The Effects of Transcranial Direct Current Stimulation on Mind-Wandering

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Author Note

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Abstract

The current study investigated whether transcranial direct current stimulation (tDCS) to the left dorsolateral prefrontal cortex (DLPFC) and the right inferior parietal lobule (IPL) independently influences mind-wandering behavior. Thirty-six participants received offline stimulation at either the left DLPFC (F3) or the right IPL (P4), both with the second electrode over Cz. Within each group, participants experienced three stimulation conditions on three separate days: anodal/return (F3 or P4/Cz), cathodal/return (F3 or P4/Cz), and sham. When all stimulation conditions were combined, participants in the F3 group reported significantly more task-unrelated thoughts (TUTs) during a monotonous task than those in the P4 group. However, no significant difference in TUTs was found between the stimulation conditions. This finding challenged existing results on tDCS and mind-wandering, but must be interpreted in light of the differences in experimental paradigm and measures of mind-wandering between the current studies and prior literature. These differences, together with limitations and suggested modifications, were discussed.

Keywords: mind-wandering, task-unrelated thoughts, transcranial direct current stimulation, prefrontal cortex, parietal lobe

The Effects of Transcranial Direct Current Stimulation on Mind-Wandering

Adults spend as much as fifty percent of their thoughts during the day meandering from their immediate surrounding (Killingsworth & Gilbert, 2010; but see Song & Wang, 2015) – a mental activity aptly named mind-wandering. Often operationalized as task-unrelated thoughts (TUTs) (Giambra, 1989) or stimulus-independent thoughts (SITs) (Antrobus et al., 1966), mind-wandering is thought to involve an attentional shift away from the task at hand (Smallwood & Schooler, 2006) and, oftentimes, perceptual decoupling from the environment (Fox et al., 2005; Smallwood et al., 2008; for a review of the evidence, see Schooler et al., 2011). Mind-wandering impedes one's performance in cognitively demanding tasks (Feng, D'Mello, & Graesser, 2013; McVay & Kane, 2012b) and often accompanies a negative mood (Smallwood et al., 2009). At the same time, it contributes to creative problem solving (Baird et al., 2012) and accumulates the benefits of prospective thinking over time, for a significant portion of mind-wandering thoughts are about future events (Baumeister et al., 2011). Despite its prevalence and widespread implications, much remains unknown about how mind-wandering is regulated by the brain, let alone our ability to modulate it externally.

Studies of mind-wandering traditionally put participants through a task, such as reading (e.g., Unsworth & McMillan, 2013), breath counting (e.g., Braboszcz & Delorme, 2011), or auditory oddball task (e.g., Ros et al., 2013), and implement measures to capture mind-wandering during this task. One of the most common tasks is the standard Sustained Attention to Response Task (SART), which requires participants to respond to critical trials in a series of critical and non-critical stimuli. The most reliable measures of mind-wandering have traditionally been self-report, two prominent examples of which are probe-caught thought sampling and retrospective sampling (for a review, see Smallwood and Schooler, 2015). The former typically involves probes that occur at random or regular intervals during the task to ask participants about the content of their thoughts. The latter is administered at the end of task blocks and asks participants to evaluate the content of their thoughts during the most recent block. Using this basic setup, additional objective measures could be employed to investigate other aspects of mind-wandering. McVay and Kane (2012a), using reaction time, accuracy rates, and probe-caught thought sampling during the SART, found that mind-wandering, together with working memory capacity, predicted extreme reaction times and errors. However, they also found that mind-wandering did not always accompany trial-to-trial changes in reaction times. Braboszcz and Delorme (2011), by collecting electroencephalographic data from 128 cortical sites and self-caught probes of mind-wandering during an auditory oddball task (which requires participants to respond to auditory stimuli that are higher in frequency than the standard stimulus), found that theta (4-7 Hz) and delta (2-3.5 Hz) EEG activity were elevated during mind-wandering. Moreover, participants showed a smaller N1 component over frontal and temporal regions (also called the mismatch negativity) and a greater P2 component over fronto-central sites (associated with disengagement from stimuli) after the onset of an oddball stimulus if they were mind-wandering. While these measures provide some observable correlates of mind-wandering, they are still coarse-grained and reveal little about the brain networks or underlining mechanisms associated with this mental activity.

Research using Functional Magnetic Resonance Imaging (fMRI) can offer additional information beyond reaction time and EEG. Mind-wandering is linked to activation in regions from the executive network such as the dorsolateral prefrontal cortex (DLPFC) and the dorsal anterior cingulate cortex (ACC), indicating some degree of resource overlap between mind-wandering and executive control (Christoff et al., 2009). In order to differentiate the roles played by the ACC and the DLPFC, MacDonald and colleagues (2000) had participants complete a color-naming task in which the word may refer to the same or to a different color than its print (i.e., the Stroop task). The ACC activated more during incongruent trials than during congruent ones, suggesting that this area played a larger role in conflict detection. In contrast, the left DLPFC did not differ in its activation between congruent and incongruent trials. This led MacDonald and colleagues (2000) to propose that the left DLPFC was important to the representation and maintenance of attentional task demands. In keeping with these observations, Christoff and colleagues (2009) speculated that activity in the executive areas during mind-wandering implied the presence of conflicts and a need for monitoring in the content of mind-wandering. A different view, proposed by McVay and Kane (2010), asserted that mind-wandering reflected failure of the executive system to enact and maintain proactive control in the face of task demands. This proactive control is dissociable from reactive control (e.g., conflict resolution), which Christoff and colleagues (2009) was concerned with. Interestingly, proactive and reactive control seem to be associated with different areas in the executive control network: the former, the DLPFC; the latter, the ACC (e.g., Braver, 2012; Braver, Gray, & Burgess, 2007). While in competition, both views advocate for the involvement of the executive network in mind-wandering.

Another network consistently found to exhibit elevated activity during mind-wandering is the default mode network (DMN) (e.g., Andrews-Hanna et al., 2014; Gruberger et al., 2011). The DMN is a core network implicated in several higher cognitive processes including episodic memory formation (Chai et al., 2014), mental simulation of future events (Øtsby et al., 2012), and creativity (Beaty et al., 2014) – many of which are linked to mind-wandering (for a review, see Smallwood & Schooler, 2015). The right inferior parietal lobule (IPL), being part of the

DMN, holds two complementary roles: sustaining goal-directed attention as well as responding to novel stimuli in the external world (Singh-Curry & Husain, 2009). Failure to attend to one's goals or to new information in the environment is an aspect of perceptual decoupling that underlies mind-wandering (Smallwood et al., 2012). Congruent with this observation, Fox and colleagues (2015), in a meta-analysis of 24 fMRI studies concerning mind-wandering, found activation in the right IPL to be consistently associated with this behavior. Despite the wealth of neuroimaging data suggesting activity in the executive network and the DMN during mind-wandering across different experimental paradigms, the correlational nature of fMRI prevents strong causal claims regarding the relationship between those networks and mind-wandering.

Transcranial direct current stimulation (tDCS) – a non-invasive form of brain stimulation – provides an avenue to explore the causal connections aforementioned (Filmer, Dux, & Mattingley, 2014; Nitsche et al., 2008). By delivering small amounts of current to a location on the scalp, tDCS changes the resting state membrane potential and thus the firing probability of the neurons at that location (Lauro et al., 2014). Anodal stimulation (current entry) increases neuronal excitability in that area while cathodal stimulation (current exit) reduces it (Stagg & Nitsche, 2011). By facilitating or inhibiting neural activity in a brain area, tDCS lends itself to making causal claims about the contribution of that area to cognitive activities. A limited but growing literature is adapting the existing experimental paradigms of mind-wandering to incorporate tDCS. In particular, the left DLPFC and right IPL may be more amenable to modulation by tDCS compared to other regions of the executive control network and the DMN given that they are closer to the cortex. Axelrod and colleagues (2015), using thought probes that occur at random periods in a task, observed an increase in mind-wandering after offline anodal/cathodal stimulation at the left/right DLPFC relative to cathodal/anodal stimulation at the same sites. This finding agreed with prior fMRI results suggesting higher activity in the left DLPFC during mind-wandering episodes than during task-focused periods (Christoff et al., 2009) insofar as anodal stimulation has excitatory effects. Kajimura and Nomura (2015), also using probe-caught thought sampling, extended this result: Anodal/cathodal tDCS of the right IPL/left lateral prefrontal cortex (LPFC) increased mind-wandering compared to cathodal/anodal tDCS of those sites.

While promising, both of the studies discussed are subject to some drawbacks. For one, both used sponge electrodes with a large contact area (7 cm x 5 cm), which reduces the efficacy of current delivery (Miranda, Faria, & Hallett, 2009) as well as the spatial focality of stimulation (Datta et al., 2008). Such low focality means that current is delivered to many more regions adjacent to the areas of interest, making it difficult to attribute behavioral changes to stimulation of particular areas. More importantly, the setup by Kajimura and Nomura (2015), while included the polarity of electrodes as a between-subjects variable, recruited the left LPFC and the right IPL for all participants without a reference node neutral to mind-wandering. As such, it is impossible to discern whether the observed changes in mind-wandering resulted from some interaction between stimulation to the left LPFC and the right IPL or from a mere additive effect of the two. Additionally, this experimental setup leaves open the question of whether tDCS to the right IPL alone could modulate mind-wandering. Thirdly, neither studies accounted for mind-wandering at the trait level even though it constitutes an individual difference measure (Kane et al., 2007; McVay & Kane, 2012a). As such, differences in mind-wandering behavior between the different stimulation conditions observed during a task could result from the effects of tDCS as well as baseline variations in mind-wandering tendencies among the participants. Fourthly, people’s ability to report mind-wandering during a task depends in no small part on their capacity to be aware of their mental experience. This capacity is termed trait dispositional mindfulness (though for a richer definition, see Bishop et al., 2004) and varies among individuals (Mrazek, Smallwood, & Schooler, 2012). Notably, trait mindfulness is related to trait mind-wandering insofar as mindfulness training reduces outward demonstrations of mind-wandering during the SART (Mrazek, Smallwood, & Schooler, 2012). However, the two need not be in opposition (Grossman & Van Dam, 2011): There could be undivided attention to a particular task or mind-wandering away from the task without meta-awareness of either of these activities. Despite this relative independence, people with low trait mindfulness may be less likely to report mind-wandering than those with higher relative trait mindfulness without differing in actual mind-wandering behavior or trait mind-wandering.

The current study introduced four revisions in response to the challenges aforementioned. A gel-based tDCS system (Starstim 8) was used in which the electrodes are in ring form (Ag/AgCl pellets) and have a smaller contact area (2 cm in diameter). Admittedly, a smaller electrode surface area does not prevent the current from being shunted through the scalp and thereby not reaching the cortex. However, it increases the current density at the stimulation site and reduces spreading activation to nearby areas (Miranda, Lomarev, & Hallett, 2006), and therefore makes tDCS delivery more targeted. This means that any observed change in behavior is more likely to result from tDCS to the areas of interest. Furthermore, the current study employed an additional reference node in the tDCS setup that is not involved in any of the networks associated with mind-wandering across existing fMRI and tDCS studies, namely Cz (on the 10/10 EEG map). This led to a mixed 2x3 study design, with stimulation site as the between-subject factor (left DLPFC versus right IPL, both in reference to Cz) and polarity as the within-subject factor (anodal/return, cathodal/return, and sham). This setup allowed us to elaborate on the results of Kajimura and Nomura (2015) by studying whether tDCS to the left DLPFC and the right IPL could independently influence mind-wandering. Thirdly, we included one measure of trait mind-wandering in order to account for individual variations in this regard: the Mind Wandering Questionnaire (MWQ) (Mrazek et al., 2013). The questionnaire provided a brief survey of a person's mind-wandering frequency, deliberate or spontaneous, in day-to-day contexts. To supplement the MWQ, we used the Daydreaming Frequency Scale (DDFS) or the daydream subscale of the Imaginal Processes Inventory (Giambra, 1995; Singer & Antrobus, 1972). This questionnaire measures one's tendency to have stimulus-independent thoughts, and as such does not probe all classes of thoughts that consist mind-wandering. However, the DDFS has shown to correlate well with other measures of mind-wandering in past studies (Mrazek, Smallwood, & Schooler, 2012) and would provide a good crosscheck for the MWQ in the current study. Fourthly, we added the Mindful Awareness and Attention Scale (MAAS) (Brown & Ryan, 2003). The MAAS was developed to measure the frequency of mindful states of an individual over time, especially with questions surrounding "automatic inattentiveness" or "automatic pilot" (Van Dam, Earleywine, & Borders, 2010), and as such provides a measure of the construct of dispositional mindfulness lacking in prior studies of behavioral mind-wandering.

In addition to changes in tDCS setup, the current study also opted for a retrospective measure of mind-wandering: the cognitive interference component (task-related and task-irrelevant) of the cognitive subscale of the Dundee Stress State Questionnaire (DSSQ) (Matthews et al., 1999; Sarason et al., 1986). The DSSQ comprises sixteen questions: The first eight questions are task-relevant questions while the rest probe task-unrelated thoughts. Unlike the probe-caught method, retrospective measures sidestep any task disruption while still allow a subjective estimate of how frequent certain thoughts occurred during a preceding task.

Our aims for the present study were two-fold. Firstly, we wanted to obtain converging evidence with Axelrod and colleagues (2015) and Kajimura and Nomura (2015) regarding the causal involvement of the left DLPFC in mind-wandering, using a tDCS system with improved spatial focality. Secondly, we hoped to expand upon findings by Kajimura and Nomura (2015) by finding any possible dissociation between the effects of tDCS to frontal and parietal sites on mind-wandering, seeing that Axelrod and colleagues (2015) showed that tDCS to the left DLPFC has been shown to modulate mind-wandering behavior independently of the right IPL. We suspected that tDCS to the left DLPFC and the right IPL could influence mind-wandering through relatively independent pathways, though this did not preclude the possibility of tDCS to the two areas interacting, as discussed earlier. Within the left DLPFC group (hereby called the F3 group), we hypothesized that anodal/return stimulation to the left DLPFC/Cz would confer more mind-wandering (i.e., higher TUT ratings in the DSSQ, barring any between-group differences in trait mind-wandering and trait mindfulness) than sham stimulation and cathodal/return stimulation to the same sites, consistent with Axelrod and colleagues (2015). Within the right IPL group (hereby called the P4 group), consistent with Kajimura and Nomura (2015), we expected that anodal/return stimulation to the right IPL/Cz would confer less mind-wandering than sham stimulation and cathodal/return stimulation to those sites, suggesting that tDCS to the right IPL could influence mind-wandering independently of the left DLPFC.

Method

Participants

36 participants (19 women, M_{age} = 20.67, *SD* = 3.51) were randomly assigned to one of the following two groups prior to coming into the lab: F3 (13 women, M_{age} = 19.38, *SD* = 1.65)

and P4 (6 women, M_{age} = 21.94, *SD* = 4.39). All participants provided written informed consent and were approved by the Tufts University Institutional Review Board.

Materials

Transcranial Direct Current Stimulation (tDCS). Offline tDCS was delivered through a pair of gel-based electrodes with 12 mm Ag/AgCl pellets (contact area: π cm^2) using StarStim 8 – an eight-electrode, ambulatory system that could deliver tDCS and record EEG concurrently (Neuroelectrics, Boston, MA). We used Signa Gel (Parker Laboratories Inc., Fairfield, NJ) as the conductor. For participants in the F3 group, one electrode was positioned over F3 (according to the EEG 10/10 system) while the other electrode was at Cz. For the P4 group, one electrode was placed over P4 while the other was placed over Cz. Within each group, participants experienced three stimulation conditions on three separate days: anodal/return (F3/Cz or P4/Cz), cathodal/return (F3/Cz or P4/Cz), and sham. For anodal and cathodal stimulation, participants received a constant electrical current for 20 minutes at 1.0 mA with 30 s of ramp-up and 30 s of ramp-down. Sham stimulation included 30 s of ramp-up followed immediately by 30 s of ramp-down during the first and last minute of the 20-minute period, leaving 18 minutes in between with no current delivery. For all of the sessions, participants gave a perceived sensation rating (Clark et al., 2012) 30 seconds into the stimulation (baseline) and two minutes before the stimulation ended (terminal). The participants gave their answers on a nine-point scale (0 = *cold* to 9 = *hurts a lot*), and were informed that the experiment would halt immediately if their rating was 7 (*burns, like a sunburn*) or above at any point in time during stimulation. None of the 36 participants had a rating of 7 or above throughout stimulation.

Standard Sustained Attention to Response Task (Standard SART). The current study implemented a variation of the standard SART used by Axelrod and colleagues (2015). The task was presented using Microsoft Visual Studio. The stimuli consisted of digits from 1 to 9 in either white font or orange font against a black background. The digits appeared at the center of the screen. Each digit was presented for a maximum of 2000 ms. The order of the digits was random and pre-determined. The interstimulus interval (ISI) consisted of a white crosshair at the center for the screen for 500 ms. White digits comprised the non-critical trials while orange digits formed the critical trials. Participants used a Logitech game console to provide their answers and were instructed to respond only to digits in orange and not those in white. They were told to press the front right button of the game console if an orange digit was even and the front left button if it was odd. Once participants provided a button press to an orange digit within the 2000 ms window, that digit would disappear immediately, giving way to the next ISI. White digits remained on screen for 2000 ms even if participants gave a false alarm response. Participants were never told to maintain high performance or accuracy at any point during the experiment.

Participants completed a practice SART at the start of session 1 prior to performing the actual task. The practice task lasted approximately 3 minutes and gave a “Correct” feedback in green if participants provided the appropriate button press for a critical trial (orange digits). No computer feedback was given for correct rejection responses. The task also gave an “Incorrect” feedback in red if they missed a critical trial, pressed the wrong button during a critical trial, or provided an answer during non-critical trials.

The actual SART consisted of three blocks with each block lasting approximately 12 minutes (222 digits per block). Approximately 12 percent of the trials in each block (27 trials) were critical and were distributed randomly within each block. Prior to the first block of the actual SART during session 1, the experimenter read the following instruction to the participants verbally: “This task is similar to the task that you practiced for earlier in session 1, but it will consist of three separate blocks, each block lasting a little more than 10 minutes. After each block, a short questionnaire will appear. During this task, the computer will not provide any feedback for your performance, so I will not see what you enter or how well you perform. Mind-wandering may occur during the experiment and is completely natural.” For sessions 2 and 3, participants completed the same SART.

Operation Span Task. During tDCS, after giving a baseline perceived sensation rating, participants completed a version of the Operation Span (OSPAN) task (Turner & Engle, 1989) on a separate laptop. The task was administered using SuperLab version 4.0. Each trial consisted of a series of simple arithmetic computations that could be true (e.g., 4+3=7) or false (e.g., 5-2=1), alternated by an equal number of English words (e.g., eye, colony – the original task in Engle (2002) used letters). None of the arithmetic computations showed any number greater than 9 or lesser than 0. Participants had to determine if the computations were true or false by pressing two different buttons on the laptop keyboard and memorize the words that appeared thereafter. After each trial, they had to enter the words shown in that trial. The task provided no feedback for the participants’ performance throughout the task. Apart from distracting participants from the discomfort associated with tDCS, the OSPAN also provides a measure of executive function by way of working memory (Coleman, Watson, & Strayer, 2017; Engle, 2002; Sanbonmatsu et al., 2013).

The actual OSPAN consisted of fifteen trials with each trial having from two to six computation-word pairs (three trials with two pairs, three trials with three pairs, three trials with four pairs, and so on). Each participant thus had to memorize 60 words in total per session. The order of the trials was randomized by SuperLab. Three different versions of the OSPAN were created for each of the three sessions, and were administered in a counterbalanced order.

Mind Wandering Questionnaire (MWQ). The MWQ consists of five items and measures the frequency of task-unrelated thoughts during task-focused episodes in daily life (for a validity check of the MWQ, see Mrazek and colleagues (2013); for the questionnaire, see Appendix A). The questionnaire includes items such as “I have difficulty maintaining focus on simple or repetitive work” and “While reading, I find I haven’t been thinking about the text and must therefore read it again.” Participants provided their answers on a 6-point Likert scale (1 = *almost never*, 2 = *very infrequently*, 3 = *somewhat infrequently*, 4 = *somewhat frequently*, 5 = *very frequently*, 6 = *almost always*).

Daydreaming Frequency Scale (DDFS). The DDFS, or the daydreaming subscale of the Imaginal Processes Inventory (Giambra, 1995; Singer & Antrobus, 1972), is a twelve-item questionnaire that focuses on the frequency of stimulus-independent thought in a person’s current, daily life (see Appendix B). The questionnaire includes items such as “As regards daydreaming, I would characterize myself as someone who” (A = *never daydreams*, B = *very rarely engages in daydreaming*, C = *tends toward occasional daydreaming*, D = *tends toward moderate daydreaming*, E = *is a habitual daydreamer*), and “I recall or think over my daydreams” (A = *infrequently*, B = *once a week*, C = *once a day*, D = *a few times during the day*, E = *many times during the day*).

Mindful Awareness Attention Scale (MAAS). The MAAS is a fifteen-item questionnaire that investigates the degree to which a person is aware of his or her mental activity in a day-to-day context (Brown & Ryan, 2003) (see Appendix C). The questionnaire includes questions such as “I could be experiencing some emotion and not be conscious of it until some time later” and “I find it difficult to stay focused on what’s happening in the present.” Participants provide their answers on a six-point Likert scale (1 = *almost never*, 2 = *very* *infrequently*, 3 = *somewhat infrequently*, 4 = *somewhat frequently*, 5 = *very frequently*, 6 = *almost always*).

Dundee Stress State Questionnaire (DSSQ). The current study used the cognitive interference component (task-related and task-irrelevant) of the cognitive subscale of the Dundee Stress State Questionnaire (Matthews et al., 1999; Sarason et al., 1986). The resulting questionnaire consisted of sixteen items that assessed the level of engagement in a recent cognitive task and the content of thoughts during that time. The first eight items pertained to task-related thoughts (TRTs); the next eight items asked about task-unrelated thoughts and were thus a measure of TUT rating (for the full questionnaire, see Appendix D).

Experimental room. Participants sat in an armchair in the experimental room adjacent to the control room. The overhead lights in the experimental room were turned on during cap preparation, tDCS, and cap removal. They were turned off during the SART.

Procedure

The study was advertised on SONA and through flyers on the Medford campus of Tufts University as an investigation of the relationship between external brain stimulation and simple mathematical judgment. Participants visited the lab on three separate days with at least an interval of one day between them. None of the participants were made aware of the aim to investigate mind-wandering of the present study until debriefing on the third day. On the first day, participants came into the lab and read the informed consent form in privacy. The experimenter emphasized to the participants that they could withdraw their participation at any point and would be compensated for the time that they completed. Participants who consented to participate then filled out the MWQ, the DDFS, and the MAAS on Qualtrics using a tablet. After that, participants received verbal instructions from the experimenter on how to use the Logitech game console and completed the practice SART. After that, participants received tDCS according to their assigned condition for 20 minutes. After the first 30 seconds of ramp-up, participants provided a baseline perceived sensation rating and were informed that the experiment would be halted if their ratings ever exceeded seven during tDCS. After that, participants completed the Operation Span task to alleviate the cutaneous sensation triggered by the stimulation. At two minutes before the end of the stimulation, participants gave a second perceived sensation rating. After offline stimulation, the experimenter turned off the lights in the experimental room. Finally, participants completed the SART in three blocks; at the end of each block, they filled out the DSSQ. The second and third sessions only required the participants to receive offline stimulation while completing the distractor task and carry out the SART. At the end of the third session, participants were asked whether they had any guess what the study was about. One of the participants thought that the current study concerned attention and distraction; the rest of the participants either had no guess about the purpose of the study or believed that it was an investigation of the influence of external brain stimulation on mathematical judgment. They were then debriefed on the purpose of the study and given compensation for their time.

Analyses

Behavioral and self-report data were compiled on Microsoft Excel and analyzed with IBM SPSS Statistics version 22. A *p*-value of 0.05 was used for alpha in all statistical analyses and all results were for two-tailed tests. For all ANOVA tests, a Greenhouse-Geisser correction was applied for cases where sphericity was violated.

The correctness of the even/odd judgment during the SART was not analyzed as it was only meant to mask the actual purpose of the study. Hit rate was calculated as the ratio between the number of critical trials (orange digits) in which a button press was provided and the total number of critical trials. False alarm rate was the ratio between the number of non-critical trials in which a button press was provided and the total number of non-critical trials. RT was taken as the time between the onset of an orange digit to the registration of a button press. Since all digits automatically disappeared after 2000 ms, a button press registered after the 2000 ms mark was not registered; such trials were recorded as miss trials.

TUT ratings were analyzed in three different ways. The first way involved averaging the eight TUT items of the DSSQ, which is the original method of analysis associated with this questionnaire (Sarason et al., 1986). The second way, however, took the maximal rating of those eight items to be the TUT score. Participants, during any block, could be preoccupied with only one or two task-unrelated topics (e.g., future events). If so, they would give a high rating to questions pertaining to those topics and low ratings for the rest of the questions. Taking the average, in this case, would skew the results for TUT in a downward direction and inaccurately reflect the degree to which mind-wandering took place. A third way required taking the sum of the eight TUT items and has been adopted by more recent studies on mind-wandering (Banks, Welhaf, & Srour, 2015; Hao et al., 2015). This method accounts for all components of the TUT portion of the DSSQ while also highlights their specific contribution to the total score. TRT ratings were analyzed using the same three techniques.

The mean RT for each block of SART was the mean RT of all of the hit trials of that block, in keeping with Axelrod and colleagues (2015) as well as Kajimura and Nomura (2015). Additionally, we performed a logarithmic transformation of RT data in order to correct for the negative skew of the distribution. We removed two participants’ reaction time (RT), hit rate, and false alarm rate data from the pool (one from the F3 group, one from the P4 group), as each had one block in one of their three sessions in which they provided no button press response for the SART due to technical issues. Their TUT ratings were kept for TUT analysis.

The “total number correct” OSPAN score for each session was calculated by summing the numbers of words recalled accurately and in their correct order for each trial. This was in keeping with Turner and Engle (1989)’s analysis of OSPAN performance, which has been shown to correlate with current analysis methods such as the absolute OSPAN performance score (e.g., Sanbonmatsu et al., 2013; Unsworth et al., 2005). In order to ensure that participants did not compromise their mathematical judgments to memorize the words, only participants who responded accurately to at least 85% of the computations were included in the analysis. Based on this criterion, one participant from the F3 group and one from the P4 group were removed from the OSPAN data pool. One other participant from the P4 group was excluded due to technical issues during the experiment. This left us with 33 participants for OSPAN analysis.

Results

Group Comparison

The MWQ, DDFS, and MAAS scores for each participant were calculated as the sum of all items of each questionnaire, respectively (for descriptive statistics, see Table 1). The two stimulation groups did not differ significantly in their total scores for the MWQ ($t(34) = 0.66$, $p = 0.52$), the DDFS ($t(34) = 1.00$, $p = 0.32$), and the MAAS ($t(34) = 0.34$, $p = 0.73$). A Pearson product-moment correlation analysis revealed significant positive correlations between the participants’ MWQ, DDFS, and MAAS scores across both stimulation groups (F3/P4) (Table 2). This correlation was in agreement with prior literature suggesting connections between the constructs measured by the MWQ (trait mind-wandering in daily life), the DDFS (daydreaming tendencies in daily activities), and the MAAS (meta-awareness of one's mental life) (for a brief review, see the introduction of Mrazek et al., 2013).

Task-Unrelated Thoughts (TUTs)

A 2x3 mixed AVOVA was conducted for TUT data with stimulation group (F3/P4) as the between-subjects variable and stimulation condition (anodal/cathodal/sham) as the within-subjects variable. No significant differences were found between the stimulation conditions for averaged TUT ratings ($F(2,36) = 1.00$, $p = 0.38$), maximal TUT ratings ($F(1.66,36) = 1.32$, $p = 0.27$), and total TUT ratings ($F(2,36) = 1.16$, $p = 0.32$) (for descriptive statistics, see Table 3). Additionally, there was no interaction effect between stimulation condition and stimulation site for averaged TUT ratings ($F(2,36) = 0.15$, $p= 0.87$), maximal TUT ratings ($F(1.66,36) = 1.00$, $p = 0.36$), or total TUT ratings ($F(2,36) = 0.28$, $p = 0.76$). When the three stimulation conditions (anodal/cathodal/sham) were averaged, the two stimulation groups were significantly different in averaged TUT ratings ($t(34) = 2.14$, $p = 0.039$, $d = 0.72$), maximal TUT ratings ($t(34) = 2.17$, $p = 0.037$, $d = 0.72$), and total TUT ratings ($t(34) = 2.18$, $p = 0.036$, $d = 0.73$) (for descriptive statistics, see Table 4). For all three methods of analyzing TUTs, participants in the F3 group reported more TUTs when all stimulation conditions were averaged than those in the P4 group (Figure 1, 2, and 3). Across the three blocks, there was no significant difference between the two stimulation groups (F3/P4) in averaged TUT ratings ($F(2,36) = 0.03$, $p = 0.97$), maximal TUT ratings ($F(2,36) = 0.28$, $p = 0.76$), or total TUT ratings ($F(2,36) = 0.027$, $p = 0.97$).

Behavioral Data

In order to thoroughly investigate the ways in which tDCS could affect mind-wandering behavior, we analyzed reaction time data for the SART. A 2x3 mixed ANOVA with stimulation group (F3/P4) as the between-subjects factor and stimulation condition (anodal/cathodal/sham) as the within-subjects condition was used to analyze hit rates. The average hit rate and average false alarm rate for each stimulation condition were calculated from the three blocks of that condition. Across three stimulation conditions, participants showed no significant difference in their hit rates ($F(2,34) = 0.12$, $p = 0.87$) or their false alarm rates ($F(2,34) = 0.90$, $p = 0.36$). Similarly, no significant interaction between stimulation group and stimulation condition was found for their hit rates ($F(2,34) = 0.49$, $p = 0.58$) or their false alarm rates ($F(2,34) = 0.82$, $p = 0.38$). When all three stimulation conditions were averaged, there was no significant difference in hit rates ($t(32) = -0.67$, $p = 0.51$) or false alarm rates ($t(32) = -1.45$, $p = 0.17$) between the two stimulation groups (for descriptive statistics, see Table 5).

A 2x3 mixed ANOVA with stimulation group (F3/P4) as the between-subjects factor and stimulation condition (anodal/cathodal/sham) as the within-subjects condition was conducted on the mean log-transformed RT data (for descriptive statistics of raw and log-transformed RT data, see Table 6). No significant difference were found across the three stimulation conditions ($F(2,36) = 0.633$, $p = 0.53$). Additionally, no interaction effect between stimulation condition and stimulation group could be found ($F(2,36) = 0.70$, $p = 0.50$). When all three stimulation conditions were averaged, there was no significant difference in mean RT between the two stimulation groups ($t(32) = 0.91$, $p = 0.37$).

To investigate the changes of mean log-transformed RT over the course of three sessions, we performed a 2x3 mixed ANOVA with stimulation group (F3/P4) as the between-subjects variable and block order (1/2/3) as the within-subjects variable (for descriptive statistics, see Table 7). There was a significant main effect of block ($F(2,34) = 7.54$, $p = 0.001$): Participants responded more slowly as the SART progressed from block 1 to 3, likely due to fatigue. No interaction effect between block and stimulation site was found ($F(2,34) = 0.13$, $p = 0.88$).

Perceived Sensation Ratings

In an effort to identify potential sources for the overall stimulation group difference (F3/P4) in TUT ratings, we analyzed the perceived sensation ratings. A 2x2x3 mixed ANOVA with stimulation group (F3/P4) as the between-subjects variable and with time point (baseline/terminal) and stimulation condition (anodal/cathodal/sham) as the within-subjects variables was performed on the Perceived Sensation ratings (for descriptive statistics, see Table 8). There was a main effect of time point ($F(1,36) = 92.13$, $p < 0.001$, $\eta^2 = 0.59$): Participants generally habituated to the cutaneous sensation of tDCS over the duration of offline stimulation. Additionally, there was a significant interaction effect between time point and stimulation group ($F(1,36) = 9.10$, $p = 0.005$, $\eta^2 = 0.06$). Participants in the F3 group generally had higher baseline ratings than those in the P4 group; however, this difference diminished by the terminal time point. No significant main effect was found for stimulation condition ($F(2,36) = 0.92$, $p = 0.41$), indicating that participants' ratings of cutaneous sensation in the current study did not depend critically on their stimulation condition. Last but not least, no significant interaction effect was observed between stimulation condition and stimulation group ($F(2,36) = 0.05$, $p = 0.95$).

Task-Related Thoughts (TRTs)

A 2x3 mixed ANOVA with stimulation group (F3/P4) as the between-subjects variable and stimulation conditions (anodal/cathodal/sham) as the within-subjects variable was conducted for TRT data. Across all stimulation conditions, participants of both stimulation groups showed no significant difference in their average TRT ratings ($F(2,36) = 0.35$, $p = 0.71$), maximal TRT ratings ($F(2,36) = 0.40$, $p = 0.67$), or total TRT ratings ($F(2,36) = 0.12$, $p = 0.89$) (for descriptive statistics, see Table 9). Additionally, there was no interaction effect between stimulation condition and stimulation site for average TRT ratings ($F(2,36) = 0.89$, $p= 0.42$), maximal TRT ratings (*F*(2,36) = 0.64, *p* = 0.94), or total TRT ratings (*F*(2,36) = 1.38, *p* = 0.26). When all stimulation conditions were averaged, a significant difference was found with maximal TRT ratings (*t*(34)= 3.12, *p* = 0.004, *d* = 4.41); averaged TRT ratings (*t*(34) = 2.00, *p* = 0.053, *d* = 2.84) and total TRT ratings (*t*(34) = 2.00, *p* = 0.053, *d* = 2.84) trended toward significance. For all three analysis methods of TRT ratings, participants in the F3 group reported having more task-related thoughts than those in the P4 group (for descriptive statistics, see Table 10).

“Total Number Correct” OSPAN Task Score

A 2x3 mixed ANOVA with stimulation group (F3/P4) as the between-subjects variable and stimulation condition (anodal/cathodal/sham) as the within-subjects variable was conducted on participants’ “total number correct” OSPAN task performance. There was no main effect of stimulation condition (*F*(1.36,33) = 0.11, *p* = 0.82) and no interaction effect between stimulation condition and stimulation group (*F*(1.36, 33) = 0.26, *p* = 0.69). Additionally, when each participant’s “total number correct” OSPAN scores for all three sessions were averaged, no significant difference was found between participants in the F3 group and those in the P4 group (*t*(29.74) = -0.29, *p* = 0.77) (for descriptive statistics, see Table 11).

General discussion

The current study found that tDCS to the left DLPFC resulted in more mind-wandering (i.e., TUTs) during the standard SART than that to the right IPL when all three stimulation conditions of each group (anodal, cathodal, sham) were aggregated – a surprising finding. Notably, this observation could not be attributed to differences in trait level mind-wandering between the two groups, as the analysis of the MWQ, the DDFS, and the MAAS suggested. However, this difference disappeared at the level of stimulation condition: No significant difference in TUTs was found between anodal, cathodal, and sham stimulation to the left DLPFC and to the right IPL, respectively. In addition, no significant difference was found between the reaction times of participants in the left DLPFC and in the right IPL groups regardless of whether the three stimulation conditions were combined or separated. Insofar as the reference node (Cz) of both the left DLPFC group and the right IPL group was neutral to most networks concerning mind-wandering and attention (e.g., the default mode network, the fronto-parietal network), our results were at odds with previous studies that employed tDCS to show a causal relationship between the left DLPFC, the right IPL, and mind-wandering.

A post hoc analysis of the perceived sensation ratings revealed that participants in the F3 group felt the stimulation more intensely than those in the P4 group at the start of stimulation. Limited past research suggested that cutaneous sensation of stimulation alone could not account for the difference in performance between control and experimental conditions in tDCS (Brunyé et al., 2014). It is important to note, however, that the focus of the current study is mind-wandering and not task performance per se. More importantly, little is known about the effects of relative scalp sensitivity to stimulation on cognitive behavior. That participants in the F3 group experienced heightened cutaneous sensations and reported more TUTs compared to those in the P4 group overall may suggest a relationship between sensory experiences of stimulation and mind-wandering. However, this is a post hoc speculation that requires careful experimental verification. Future studies should investigate whether variations in mind-wandering frequency could be attributed, even if partially, to how sensitive certain locations on the scalp are to tDCS.

An analysis of TRT data and OSPAN performance warned us against a suggestion by Axelrod and colleagues (2015) that tDCS to the left DLPFC could have increased mind-wandering by way of enhancing executive resources on grounds that mind-wandering seems to use executive resources (Christoff et al., 2009; Smallwood & Schooler, 2006). If this was true, we would have expected participants in the current study to perform differentially during the OSPAN task at least by stimulation groups (F3/P4), given that this task probes working memory and executive functions (Turner & Engle, 1989), but this was not the case. On the other hand, participants in the F3 group reported having more TRTs than those in the P4 group, though this difference disappeared at the level of stimulation conditions, mirroring the result pattern of TUTs. Given that the left DLPFC is implicated in maintaining attention to task demands (MacDonald et al., 2000), this observation might suggest that our tDCS setup for the F3 group had some effect on this area (when compared to the P4 group), though this effect was possibly confounded with that of cutaneous sensation of tDCS, as discussed above. Future replications of the current study should consider the possibility that that the two trends observed in the current study (increased TRTs and increased TUTs due to tDCS to F3) have different underlying mechanisms.

Our failure to acquire converging observations with prior studies, in particular Axelrod and colleagues (2015), and Kajimura and Nomura (2015), regarding the effect of polarity on mind-wandering might be explained by our various methodological divergences from said studies. The most prominent difference concerns the way in which mind-wandering was operationalized and measured. Both papers on which we based our study used variations of probe-caught thought sampling, all of which involve thought probes that occur at different intervals during the task. Both of these variants concern the participants' thought(s) immediately before the probe occurs; consequently, the frequency of TUTs is determined by aggregating the results across all the thought probes. The DSSQ, on the other hand, allows participants to report their frequency of TUTs retrospectively and over a longer duration of time. Each of these methods differ in their strengths and weaknesses. Thought sampling grants experimenters access to the participants' thought(s) immediately prior to the probe, which they may have a higher chance of remembering. Axelrod and colleagues (2015) required participants to indicate the extent to which they experienced TUTs on a four-point Likert scale. Kajimura and Nomura (2015), on the other hand, distributed thought probes at regular intervals (every 22.4 – 28.8 s), and asked participants to categorize their thoughts according to seven options. The second method of probing, similar to the DSSQ, gives a glimpse of the content of the participants' thoughts. However, like the DSSQ, the categories were listed in fixed order for Kajimura and Nomura (2015) and were thus vulnerable to acquiescence bias: Participants might choose the first option that accounts for their thought content satisfactorily rather than the option that best describes it, which depresses the ratings across the board (Weinstein, in press). The DSSQ, in addition to acquiescence bias, is a retrospective measure and thus depends on the participants' memory of their thoughts in the previous task block, which needs not be reliable. As such, the DSSQ might not be sensitive enough to fine-grained differences in mind-wandering behavior across the different stimulation conditions, especially if the task blocks are too long. In order to sidestep these challenges, future replications of the current study should use thought sampling to measure TUTs. Experiments that use the DSSQ to probe mind-wandering should shorten the task blocks in order to reduce interference and decay of memories of past thoughts.

The second difference between the prior studies and the current experiment that may contribute to our failure to replicate concerns the tDCS system. The electrodes used in the current study have a smaller surface area compared to saline-soaked sponge electrodes. Previous studies have suggested a link between reduced surface area of electrode and improved spatial focality (Datta et al., 2008; Minhas et al., 2010), which translates to more targeted current delivery at the areas of interest and less diffused activation in adjacent areas (Villamar et al., 2013). Indeed, Axelrod and colleagues (2015) suggested the possibility that their tDCS setup led to stimulation of regions in the prefrontal cortex other than the left DLPFC. Similarly, tDCS over P4 in the case of Kajimura and Nomura (2015) could affect regions other than the right IPL – examples include the temporoparietal junction (Mars et al., 2012) which is implicated in attentional shifts to unexpected stimuli (Krall et al., 2015), or the right intraparietal sulcus which is involved in spatial and nonspatial attention (Coull & Frith, 1998). While the current study could not determine whether our non-significant results were due to increased focality of tDCS, future experiments should replicate prior results with high-definition tDCS systems in order to reduce spreading activation and isolate the areas of interest better.

While the current study found little evidence for the effects of polarity of tDCS on mind-wandering, this mental phenomenon continues to be of interest at least partly due to its relationship with neuroatypical and clinical populations. Spontaneous (i.e., non-deliberate) mind-wandering is also associated with attention-deficit/hyperactivity disorder (ADHD) (Seli et al., 2015). This suggests that individuals with ADHD may not have the metacognitive skills necessary to catch mind-wandering episodes (Smallwood, Fishman, & Schooler, 2007). It is important to note that the metacognitive skills discussed here are related to the cognitive control skills discussed in our introduction: For example, the DLPFC and the ACC – crucial nodes in the executive control network – were more activated during mind-wandering without meta-awareness than with it (Christoff et al., 2009), suggesting some overlapping in resources between meta-awareness and cognitive control of mind-wandering. However, metacognition differs from cognitive control in at least one respect: The former involves the re-representation of the content of experienced thoughts, which could sometimes lead to a time lag between having an experience and realizing that one is having it (Schooler, 2002). This explains why it is possible to be able to report the content of a task-unrelated thought immediately preceding a thought probe (i.e., being conscious of the content of this thought) while not recognizing that one was having such a thought until being asked (i.e., being meta-aware of one’s mind-wandering activity at a specific moment) (Schooler, Reichle, & Halpern, 2004). On the other hand, one does not need an experience of (or being aware of) cognitive control in order to exert it. Additionally, mind-wandering frequencies positively correlate with dysphoria (Smallwood et al., 2007) and depression (Deng, Li, & Tang, 2014), perhaps because both lead to maladaptive metacognitive strategies to maintain attention during a task (Smallwood, Fishman, & Schooler, 2007). Individuals with a negative mood were found to mind-wander more than controls, especially about past events (Smallwood & O’Connor, 2011). In a different vein of research, Hao and colleagues (2015) found that mind-wandering during idea generation was associated with having fewer original ideas. As such, mind-wandering has real consequences on our daily life, including during reading (Feng, D’Mello, & Graesser, 2013) and in classroom settings (Smallwood, Fishman, & Schooler, 2007). Future studies should continue to explore how mind-wandering manifests in different contexts and the metacognitive strategies that are appropriate to those contexts for maintaining attention, but only when attention maintenance is truly conducive to the task at hand.

In conclusion, the current study calls into question positive results regarding the influence of tDCS on mind-wandering frequency, a major reason of which is the type of tDCS system and electrodes used to obtain those results. The overall group difference in TUT ratings between participants in the F3 group and those in the P4 group sees a parallel trend in their cutaneous sensations of the current at baseline during offline stimulation. However, this observation must be interpreted conservatively due to its post hoc nature and requires careful experiments to unearth any possible effect that relative scalp sensitivity to electrical current may have on mind-wandering. These results, while unexpected, do not challenge our need to understand the ways in which mind-wandering can be modulated, internally or externally, precisely because of how prevalent and integral mind-wandering is to our mental life.

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Table 1

Descriptive Statistics for Measures of Trait Mind-Wandering by Stimulation Groups

	F3		P4	
Measure	*M* (*SD*)	95% CI	*M* (*SD*)	95% CI
MWQ	16.28 (4.13)	[14.22, 18.33]	15.33 (4.49)	[13.10, 17.56]
DDFS	34.00 (7.29)	[30.37, 37.63]	31.00 (10.42)	[25.82, 36.18]
MAAS	41.39 (10.55)	[36.14, 46.64]	40.28 (8.72)	[35.94, 44.61]

Note. F3 = left dorsolateral prefrontal cortex; P4 = right inferior parietal lobule; CI = confidence interval; the Mind-Wandering Questionnaire (MWQ) is from Mrazek et al. (2013); the Daydreaming Frequency Scale (DDFS) is from Singer & Antrobus (1972); and the Mindful Attention and Awareness Scale (MAAS) is from Brown & Ryan (2003).

Table 2

Summary of Intercorrelations for Measures of Trait Mind-Wandering

Measure	*1*	*2*	*3*
1. MWQ	_	0.59*	0.71*
2. DDFS	0.59*	_	0.71*
3. MAAS	0.71*	0.71*	_

Note. The Mind-Wandering Questionnaire (MWQ) is from Mrazek et al. (2013); the Daydreaming Frequency Scale (DDFS) is from Singer & Antrobus (1972); and the Mindful Attention and Awareness Scale (MAAS) is from Brown & Ryan (2003). Intercorrelations for the MWQ, DDFS, and MAAS are calculated for the entire sample ($n = 36$).

*$p < .01$.

Table 3

Descriptive Statistics for TUT Ratings by Stimulation Groups and Stimulation Conditions

Stimulation condition	F3		P4	
	M (*SD*)	95% CI	*M* (*SD*)	95% CI
Average				
Anodal	1.94 (0.45)	[1.72, 2.16]	1.68 (0.31)	[1.53, 1.83]
Cathodal	1.95 (0.41)	[1.75, 2.15]	1.77 (0.59)	[1.47, 2.06]
Sham	2.06 (0.44)	[1.84, 2.28]	1.79 (0.39)	[1.60, 1.98]
Maximal				
Anodal	3.26 (0.93)	[2.80, 3.72]	2.87 (0.78)	[2.48, 3.25]
Cathodal	3.30 (0.82)	[2.89, 3.70]	2.87 (0.87)	[2.43, 3.30]
Sham	3.59 (0.84)	[3.17, 4.01]	2.89 (0.65)	[2.56, 3.21]
Total				
Anodal	15.50 (0.84)	[13.73, 17.27]	13.44 (0.58)	[12.21, 14.68]
Cathodal	15.50 (0.79)	[13.83, 17.17]	14.17 (1.10)	[11.84, 16.50]
Sham	16.1 (0.84)	[14.85, 18.38]	14.33 (0.75)	[12.75, 15.92]

Note. CI = confidence interval.

Table 4

Descriptive Statistics for TUT Ratings by Stimulation Groups

Measure	F3		P4	
	M (*SD*)	95% CI	*M* (*SD*)	95% CI
Average	1.98 (0.33)	[1.82, 2.15]	1.74 (0.33)	[1.58, 1.91]
Maximal	3.38 (0.72)	[3.03, 3.74]	2.87 (0.69)	[2.53, 3.22]
Total	15.94 (0.63)	[14.62, 17.27]	14.00 (0.63)	[12.67, 15.33]

Note. CI = confidence interval.

Table 5

Descriptive Statistics for Hit Rates and False Alarm Rates by Stimulation Groups and Stimulation Conditions

Variables	F3		P4	
	M (*SD*)	95% CI	*M* (*SD*)	95% CI
Hit				
Anodal	0.84 (0.18)	[0.75, 0.93]	0.89 (0.12)	[0.83, 0.95]
Cathodal	0.86 (0.14)	[0.79, 0.93]	0.88 (0.15)	[0.80, 0.96]
Sham	0.86 (0.14)	[0.79, 0.93]	0.88 (0.11)	[0.82, 0.94]
False alarm				
Anodal	0.00 (0.00)	[0.00, 0.00]	0.00 (0.00)	[0.00, 0.00]
Cathodal	0.00 (0.00)	[0.00, 0.00]	0.01 (0.03)	[0.00, 0.02]
Sham	0.00 (0.00)	[0.00, 0.00]	0.00 (0.00)	[0.00, 0.00]

Note. Hit = no. of responses to critical trials/no. of critical trials; False alarm = no. of responses to non-critical trials/no. of non-critical trials; CI = confidence interval.

Table 6

Descriptive Statistics for Raw (ms) and Logarithmic Reaction Times by Stimulation Groups and Stimulation Conditions

Stimulation condition	F3		P4	
	M (*SD*)	95% CI	*M* (*SD*)	95% CI
Raw				
Anodal	877.27 (147.09)	[801.27, 952.89]	836.76 (131.01)	[769.41, 904.12]
Cathodal	851.06 (94.64)	[802.40, 899.72]	809.54 (126.00)	[744.75, 874.32]
Sham	846.93 (101.41)	[844.88, 899.06]	846.26 (131.05)	[778.88, 913.64]
Logarithmic				
Anodal	2.92 (0.07)	[2.89, 2.96]	2.91 (0.06)	[2.87, 2.94]
Cathodal	2.92 (0.05)	[2.89, 2.94]	2.89 (0.06)	[2.86, 2.92]
Sham	2.91 (0.05)	[2.87, 2.94]	2.91 (0.06)	[2.88, 2.94]

Note. RT = reaction time; CI = confidence interval.

Table 7

Descriptive Statistics for Raw (ms) and Logarithmic Reaction Times by Stimulation Groups and Blocks

Block	F3		P4	
	M (*SD*)	95% CI	*M* (*SD*)	95% CI
Raw				
1	828.33 (87.06)	[783.57, 873.09]	796.27 (97.97)	[745.90, 846.65]
2	849.24 (85.46)	[805.30, 893.18]	840.32 (98.26)	[789.79, 890.84]
3	897.69 (154.52)	[818.24, 977.14]	855.97 (172.33)	[767.37, 944.57]
Logarithmic				
1	2.91 (0.04)	[2.89, 2.93]	2.89 (0.05)	[2.86, 2.91]
2	2.92 (0.05)	[2.90, 2.95]	2.91 (0.05)	[2.88, 2.93]
3	2.92 (0.05)	[2.90, 2.95]	2.91 (0.06)	[2.88, 2.94]

Note. RT = reaction time; CI = confidence interval.

Table 8

Descriptive Statistics for Perceived Sensation Ratings by Stimulation Groups and Stimulation Conditions

Time point	F3		P4	
	M (*SD*)	95% CI	*M* (*SD*)	95% CI
Baseline				
Anodal	3.67 (1.74)	[2.80, 4.53]	2.47 (0.95)	[2.00, 2.94]
Cathodal	3.78 (1.73)	[2.92, 4.64]	2.42 (1.43)	[1.71, 3.13]
Sham	3.97 (1.54)	[3.21, 4.74]	2.53 (1.34)	[1.86, 3.20]
Terminal				
Anodal	1.17 (1.10)	[0.62, 1.71]	1.03 (0.90)	[0.58, 1.47]
Cathodal	1.22 (0.88)	[0.79, 1.66]	1.33 (1.10)	[0.79, 1.88]
Sham	0.72 (0.75)	[0.35, 1.10]	0.72 (0.77)	[0.34, 1.11]

Note. CI = confidence interval.

Table 9

Descriptive Statistics for TRT Ratings by Stimulation Groups and Stimulation Conditions

Stimulation condition	F3		P4	
	M (*SD*)	95% CI	*M* (*SD*)	95% CI
Average				
Anodal	1.82 (0.93)	[1.63, 2.02]	1.71 (0.10)	[1.50, 1.93]
Cathodal	1.88 (0.14)	[1.58, 2.17]	1.56 (0.06)	[1.43, 1.69]
Sham	1.86 (0.74)	[1.71, 2.02]	1.70 (0.07)	[1.55, 1.85]
Maximal				
Anodal	3.61 (0.20)	[3.19, 4.03]	3.22 (0.24)	[2.72, 3.72]
Cathodal	3.50 (0.20)	[3.07, 3.93]	3.06 (0.19)	[2.66, 3.45]
Sham	3.61 (0.22)	[3.16, 4.07]	3.11 (0.18)	[2.73, 3.49]
Total				
Anodal	14.48 (0.76)	[12.87, 16.09]	13.83 (0.80)	[12.14, 15.52]
Cathodal	15.46 (1.11)	[13.13, 17.80]	12.76 (0.57)	[11.56, 13.96]
Sham	14.54 (0.58)	[13.31, 15.76]	13.20 (0.55)	[12.04, 14.37]

Note. CI = confidence interval.

Table 10

Descriptive Statistics for TRT Ratings by Stimulation Groups

Measure	F3		P4	
	M (*SD*)	95% CI	*M* (*SD*)	95% CI
Average	1.85 (0.08)	[1.69, 2.02]	1.66 (0.58)	[1.53, 1.78]
Maximal	3.67 (0.14)	[3.37, 3.96]	3.00 (0.16)	[2.53, 3.22]
Total	14.83 (0.62)	[13.51, 16.14]	13.27 (0.47)	[2.66, 3.34]

Note. CI = confidence interval.

Table 11

Descriptive Statistics for "Total Number Correct" OSPAN Task Score by Stimulation Groups and Stimulation Conditions

Stimulation condition	F3		P4	
	M (*SD*)	95% CI	*M* (*SD*)	95% CI
Anodal	48.71 (5.97)	[45.63, 51.78]	48.96 (5.46)	[46.96, 51.79]
Cathodal	47.65 (9.81)	[42.60, 52.69]	49.25 (8.43)	[44.76, 53.74]
Sham	49.06 (4.39)	[46.80, 51.32]	49.00 (6.36)	[45.61, 52.39]
Averaged	48.47 (5.21)	[45.79, 51.15]	49.04 (6.02)	[45.83, 52.25]

Note. CI = confidence interval.

Figure 1. Average TUT score calculated as the mean of all the TUT items in the cognitive interference of the DSSQ (Matthews et al., 1999) to represent the degree of mind-wandering for each stimulation group (all stimulation conditions aggregated). The error bars affixed to each column represented standard errors.

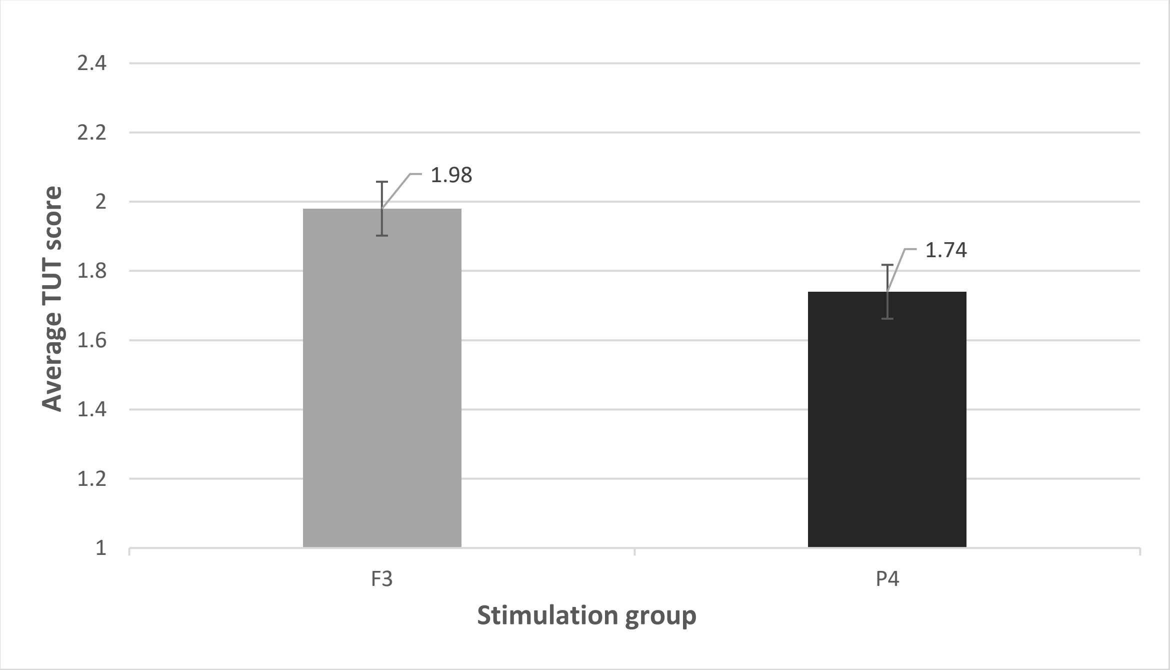


Figure 2. Maximal TUT score calculated as the highest-rated item of all the TUT questions in the cognitive interference of the DSSQ (Matthews et al., 1999) to represent the degree of mind-wandering for each stimulation group (all stimulation conditions aggregated). The error bars affixed to each column represented standard errors.

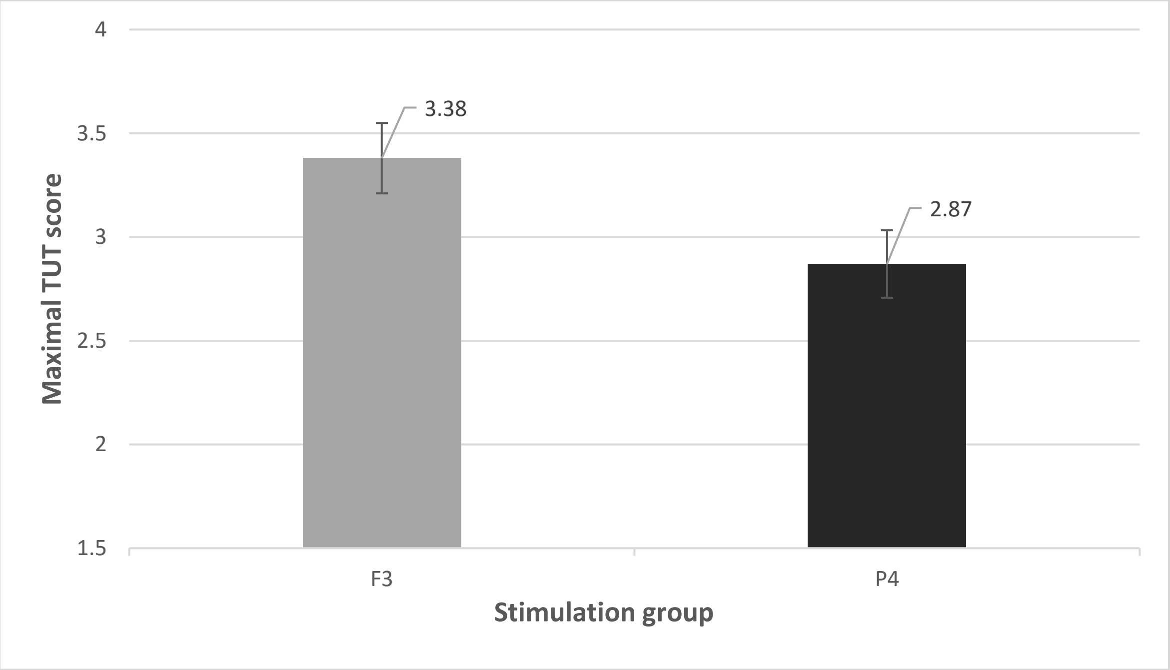
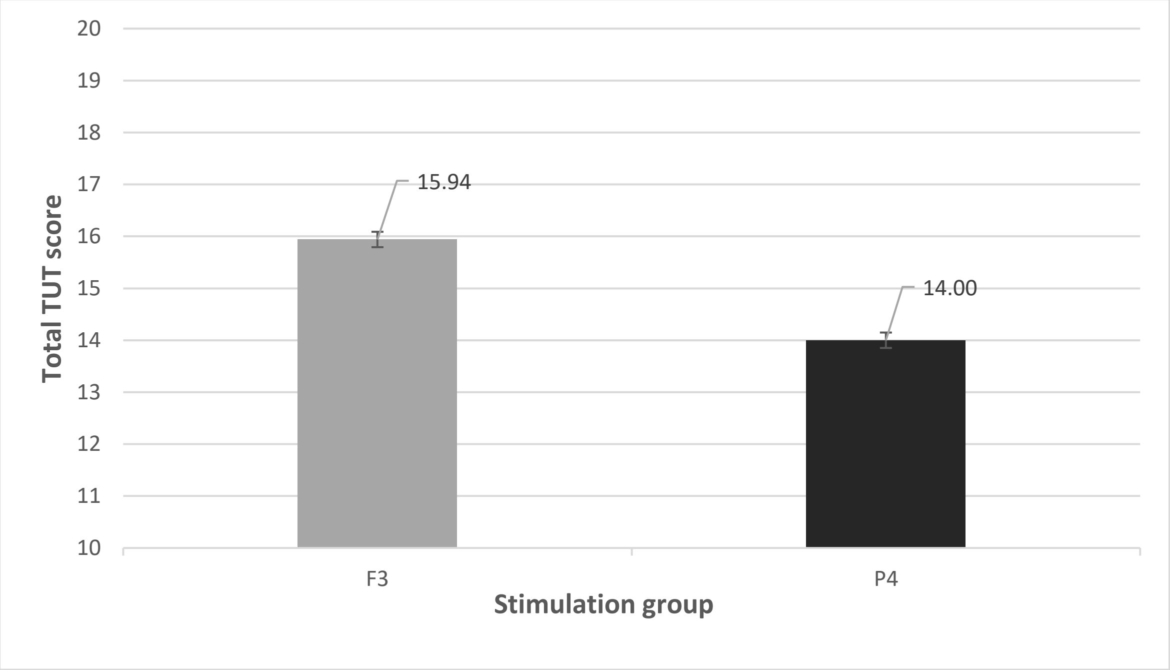


Figure 3. Total TUT score calculated as the sum of all TUT items in the cognitive interference of the DSSQ (Matthews et al., 1999) to represent the degree of mind-wandering for each stimulation group (all stimulation conditions aggregated). The error bars affixed to each column represented standard errors.



Appendix A

The Mind-Wandering Questionnaire (MWQ) (Mrazek et al., 2013)

For each of the following statements, please indicate how frequently or infrequently you have each experience in your daily life.

1. I have difficulty maintaining focus on simple or repetitive work.
2. While reading, I find I haven’t been thinking about the text and must therefore read it again.
3. I do things without paying full attention.
4. I find myself listening with one ear, thinking about something else at the same time.
5. I mind-wander during lectures or presentations.

Answers were given on a six-point Likert scale and were coded as follows during data analysis: 1 = *almost never*, 2 = *very infrequently*, 3 = *somewhat infrequently*, 4 = *somewhat frequently*, 5 = *very frequently*, 6 = *almost always*.

Appendix B

The Daydreaming Frequency Subscale (DDFS) (Singer & Antrobus, 1972)

We are asking for your cooperation in responding to a questionnaire about your inner experiences, your images, and daydreams. Daydreams involve two components: First, they are spontaneous thoughts, that is, they come about by themselves, and secondly, they are relatively unrelated to what you were doing or thinking about at the time. Make a distinction between thinking about an immediate task you're performing, e.g., working, doing school work, thinking directly about it while you are doing it and daydreaming which involves thought unrelated to a task you are working on or thoughts that continue while you're getting ready for sleep or on a long bus or train ride.

Each of the questions have 5 alternatives. For each item choose the alternative which is most true or appropriate for you. Answer all questions as they apply to your life today, not 1 or 2 or 20 years ago.

1. I daydream

    A. infrequently.

    B. once a week.

    C. once a day.

    D. a few times during the day.

    E. many different times during the day.

2. Day dreams or fantasies make up

    A. no part of my waking thoughts.

    B. less than 10% of my waking thoughts.

    C. at least 10% of my waking thoughts.

D. at least 25% of my waking thoughts.

E. at least 50% of my waking thoughts.

3. As regards daydreaming, I would characterize myself as someone who

A. never daydreams.

B. very rarely engages in daydreaming.

C. tends towards occasional daydreaming.

D. tends towards moderate daydreaming.

E. is a habitual daydreamer.

4. I recall or think over my daydreams

A. infrequently.

B. once a week.

C. once a day.

D. a few times during the day.

E. many different times during the day.

5. When I am not paying close attention to some job, book or TV, I tend to be daydreaming

A. 0% of the time.

B. 10% of the time.

C. 25% of the time

D. 50% of the time.

E. 75% of the time.

6. Instead of noticing people and events in the world around me, I will spend approximately

A. 0% of my time lost in thought.

B. less than 10% of my time lost in thought.

C. 10% of my time lost in thought.

D. 25% of my time lost in thought.

E. 50% of my time lost in thought.

7. I daydream at work (or school) [Note: Work is defined as any kind, not just for pay.]

A. infrequently.

B. once a week.

C. once a day.

D. a few times during the day.

E. many different times during the day.

8. Recalling things from the past, thinking of the future, or imagining unusual kinds of events occupies

A. 0% of my waking day.

B. less than 10% of my waking day.

C. 10% of my waking day.

D. 25% of my waking day.

E. 50% of my waking day.

9. I lose myself in active daydreaming

A. infrequently.

B. once a week.

C. once a day.

D. a few times during the day.

E. many different times during the day.

10. Whenever I have time on my hands I day dream

A. never.

B. rarely.

C. sometimes.

D. frequently.

E. always.

11. When I am at a meeting or show that is not very interesting, I day dream rather than pay attention

A. never.

B. rarely.

C. sometimes.

D. frequently.

E. always.

12. On a long bus, train, or airplane ride I daydream

A. never.

B. rarely.

C. occasionally.

D. frequently.

E. a great deal of the time.

During data analysis, the answers were coded numerically as follows: 1 = *A*, 2 = *B*, 3 = *C*, 4 = *D*, 5 = *E*.

Appendix C

The Mindfulness and Attention Awareness Scale (MAAS) (Brown & Ryan, 2003)

Below is a collection of statements about your everyday experience. Please indicate how frequently or infrequently you have each experience. Please answer according to what *really reflects* your experience rather than what your experience should be.

1. I could be experiencing some emotion and not be conscious of it until some time later.
2. I break or spill things because of carelessness, not paying attention, or thinking of something else.
3. I find it difficult to stay focused on what's happening in the present.
4. I tend to walk quickly to get where I'm going without paying attention to what I experience along the way.
5. I tend not to notice feelings of physical tension or discomfort until they really grab my attention.
6. I forget a person's name almost as soon as I've been told it for the first time.
7. It seems I am "running on automatic," without much awareness of what I'm doing.
8. I rush through activities without being really attentive to them.
9. I get so focused on the goal I want to achieve that I lose touch with what I'm doing right now to get there.
10. I do jobs or tasks automatically, without being aware of what I'm doing.
11. I find myself listening to someone with one ear, doing something else at the same time.
12. I drive places on "automatic pilot" and then wonder why I went there.
13. I find myself preoccupied with the future or the past.
14. I find myself doing things without paying attention.

15. I snack without being aware that I'm eating.

For all of the questions, the answers were given in a six-point Likert scale and were coded as follows: 1 = *almost never*, 2 = *very infrequently*, 3 = *somewhat infrequently*, 4 = *somewhat frequently*, 5 = *very frequently*, 6 = *almost always*.

Appendix D

The Cognitive Interference component of the Dundee Stress State Questionnaire (DDSQ)

(Matthews et al., 1999; Sarason et al., 1986)

1. I thought about how I should work more carefully.

2. I thought about how much time I had left.

3. I thought about how others have done on this task.

4. I thought about the difficulty of the problems.

5. I thought about my level of ability.

6. I thought about the purpose of the experiment.

7. I thought about how I would feel if I were told how I performed.

8. I thought about how often I get confused.

9. I thought about members of my family.

10. I thought about something that made me feel guilty.

11. I thought about personal worries.

12. I thought about something that made me feel angry.

13. I thought about something that happened earlier today.

14. I thought about something that happened in the recent past (last few days, but not today).

15. I thought about something that happened in the distant past.

16. I thought about something that might happen in the future.

The first eight items assess task-related thoughts (TRTs) and the last eight items assess task unrelated thoughts (TUTs). Participants rate their agreement with each item on a scale from 1 to 5 (1 = *never*, 2 = *once*, 3 = *a few times*, 4 = *often*, 5 = *very often*).