after stimulation, requiring frequent responses to go cues but infrequent withholding of responses to no-go cues. Throughout the vigilance task, intermittent "thought probes" assessed whether participants were mind wandering. Frontal lobe tDCS increased self-reported mind wandering relative to sham or occipital lobe tDCS, with no significant change to performance on the vigilance task (9).

The favored interpretation of Axelrod et al. for their findings is that stimulating the left DLPFC temporarily enhanced working memory capacity, with the result that more capacity was available to engage in mind wandering while maintaining high task performance. This interpretation, if true, speaks to a long-running debate concerning the role of executive function in mind wandering. Three hypotheses predominate in this debate. According to the executive recruitment view (6, 11), executive processes are recruited during mind wandering in the service of distal goals (12) and possibly to maintain the inner stream of consciousness (6) or insulate it from interference from the task environment (11). According to the executive failure view (13), mind wandering occurs when executive control processes temporarily fail to maintain goal representations that would ordinarily keep a person on task. According to the meta-awareness view (14), executive control plays a role in gaining meta-awareness of the fact that one is now or has been mind wandering, so that one may reallocate resources to the task at hand. The results of Axelrod et al. are potentially informative with respect to resolving this debate.

The alternative hypotheses make different predictions about the neural mechanisms underlying mind wandering, particularly about the relationship between the executive control network and the default network—a collection of regions most active at rest and under conditions of low task demands. Although these networks are often anticorrelated, regions within both the default and executive networks are coactive during mind wandering (15). However, these findings are correlational and do not possess sufficient temporal resolution to support inferences about temporal order of brain states.

Direct manipulations of neural function such as tDCS could in principle provide causal evidence regarding brain networks underlying cognitive processes. However, as Axelrod et al. acknowledge, the spatial resolution of tDCS in their experiments is coarse. Electrical current probably passed diffusely

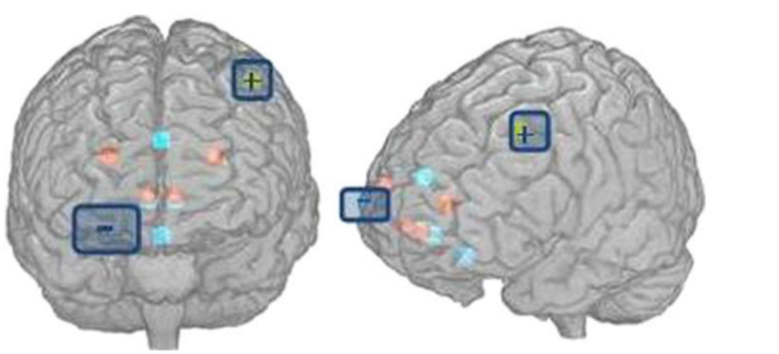

Fig. 1. Schematic depiction of two views of the tDCS montage as in ref. 9, at anode (+) and cathode (–) locations and neighboring frontal areas that were likely to have been in the path of current flow: left DLPFC of the executive control network (yellow, under anode), medial PFC of the default mode network (light blue), and more anterior PFC involved in metacognition (red).

Author contributions: J.M.B., C.M.Z., B.W.M., M.D.M., and J.W.S. wrote the paper.

The authors declare no conflict of interest.

See companion article on page 3314.

[1]To whom correspondence should be addressed. Email: broadway@psych.ucsb.edu.

www.pnas.org/cgi/doi/10.1073/pnas.1503093112

through a number of cortical areas intervening between the two frontal scalp locations in their montage, and even outside this path, and not just focally to the left DLPFC. This lack of spatial specificity suggests three possible interpretations for their results, roughly parceling cognitive functions according to distinct frontal areas that might have been affected. The brain regions relevant to these alternative accounts are visualized in Fig. 1, with the approximate locations of the anode and cathode for the montage used for stimulating the left DLPFC.

Axelrod et al. interpret their findings as resulting from stimulation of the DLPFC, an area centrally involved in executive control (Fig. 1, yellow, under anode). This interpretation is in line with the executive recruitment view, in which increased mind wandering is the result of enhanced working memory capacity, which provides additional cognitive resources for task-unrelated thoughts. Alternatively, it is possible the electrical current passing through medial PFC activated the default mode network (Fig. 1, light blue), which thereby increased mind wandering directly. This scenario would not directly inform the debate regarding the role of executive functions in mind wandering. A third possibility is that by stimulating anterior regions of PFC known to be associated with metacognitive processes (Fig. 1, red), participants became more meta-aware of their mind wandering. In this third scenario, tDCS enhanced participants' sensitivities to mind wandering episodes, thereby increasing the frequency of reports, without necessarily affecting the frequency of mind wandering itself.

Until more evidence is available, we view the results of Axelrod et al. as compatible with each of these interpretations, which are not necessarily mutually exclusive. It has been shown that tDCS to DLPFC increases functional connectivity between subregions of the DLPFC and executive and default mode networks (16). Increased DLPFC-to-default network connectivity might help explain the increased mind wandering that was observed, whereas increased DLPFC-to-executive network connectivity might account for the absence of reduced task performance that typically accompanies greater task-unrelated thought.

Although the poor spatial precision of conventional two-channel tDCS allows for such ambiguities of interpretation, these

Axelrod et al. demonstrate that mind wandering can be increased by direct experimental manipulation of brain activity using transcranial direct current stimulation to the prefrontal cortex.

results pave the way for more definitive evidence about the neural and cognitive processes underlying mind wandering. This might be achieved by integrating high-definition tDCS, in which more focal stimulation is achieved with multiple electrodes arranged in a ring over the target site, with effective connectivity MRI, a class of analytic approaches capable of modeling causal relationships between brain regions (17). As a widely available technology, tDCS promises to support ever-increasing experimentation and direct manipulation of brain activity, bringing new insight about cognitive processes and their neural instantiations. However, discerning the full value of tDCS will require disentangling the sources of its varied effects. Viewing the literature as a whole, there are concerns about the replicability of tDCS findings. For example, tDCS of left DLPFC, using the same electrode montage as the authors, is sometimes associated with increases in working memory capacity and other times with decreases (18). Moreover, Horvath et al. (19) suggested that the cognitive effects of single-session tDCS may have been overstated and that neurophysiological effects may not extend beyond enhancement of motor-evoked potentials (20). For these reasons, it is noteworthy that the findings of Axelrod et al. were replicated across two studies. It is also important that these experiments be replicated and parametrically extended by independent laboratories. Although some caution in interpretation is warranted, we are hopeful that this pioneering work will stimulate continued innovation and experimentation, leading to ever greater insights into the mind's restless tendency to wander.

1 Killingsworth MA, Gilbert DT (2010) A wandering mind is an unhappy mind. *Science* 330(6006):932.
2 Baird B, et al. (2012) Inspired by distraction: Mind wandering facilitates creative incubation. *Psychol Sci* 23(10):1117–1122.
3 Baird B, Smallwood J, Schooler JW (2011) Back to the future: Autobiographical planning and the functionality of mind-wandering. *Conscious Cogn* 20(4):1604–1611.
4 Mooneyham BW, Schooler JW (2013) The costs and benefits of mind-wandering: A review. *Can J Exper Psychol* 67(1):11–18.
5 Randall JG, Oswald FL, Beier ME (2014) Mind-wandering, cognition, and performance: A theory-driven meta-analysis of attention regulation. *Psychol Bull* 140(6):1411–1431.
6 Smallwood J (2013) Distinguishing how from why the mind wanders: A process-occurrence framework for self-generated mental activity. *Psychol Bull* 139(3):519–535.
7 Smallwood J, Fitzgerald A, Miles LK, Phillips LH (2009) Shifting moods, wandering minds: Negative moods lead the mind to wander. *Emotion* 9(2):271–276.
8 Smallwood J, Obonsawin M, Reid H (2003) The effects of block duration and task demands on the experience of task unrelated thought. *Imagin Cogn Pers* 22(1):13–31.
9 Axelrod V, Rees G, Lavidor M, Bar M (2015) Increasing propensity to mind-wander with transcranial direct current stimulation. *Proc Natl Acad Sci USA* 112:3314–3319.
10 Stagg CJ, Nitsche MA (2011) Physiological basis of transcranial direct current stimulation. *Neuroscientist* 17(1):37–53.
11 Smallwood J (2010) Why the global availability of mind-wandering necessitates resource competition: Reply to McVay and Kane (2010). *Psychol Bull* 136(2):202–207.
12 Smallwood J, Schooler JW (2006) The restless mind. *Psychol Bull* 132(6):946–958.
13 McVay JC, Kane MJ (2010) Does mind wandering reflect executive function or executive failure? Comment on Smallwood and Schooler (2006) and Watkins (2008). *Psychol Bull* 136(2):188–197, discussion 198–207.
14 Schooler JW, et al. (2011) Meta-awareness, perceptual decoupling and the wandering mind. *Trends Cogn Sci* 15(7): 319–326.
15 Christoff K, Gordon AM, Smallwood J, Smith R, Schooler JW (2009) Experience sampling during fMRI reveals default network and executive system contributions to mind wandering. *Proc Natl Acad Sci USA* 106(21):8719–8724.
16 Keeser D, et al. (2011) Prefrontal transcranial direct current stimulation changes connectivity of resting-state networks during fMRI. *J Neurosci* 31(43):15284–15293.
17 Friston KJ (1994) Functional and effective connectivity in neuroimaging: A synthesis. *Hum Brain Mapp* 2(1-2):56–78.
18 Tremblay S, et al. (2014) The uncertain outcome of prefrontal tDCS. *Brain Stimulat* 7(6):773–783.
19 Horvath JC, Forte JD, Carter O (2015) Quantitative review finds no evidence of cognitive effects in healthy populations from single-session transcranial direct current stimulation (tDCS). *Brain Stimulation*, 10.1016/j.brs.2015.01.400.
20 Horvath JC, Forte JD, Carter O (2015) Evidence that transcranial direct current stimulation (tDCS) generates little-to-no reliable neurophysiologic effect beyond MEP amplitude modulation in healthy human subjects: A systematic review. *Neuropsychologia* 66C:213–236.