The interplay between executive control, behavioral variability and mind wandering: Insights from a high-definition transcranial direct-current stimulation study

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ABSTRACT

While the involvement of executive processes in mind wandering is largely undebated, their exact relationship is subject to an ongoing debate and rarely studied dynamically within-subject. Several brain-stimulation studies using transcranial direct current stimulation (tDCS) have attempted to modulate mind-wandering propensity by stimulating the left dorsolateral prefrontal cortex (DLPFC) which is an important hub in the prefrontal control network. In a series of three studies testing a total of $N = 100$ participants, we develop a novel task that allows to study the dynamic interplay of mind wandering, behavioural varibility and the flexible recruitment of executive resources as indexed by the randomness (entropy) of movement sequences generated by our participants. We consistently find that behavioural variability is increased and randomness is decreased during periods of mind wandering. Interestingly, we also find that behavioural variability interacts with the entropy-MW effect, opening up the possibility to detect distinct states of off-focus cognition. When applying a high-definition transcranial direct-current stimulation (HD-tDCS) montage to the left DLPFC, we find that propensity to mind wander is reduced relative to a group receiving sham stimulation.

Keywords: mind wandering, tDCS, attention, task-unrelated thought, behavioural variability, randomness, approximate entropy

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1 Introduction

We spend a surprising amount of our daily lives thinking about things that are unrelated to what we are currently doing (Killingsworth & Gilbert, 2010), a state that has been characterized as mind wandering (MW). For example, we might be internally planning our next renovation project even as we are washing the dishes or reflect on a scientific problem while driving our car into the garage. Not paying attention to an ongoing task can have severe consequences and can result in accidents, e.g., in aviation (Casner & Schooler, 2014) or driving (Yanko & Spalek, 2014; Baldwin et al., 2017). In learning situations, excessive MW can negatively impact academic achievment in the classroom (Unsworth & McMillan, 2017). Furthermore, mind wandering appears to be related to mood (Ottaviani et al., 2015) and has also been related to psychiatric conditions such as depression (Hoffmann, Banzhaf, Kanske, Bermpohl, & Singer, 2016) and ADHD (Seli, Smallwood, Cheyne, & Smilek, 2015; Van den Driessche et al., 2017). In most everyday-situations, consequences of mind wandering are benign and are typically studied in situations that require sustained attention (Smallwood & Schooler, 2006).

It is, in general, difficult to establish a proper definition of mind wandering, a fact that is reflected in the multitude of different terms, such as "task-unrelated thoughts", "mind wandering" or "spontaneous cognition", used to study related phenomena (Callard, Smallwood, Golchert, & Margulies, 2013). One recent attempt to unify existing research has proposed a family-resemblances view of mind wandering (Seli et al., 2018), emphasizing that the definition of mind wandering may involve looking for similarities between the diverging operationalizations used in the literature and accepting that there may not be a single characteristic unifying all of them. However, this view has been criticised because of its all-encompassing and hence not selective viewpoint (Christoff et al., 2018), emphasizing the importance of the dynamical properties of spontaneous thought. Other attempts establishing a working definition of MW have therefore attempted to delineate mind wandering from other types of spontaneous cognition, such as rumination or dreaming (Christoff, Irving, Fox, Spreng, & Andrews-Hanna, 2016) or to provide distinctions based on the underlying brain mechanisms (Mittner, Hawkins, Boekel, & Forstmann, 2016).

Furthermore, distinguishing between intentional (deliberate) and unintentional (spontaneous) mind wandering has been found to be important because these types of MW have different behavioural consequences and psychological and neural profiles (Seli, Risko, Smilek, & Schacter, 2016). In addition, a variety of factors have been found to be relevant for studying MW including cognitive factors (e.g., working memory capacity; Kane & McVay, 2012), personal dispositions (e.g., neuroticism; Robison, Gath, & Unsworth, 2017) and context (e.g., motivation and affect) and efforts have been made to integrate them in a multi-faceted approach (Robison, Miller, & Unsworth, 2020). In the present study, we are less interested in studying between-subject individual differences or different types of task-unrelated mental activity, but rather, we focus on the dynamical fluctuations of attention and executive control within a single experimental session. As a consequence, we conceptualize MW as task-unrelated thought, i.e., any mental activity that is not related to the task at hand. Based on experimental evidence that links MW to poor performance in tasks requiring executive control (Smallwood et al., 2004), it has been theorized that mind wandering is tightly linked to (the loss off) executive control (Smallwood & Schooler, 2006; McVay & Kane, 2010) even though the exact nature of this relationship is still unclear.

Hence, recent research has begun looking into the possibility of actively manipulating MW by means of non-invasively stimulating brain areas involved in executive control (Axelrod, Rees, Lavidor, & Bar, 2015; Chaieb, Antal, Derner, Leszczyński, & Fell, 2019). Most of these studies have focused on the dorsolateral prefrontal cortex (DLPFC; usually in the left hemisphere) which is one of the core brain regions consistently linked to executive functioning and hence highly likely to be related to maintaining sustained attention and avoiding mind wandering. Due to its extended size and accessible location near the surface of the brain, the DLPFC is a good target for non-invasive brain stimulation techniques such as transcranial direct current stimulation (tDCS). This non-invasive brain stimulation method operates by injecting low-intensity currents (typically 1 or 2 mA resulting in electric fields of about 0.5 – 0.8 mV/mm; Opitz et al., 2016; Huang et al., 2017) into the brain through electrodes attached to the scalp. The tDCS method is safe with little adverse effects (Antal et al., 2017) and is typically assumed to operate by changing the resting membrane potential of pyramidal neurons perpendicular to the cortical surface (Filmer, Dux, & Mattingley, 2014). Importantly, the effect of tDCS is assumed to be polarity dependent: While anodal (inward-flowing) currents are supposed to elevate the neural resting membrane potential and hence result in higher excitabiliy of the neurons, cathodal (outward-flowing) currents are believed to have the opposite effect.

A multitude of tDCS studies has reported positive effects on many cognitive functions including attention (Coffman, Trumbo, & Clark, 2012), working memory (Zaehle, Sandmann, Thorne, Jäncke, & Herrmann, 2011) and language (Meinzer et al., 2014). However, different studies show little consistency in terms of the directionality of the effects and it has been questioned whether and to what extent there is sufficient evidence that tDCS affects cognitive functions at all (Horvath, Forte, & Carter, 2015; Hill, Fitzgerald, & Hoy, 2016; Mancuso, Ilieva, Hamilton, & Farah, 2016). As a consequence, high-powered and pre-registered studies are gaining popularity in the tDCS literature (Minarik et al., 2016; Boayue et al., 2019; Filmer, Griffin, & Dux, 2019) because of their stronger potential to establish replicable results.

As mentioned above, in the field of mind wandering, a range of brain-stimulation studies attempted to non-invasively modulate mind-wandering propensity using transcranial direct current stimulation (tDCS) of the DLPFC (Chaieb et al., 2019). Initially, several studies reporting successful modulation of mind-wandering propensity using traditional non-focal, low-intensity tDCS over the DLPFC provided an optimistic outlook (Axelrod et al., 2015; Kajimura & Nomura, 2015; Kajimura, Kochiyama, Nakai, Abe, & Nomura, 2016). However, since then several studies have failed to replicate this effect (Boayue et al., 2019; Coulborn, Bowman, Miall, & Fernández-Espejo, 2020) including a large-scale, pre-registered direct replication study (Boayue et al., 2019), suggesting that the initial positive results that were based on very low sample-sizes might have been a false positive (but see Axelrod, Zhu, & Qiu, 2018; Csifcsák et al., 2019, for a discussion). Furthermore, those studies that did find an effect of tDCS on mind wandering were inconsistent with respect to the directionality of the effect, some finding an increase (e.g., Axelrod et al., 2015; Filmer et al., 2019) and some finding a decrease (e.g., Kajimura & Nomura, 2015; Chou, Hooley, & Camprodon, 2019) in mind-wandering propensity (see Chaieb et al., 2019, for a review).

In summary, there seems to be insufficient evidence for the effectiveness of tDCS over the DLPFC to modulate mind-wandering propensity. This failure to produce replicable results across studies may be due to various methodological reasons. First, the commonly used stimulation protocols may be ineffective. Second the universally applied sustained attention to response task (SART; Robertson, Manly, Andrade, Baddeley, & Yiend, 1997) may not be optimal in studying the relationship between executive control and mind wandering because executive control is barely needed. And finally, the analytical methods applied in previous studies may be too coarse to allow localizing the possibly subtle effects of tDCS protocols. In the current study, we aim to improve all of these shortcomings to provide a more powerful experimental design for studying the relationship between executive functioning and mind wandering.

It has been questioned whether traditional stimulation montages using weak stimulation intensities (1mA is often used in the relevant studies; Axelrod et al., 2015; Boayue et al., 2019) provides strong and sufficiently focal fields to produce any neural effects at all (Huang et al., 2017). While we are not suggesting that commonly used tDCS protocols are entirely ineffective, it seems clear that higher electric fields are desirable in general to produce more tangible neural and behavioural effects (Vöröslakos et al., 2018). So far, no study has used a high-definition tDCS (HD-tDCS; Edwards et al., 2013) stimulation setup over the prefrontal cortex in a mind-wandering context despite its strong potential for increasing the focality of the stimulation (Datta et al., 2009; Dmochowski, Datta, Bikson, Su, & Parra, 2011; Boayue et al., 2019). HD-tDCS setups use multiple, smaller-sized electrodes positioned in strategic locations on the scalp, thereby shaping the electric field to more focally stimulate the target-region. Targeting the DLPFC, we implemented a ring-shaped 4-by-1 HD-tDCS stimulation protocol (Dmochowski et al., 2011; Villamar et al., 2013; Csifcsák, Boayue, Puonti, Thielscher, & Mittner, 2018) centered over prefrontal electrode F3 that greatly increases both the focality and strength of the elicited electric field in the DLPFC (see Methods).

Furthermore, while the SART is omnipresent in the literature on mind wandering and has certainly produced many important insights, it is unclear whether this task is best-suited to study the relationship between executive control and mind wandering. Due to the low occurrence of target stimuli in this task (target-rates vary but are as low as 1 in 40 trials in the tDCS literature; Axelrod et al., 2018; Boayue et al., 2019), executive control is only rarely probed and cannot be tracked over the course of the experimental session. As a consequence, commission error rates (i.e., failed NoGo) are typically quite high indicating that employment of executive control may be low in general. Therefore, it is difficult to study the interaction of fluctuations in executive control and mind wandering in this task. Here we propose a novel, fast-paced paradigm that allows to study how executive control is employed over the course of the experiment at high temporal resolution. The task is based on the classical random-number generation task (RNGT; Baddeley, 1998) which is generally being used for measuring executive functioning: Generating sequences of random numbers requires constant monitoring and quick updating of working-memory content (to keep sufficiently long sub-sequences in memory that enable the calculation of the next item) and the suppression of pre-potent response patterns such as increasing sequences of integers (response inhibition). Both of these processes are integral parts of executive functioning (Miyake et al., 2000). In a mind-wandering context, this task has been shown to be sensitive to attentional fluctuations (Teasdale et al., 1995). We combined this task with a standard finger-tapping procedure (similar to the metronome response task, MRT; Seli, Cheyne, & Smilek, 2013) where we asked our participants to rhythmically press one of two keys on the keyboard in a random sequence. This setup allows to investigate how behavioural variability (BV) is related to both executive functioning and mind wandering (Kucyi, Hove, Esterman, Hutchison, & Valera, 2017; Kucyi, Esterman, Riley, & Valera, 2016) and to study the relationship of these three variables dynamically over the course of the experimental session. It has previously been shown that BV is an early sign of deteriorating task-focus (Seli et al., 2013) that can occur before other, more severe performance decrements ("tuning out"; Cheyne, Solman, Carriere, & Smilek, 2009; Smallwood, McSpadden, & Schooler, 2007). Therefore, investigating BV, executive control and self-reported MW together may give insights into the dynamics of the transition between on- and off-task states.

Finally, the effectiveness of tDCS stimulation on mind wandering is usually evaluated by comparing mean thought-probes across the entire experimental session between sham and active tDCS groups. As described in Boayue et al. (2019), this is problematic for three reasons: First, the ordinal thought-probe variable is treated as continuous which can be problematic (Liddell & Kruschke, 2018), second, information about within-subject variability is lost by the averaging process and thirdly, known influences on mind-wandering propensity are ignored (e.g., the well-established time-on-task effect; Thomson, Seli, Besner, & Smilek, 2014). Arguably, by explicitly modeling the ordinal data in a more realistic way, the statistical power for detecting the possibly subtle effect of tDCS on the outcome measures can be increased. For these reasons, analyzing thought-probes using Bayesian hiearchical ordered probit regression models is becoming more commonly used (Filmer et al., 2019; Boayue et al., 2019).

1.1 Overview

This paper develops a novel experimental paradigm that is designed to allow the tracking of attentional fluctuations at short time-scales and uses it to investigate the effectiveness of HD-tDCS on manipulating mind-wandering propensity. The purpose of study 1 was to establish a link between the randomness of the left-right finger-tapping sequences generated in our task and the use of executive resources. In addition, the parameters of the task, in particular the inter-stimulus-interval (ISI) and the parameters of our used measure of randomness, approximate entropy (Steve Pincus & Kalman, 1997), were optimized. In study 2, we introduced mind-wandering thought-probes into our task that were used to establish a link between behavioural variability, randomness and attentional fluctuations. Finally, in study 3, we investigated whether an optimized HD-tDCS brain-stimulation intervention over the DLPFC could change the degree of mind wandering experienced by our subjects.

2 General Methods

2.1 Participants

Participants were recruited at the university of Tromsø through standard procedures including fliers around campus and entries in student groups and other interest groups on social media networks. All studies were approved by the ethics committee at the institute for psychology at the university of Tromsø.

2.2 Finger-Tapping Random-Sequence Generation Task (FT-RSGT)

All studies used a novel Finger-Tapping Random-Sequence Generation Task (FT-RSGT). This task is a combination of a modified version of the random number generation task (Baddeley, 1998; Towse, 1998) and a finger-tapping task (Seli et al., 2013; Kucyi et al., 2017): It consists of a combination of rhythmic finger-tapping in response to an ongoing metronome and the generation of random sequences by pressing the two available response-buttons in a random sequence. The idea behind this task is as follows: Generating random sequences is a task that draws heavy on executive resources. As a consequence, we expect the randomness of the generated sequence to be related to the amount of executive resources diverted to it. In the context of mind wandering, this has been confirmed by the finding that sequences generated while mind wandering are typically less random (Teasdale et al., 1995). Furthermore, behavioural variability as measured by the deviation of the taps from the on-going metronome in finger-tapping studies has also been found to be an indicator of mind wandering (Seli et al., 2013; Kucyi et al., 2017) with behaviour becoming more variable when attention is drawn away from the task. By combining both measures in a single experiment, the dynamic interplay of behavioral variability and executive control can be studied and related to mind wandering as measured by thought-probes.

Concretely, participants were instructed to press two buttons with their left or right index finger in a random order. In order to establish a comparable level of understanding of the meaning of "randomness" when applied to a sequence of button-presses, participants were carefully instructed using the flipping of a coin as an example. They were told that their button-presses should resemble the result of repeatedly flipping a fair coin and that, therefore, each of the two buttons should have equal probability of being pressed in each trial (see online materials). After receiving the explanation, subjects had to fill out a quiz asking them about various aspects of the procedure and they were allowed to continue only after correctly answering all questions.

Participants also had to match every single button press as accurately as possible to the occurrence of a rhythmic tone (440 Hz presented for a duration of 75 ms) that was presented to them via high-quality stereo headphones (Multi Function Headset 210, Trust International B.V., Dordrecht, Netherlands). The inter-stimulus interval (ISI) of the metronome tones was optimized in study 1. Finally, participants were randomly interrupted by thought-probes asking about the current state of their attentional focus ranging from being on-task to mind wandering (studies 2 and 3).

2.2.1 Measuring Randomness

Measuring randomness of a finite sequence is a non-trivial problem as, strictly speaking, entropy for a finite sequence is not defined. Rather, entropy is defined for a system that can generate sequences and any given generalization can be seen as stemming from an infinite number of generating systems. As a consequence, it is mathematically impossible to infer the entropy of a system from a finite sequence. As an example, consider a perfectly random process that flips a fair coin in every trial and outputs a 0 for heads and a 1 for tails. Given that perfectly random system, the sequence [1,0,1,0,1,0,1,0,1,0] that contains an obvious structure of alternating heads and tails has the exact same probability, $P = 0.5^{10}$, as, for example, this sequence [1,0,0,1,0,1,1,1,0,1]. In fact, any sequence of exactly ten items has that exact same probability. However, there are fewer sequences that have such obvious patterns and more sequences that look more random and hence, the chances to get a sequence with few repetitive patterns is relatively high if the system is indeed producing random sequences.

To circumvent this problem, we use a statistic called approximate entropy (AE; Pincus, 1991; Steve Pincus & Singer, 1996; Steve Pincus & Kalman, 1997) that is defined at the sequence level. This measure allows to evaluate the extent of irregularity in a sequence. Specifically, AE(m) measures the logarithmic frequency with which blocks of length m that are close together remain close together for blocks augmented by one position, with larger values of AE implying greater irregularity in the sequence. In other words, for a given sequence of numbers, AE(m) gives an indication of the predictability of the next item in a sequence given the previous sequence of m numbers. AE has proven useful across applications as diverse as analyzing the (ir-)regularity of physiological (e.g., EEG; Sabeti, Katebi, & Boostani, 2009) or financial market time series (Steve Pincus & Kalman, 2004).

Approximate entropy is parametrized by the parameter m that dictates the length of subsequences being evaluated. Hence, comparisons regarding the randomness of two sequences should be made for a fixed value of m (Pincus, 1991). Higher values of m require longer sequences for ensuring the validity of the calculation. In oder to establish the value of this parameter m that is most sensitive for detecting differences in the randomness of the sequences, we conducted study 1 and study 2 in which we compared the performance of different setting of this parameter. Concretely, in our study, the sequence of N left-right taps (left coded as 0, right coded as 1) enter the calculation of the AE(m) measure. During the calculation, this long sequence is being partioned into all possible sub-sequences of length $m+1$ taps and all of these are averaged into the final AE measure.

2.3 Statistical Methods

We used exclusively Bayesian statistics because of their many advantages over classical frequentist methods (Wagenmakers et al., 2018). For all regression analyses, we used the R package `brms` (Bayesian Regression Models using Stan; Bürkner, 2017) with default, uniform priors for the regression coefficients. This package uses Hamiltonian Monte-Carlo (HMC) techniques implemented in Stan (Carpenter et al., 2017) to fit the models. We used 4 chains, each chain had a warm-up period of 1000 samples and 4000 post warm-up samples. We used the Gelman-Rubin diagnostic (Gelman, Rubin, et al., 1992) to ensure that all reported results had $\hat{R} \leq 1.05$. For model comparison, we used Leave-One-Out Information Criterion (LOOIC; Vehtari, Gelman, & Gabry, 2017, 5), where smaller scores of the LOOIC suggest a better model fit. Specifically, a model is considered better relative to another model if the LOOIC score is smaller, and if the ΔLOOIC score is at least the double of the corresponding LOOIC standard error.

When reporting regression coefficients, we report posterior mean b, 95% highest-density intervals (HDI) and the evidence ratio (ER) in favor of a positive (ER_+) or a negative effect (ER_-). These ratios are calculated as the ratio of two probabilities: The probability of the effect being positive divided by the inverse probability of the effect being zero or negative (ER_+) or the inverse of that ratio (ER_-). For example, the statement $b = 0.09$ $[0.01, 0.18]$, ER_+=27.0 indicates a positive regression coefficient of 0.09 units with a positive 95% HDI going from 0.01 to 0.18 and an evidence-ratio of 27.0 in favor of a positive effect. The evidence ratio can be interpreted as an odds-ratio. In the previous example, we can for example state that it is 27 as likely that the effect is positive than that it is zero or negative.

2.3.1 Hierarchical ordered probit regression

In the mind-wandering literature, responses to thought-probes are often treated as continuous variables and mean and standard-deviation calculated per subject and session are used. This approach has been identified as problematic for several reasons (Boayue et al., 2019): it "wastes" data because within-subject variability is completely lost; it is a misspecification of reality as treating ordinal variables as continuous can have severe consequences (Liddell & Kruschke, 2018); and it ignores known modulating factors such as the time-on-task effect (Thomson et al., 2014). All of these factors can readily be integrated in more sophisticated analyses. Hence, we used the model developed by Boayue et al. (2019) that has already been applied in several studies (Filmer et al., 2019; Turi et al., 2019).

With this analysis method, the answers to our thought-probes was the dependent variable which was modeled as an ordinal response-variable. Each subject received a random intercept (and one for "experiment part" nested in participants of study 3) and we use behavioural variability, entropy of the sequences and current trial-number (as well as their interactions) as predictor variables.

3 Study 1

The first study served as a proof-of-concept that fluctuations in randomness as operationalized by approximate entropy as well as behavioural variability can be readily measured across the experimental session at high temporal resolution. We also aimed to establish that randomness measured by our FT-RSG task would be correlated to the classical version of the random number generation task as proposed by Baddeley (1998). Finally, we wanted to optimize the parameters of the experimental protocol (notably the inter-stimulus interval, ISI and the parameter of the AE measure) for our further studies.

3.1 Methods

3.1.1 Participants

We collected data from 19 students and employees (12 males) of the University of Tromsø with a mean age of 25.2 years (range from 21 to 42). All of the participants gave written informed consent before the start of the experiment and received a non-monetary compensation, worth around 40 Norwegian kroner for participation. The experimental instructions were given in English or Norwegian language, depending on the preference of the participant.

3.1.2 Design

We implemented five sessions of 5 minutes each using different inter-stimulus intervals including 0.3, 0.5, 0.75, 1.0, and 1.25 seconds. The order of presentation of these sessions was randomized across participants. After each session we asked our partipants to judge how random they thought the sequence they created over the preceding five minutes was. The answer was recorded using a 5-point Likert scale ranging from "very predictable" to "very random". To compare the FT-RSG task to the classical RNG-task used by Baddeley (1998), we implemented a version of that task in which participants had to press 10 instead of two buttons in a random order, with one finger assigned to one key. The duration of that task was set to 5 minutes and the inter-stimulus-interval was 1.0 seconds in accordance with the original study (Baddeley, 1998).

The experimental tasks were programmed with PsychoPy, Standalone version 1.83.04_win32 (Peirce, 2007). The keyboard was invisible to the participants during the task, since they had to place their head in the inbuilt chin- and forehead-rest of the eye tracking column of an infrared video-based eye tracker (iView X Hi-Speed 1250, SMI GmbH, Teltow, Germany). During this experiment, the eyes were not actually tracked but the setup was used for comparability to future studies. Participants were instructed to keep their eyes on a fixation cross (white on grey ground, height 0.15 degrees of visual angle), displayed in the center of the screen. Task instructions in the beginning of the experiment and the probe items during the course of the experiment were also presented on that screen (both in white letters on grey ground).

3.1.3 Procedure

Each experimental session started with the classical 10-digit version of the RNG task. Participants received a written explanation of randomness using an example in which 10 balls were randomly drawn out of a box and put back after every draw. Following the written explanation, the participants were asked to actually draw 10 times a ball out of a box of 10 different balls and to note down the results. The results of this process were discussed together with the experimenter to exemplify the concept of randomness. During the RNG task, participants had their hands placed on a specially prepared keyboard that only contained the ten used keys in an ergonomic arrangement. Participants were told to press those ten buttons in a random order. They were also instructed to respond synchronously with the ongoing tone of the metronome so that each button press would occurs together with the tone. After a training session of 50 trials, the actual 5-minute session of that task was started, consisting of 300 tones in total.

After finishing this task, the participants were given the explanation of randomness based on the example of flipping a coin discussed in the general methods above. Again, following the written explanation, participants were asked to actually flip a coin 10 times and discuss the results of this process. In addition to the standard instructions, participants were also told that the rhythm of the tone would change after each break and that they would be asked to estimate how random the sequence that they created in the last block was. The FT-RSGT part of the experiment started with a one-minute training session using an ISI of 0.8 seconds. After that, the five blocks implementing different ISIs were presented in random order.

3.2 Results and Discussion

We started by investigating the distribution of the AE values to establish its usability for statistical analysis. We found that it was highly left-skewed (see Supplemental Materials) and we therefore implemented the transformation $-\log(\log(2)-\mathrm{AE})$ which we found to result in an approximately normal distribution of the outcome measure (see Supplemental Materials for details). All reported analyses are based on the transformed AE measure but we will refer to it as AE for simplicity.

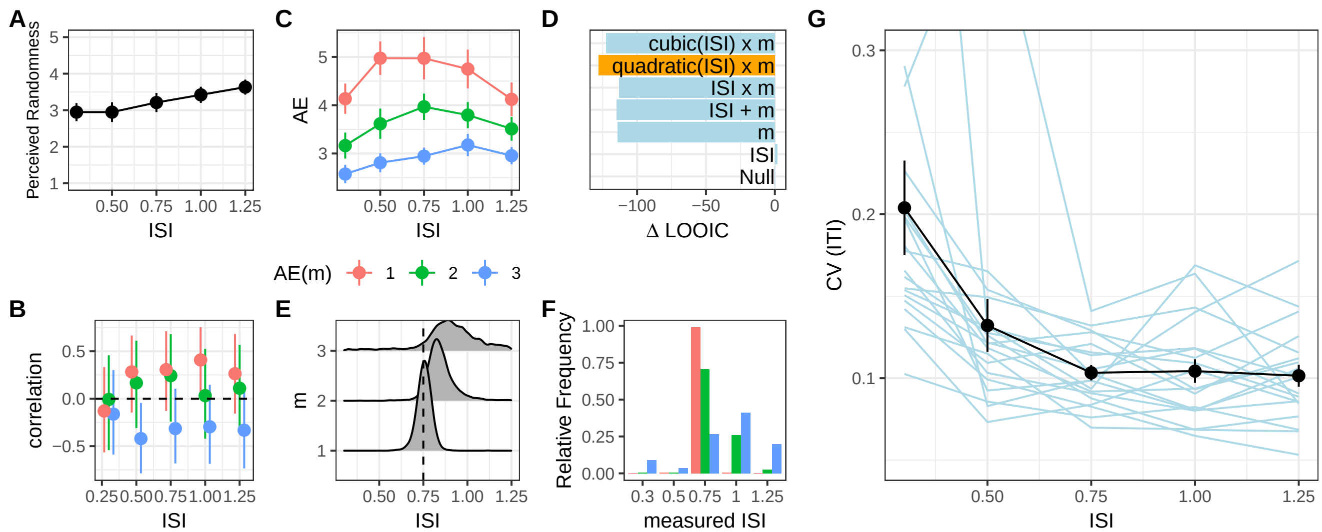

Figure 1. Results from Study 1. A: Perceived randomness of the sequences increases with longer ISIs. B: For all but the shortest ISIs, AE estimates from the finger-tapping task correlated with those from the standard RNG task for $m = 1$ and somewhat for $m = 2$. C: Randomness of the sequences quantfied by AE shows an inverse U-shaped relationship with ISI. D: A model incorporating a quadratic relationship yields the best fit in terms of model-selection (LOOIC). E: The ISI for which AE of the generated sequence was maximized according to the model from D. F: From the 5 ISI conditions actually measured in study 1, 0.75 sec was closest to the maximum estimated in E for $m = \{1,2\}$. F: The coefficient of variation (CV) of the inter-tap intervals (ITI) approached an asympote for an ISI of 0.75 seconds. Blue lines represent data from each participant, whereas the black line represents the group mean.

One goal of the first study was to optimize the protocol. In particular, we wanted to find the ISI that would allow our subjects to maximize the randomness (AE) of their generated sequences. We hypothesized that ISIs that were too short would not allow for enough processing to randomize the tapping sequences. On the other hand, too long ISIs might encourage inattention and, hence also be detrimental to the randomness of the generated sequences. In addition, we wanted to make the ISI as short as possible in order to give a design with maximum possible temporal resolution with respect to extracting the ongoing involvement of executive resources. We therefore hypothesized that there would be a saturation point at which more processing time would not help, or might even hinder, the creation of random sequences.

The results of our analyses support that hypothesis (see Figure 1 C). The average AE values, calculated for each ISI condition and $m = \{1,2,3\}$ follow an inverted U-shape with the peak of the curve moving towards higher ISI for higher values of m. In order to more formally capture the optimal ISI at which the AE was maximized, we fitted a series of Bayesian linear mixed effects models with random-intercepts per subject treating AE as the dependent variable. We found, that entering the first two powers of ISI as well as m and their interactions to the model produced the best fit in terms of the model-selection (ΔLOOIC=-2.8, SE=1.3 relative to the next best model), see Figure 1 D. Using that model, we derived the theoretical ISI at which the curves for each m would reach their maximum, carrying the uncertainty from the Bayesian model through the calculation (i.e., the calculation was made for every posterior sample and the distribution of the results calculated). The results of this analysis are plotted in Figure 1 E. The peak of the curve was located between 750 ms and 1000 ms for all values of m. Next, we calculated which of the ISIs that we measured (i.e., 250, 500, 750, 1000 and 1250 ms) was closest to theoretical peak for each m. The results of these analysis are displayed in Figure 1 F. According to this analysis, the best ISI for optimizing AE for $m = 1$ and $m = 2$ was 750 ms (99% of the values were closest to 750 ms for $m = 1$ and 71% for $m = 2$). For $m = 3$, the optimal ISI was most frequently closer to 1000 ms (41%).

We also investigated subjectively experienced randomness of the sequences. After each ISI-block, our subjects were asked to rate how well they thought they had performed at producing random sequences. Contrary to the actual randomness of the sequences, the results, displayed in Figure 1 A, indicate that subjects believed their sequences to become more random with increased ISIs. A Bayesian mixed linear regression model with self-evaluated randomness as dependent variable and ISI as (numeric) repeated measures predictor confirmed that trend, $b = 0.78\,[0.19, 1.34], \mathrm{ER}_{+} = 199$.

In addition, we opted to compare our FT-RSG task to the classical random-number generation task used by Baddeley (1998). We used robust Bayesian correlations[1] to quantify the correspondence between the classical RNG and our finger-tapping

[1] http://www.sumsar.net/blog/2013/08/robust-bayesian-estimation-of-correlation/

task. Interestingly, the degree of correlation seems to depend both on the choice of ISI for our finger-tapping task and the AE m-parameter (see Figure 1 B). For very short ISIs, there was no correlation between the randomness of the sequences generated in the two tasks (ISI=0.30, m=1: $\rho = -0.07$ $[-0.53, 0.34]$, m=2: $\rho = -0.02$ $[-0.52, 0.43]$, m=3: $\rho = -0.41$ $[-0.78, -0.03]$). We interpret this finding such that the short time between taps did not allow our participants to exert executive control necessary to produce random sequences that would manifest in the AE measures. For longer ISIs, the correlations for $m = 1$ and $m = 2$ were positive (ISI=0.75, m=1: $\rho = 0.33$ $[-0.07, 0.73]$, m=2: $\rho = 0.27$ $[-0.18, 0.70]$; ISI=1.00, m=1: $\rho = 0.47$ $[0.09, 0.79]$, m=2: $\rho = 0.05$ $[-0.42, 0.50]$) while the correlations for $m = 3$ were consistently negative (ISI=0.75: $\rho = -0.34$ $[-0.72, 0.07]$, ISI=1.00: $\rho = -0.34$ $[-0.76, 0.05]$).

Finally, we measured how behavioural variability would change as a function of the used ISI in our task. We calculated the coefficient of variation (CV) of the sequence of inter-tap intervals (ITI) for each subject (Figure 1 G). This measure of variability decreases monotonically until an ISI of 750 ms and then reaching a plateau on that level, indicating that behavioural variability was stable from 750 ms onwards. As a consequence of these analyses, we decided to continue using an ISI of 750 ms for the following studies. We also settled on using $m = 1, 2$ for calculating the AE scores and to use the transformation for the AE described above.

4 Study 2

The objective of study 2 was to evaluate to what extend the experimental design developed in study 1 allows to study the relationship between employment of executive function (operationalized by AE), behavioural variability and mind wandering. To that purpose, we conducted a longer experimental session featuring the optimal ISI of 750 ms determined in study 1. In addition, we included randomly interspersed thought-probes to assess the degree of mind wandering throughout the task. We predicted that periods of mind wandering would be characterized by less random sequences and a higher degree of behavioural variability.

4.1 Methods

4.1.1 Participants

21 subjects (7 males) with a mean age of 28 years (range from 21 to 57) participated in the experiment. All of the participants gave written informed consent before the start of the experiment and received a non-monetary compensation, worth 50 Norwegian kroner for participation. The experimental instructions were given in English or Norwegian, depending on the preference of the participant.

4.1.2 Design

The experimental task was identical to the FT-RGST task used in study 1 except that only a single ISI was used (750 ms) and the experimental session went on for 20 minutes. In addition, participants were intermittently prompted with a question asking them to estimate where their focus of attention was just before the question appeared. They answered by moving an arrow on a horizontal 6-point Likert scale ranging from “Clearly on-task” to “Clearly off-task”. The initial position of the arrow and the direction of the scale was randomized. Probes appeared randomly with a minimum of 20 and a maximum of 40 seconds between two probes. In total, there were 40 probes in each session.

4.1.3 Procedure

Participant were instructed in the same way as in study 1. As in study 1, subjects were placed in front of an eye-tracking device (iView X Hi-Speed 1250, SMI GmbH, Teltow, Germany) featuring a chin-rest. We planned to record eyetracking data and the eyetracker was therefore calibrated for each subject. However, due to a faulty device, the acquired eyetracking data was unusable and was not analysed. The training session was identical to study 1, comprising 50 trials, and an example of the thought-probes presented throughout the experiment was shown and explained. Finally, the participants started the experiment proper which lasted for 20 minutes.

4.2 Results and Discussion

In study 2, we intended to investigate the relationship between entropy of the generated sequences, behavioural variability of the responses and mind wandering. First, we calculated the AE and BV values calculated using the last $n_{\text{back}} = 20$ trials (corresponding to 15 seconds) before encountering a thought-probe. For descriptive analysis, we then split probe-responses into on-task (response 1, 2 and 3) and off-task (response 4, 5 and 6) and calculated mean AE ($m = \{1, 2, 3\}$) and BV-scores within on- vs. off-task segments, see Figure 2 A. The pattern of increased behavioural variability and decreased entropy during periods of off-task is apparent for all values of m. Next, we re-calculated the AE ($m = 2$) and BV-scores for off- vs. on-task trials using varying numbers of trials preceding each probe ($n_{\text{back}} = \{10, 15, 20, 25\}$), see Figure 2 B. The pattern is robust against the choice of n_{back} but seems to be strongest for $n_{\text{back}} = 25$.

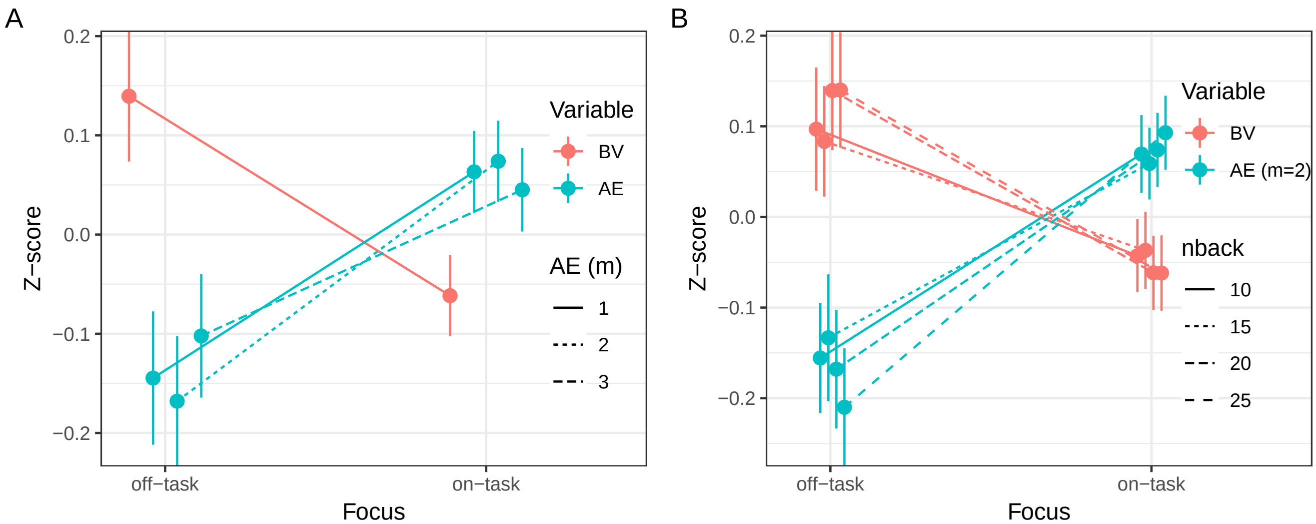

Figure 2. Results from Study 2. A, B: Behavioural variability is increased during off-task episodes while AE is decreased. This pattern holds for different choices of parameter m (A) and varying number of trials n_{back} (B).

Next we formally tested this pattern using a Bayesian hierarchical ordered probit model as described in the general methods. We first ran a model-selection procedure across 17 models that included different combinations of predictor-variables and their interactions (see Supplemental Figure 2A for details). We compared these models, according to their out-of-sample predictive performance using the leave-one-out cross-validation information criterion (LOOIC; Vehtari et al., 2017, 5). Based on this criterion, we calculated model-weights using two different methods: First, a method based on Akaike weights (Wagenmakers & Farrell, 2004) using the LOOIC instead of the AIC and second a method using Bayesian model-averaging (BMA; Yao, Vehtari, Simpson, Gelman, et al., 2018). Both of these techniques result in poster-probabilities p_{LOO} and p_{BMA} quantifying how likely it is that each of the models has the best out-of-sample predictive performance.

The two model-selection methods disagreed in their preferred models. While the LOOIC-procedure selected a model that included main effects of BV, AE ($m = 2$) and trial-number ($p_{\text{LOO}} = 0.35$, next best model: $p_{\text{LOO}} = 0.17$), the BMA procedure a model that also included the interaction between BV and AE ($p_{\text{BMA}} = 0.26$, next best model: $p_{\text{BMA}} = 0.23$). That last model was second-best in the LOOIC-procedure and we therefore chose this model as the winning one. This winning model had a Bayesian R^2 (Gelman, Goodrich, Gabry, & Vehtari, 2019) of $R^2 = 0.37$ $[0.33, 0.41]$. In this model, the coefficient for BV was positive ($b = 0.09$ $[0.01, 0.18]$, ER_+=27.0) indicating that as behavioural variability increased, so did off-task responses on the thought-probes. The coefficient for AE ($m = 2$) was negative ($b = -0.07$ $[-0.13, 0.00]$, ER_-=22.4) indicating that as the randomness of the sequences increased, mind wandering decreased. The effect of the trial-variable was positive ($b = 0.44$ $[0.38, 0.51]$), replicating the well-known time-on-task effect where mind wandering gets more likely later in the task. Finally, the AE$\times$ BV interaction was positive ($b = 0.05$ $[-0.02, 0.12]$, ER_+=7.0), even though its HDI did not exclude zero. The interpretation of this effect is that the positive relationship between BV and mind wandering was stronger for higher values of AE.

In order to establish the robustness of the main effects for AE and BV on mind wandering, we calculated the regression coefficients for all of the tested models, not only the winning one (see Supplemental Figure 2B). The coefficient for AE was negative for all fitted models and the coefficient for BV was positive for all tested models indicating that these effects were robust against analytical choices. We conclude that, in accordance with our predictions, AE and BV were related to MW in opposing ways: While randomness (AE) was increased during on-task relative to periods of mind wandering, BV showed the opposite pattern. In addition, the positive AE $\times$ BV interaction in the model indicates that the the relationship between behavioural variability and mind wandering was particularly strong when entropy was high and executive resources were strongly recruited.

5 Study 3

In study 3, we wanted to investigate whether an optimized HD-tDCS protocol designed for achieving maximal field-strength and focality in the left DLPFC would be able to manipulate mind-wandering propensity in our task. We therefore implemented a protocol similar to that of study 2. The only changes were that the study consisted of two parts using the task from study 2, a baseline task before the brain-stimulation device was turned on and another block while stimulation was ongoing. We implemented a double-blind, sham-controlled design and randomly assigned half of our subjects to a sham and the other half to the real stimulation group. As described in the introduction, we expected mind-wandering propensity to be affected by the brain-stimulation protocol. The directionality of the effect was unclear *a priori* as previous studies found both tDCS-related increases and decreases in mind-wandering propensity.

5.1 Methods

5.1.1 Participants

A total of 60 participants (19 male; age $M = 22.4$ years, SD=2.5 years, range=$[19, 31]$ years) were recruited with flyers on the university campus, on social media networks and by personal contacts. Participants received gift-cards worth 200 Norwegian kroner (approx. 20 EUR) or course credits as compensation for taking part in the study. Inclusion criteria were a signed informed consent-form, aged between 18-50 years, no psychiatric/neurological condition (e.g., depression, bipolar disorder, epilepsy, migraine, severe head trauma, brain surgery) currently or in the past, not under the influence of psychotropic drugs (except caffeine and nicotine), not taking central nervous system medications (e.g., antidepressants, antiepileptic drugs), good or corrected eyesight and that they reported to have slept enough during the preceding night.

5.1.2 Design

In this study, participants completed two sessions of the FT-RSGT with a similar study design as in study 2. The first, “baseline”, session was administered before the stimulation equipment was attached to the scalp and lasted for 10 minutes. The second, “online”, session of the task was completed during active or sham stimulation and lasted for 20 minutes. The inter-stimulus-interval of the metronome tones (440 Hz) was set to 750 ms as in study 2. Approximately every minute (minimally 40 seconds, maximally 80 seconds, uniformly distributed), a thought-probe was presented asking how focused the participant was on the task (1=“completely focused”, 4=“completely unfocused”, 10 and 20 thought-probes in the baseline online sessions, respectively).

The study was double-blind with respect to the brain-stimulation procedure, i.e., neither the experimenter nor the particpants knew whether each participant was assiged to the active or sham stimulation condition. This was ensured using a randomization list assigning each participant a unique code. This code determined whether the stimulation device would output real or sham stimulation by using pre-specified stimulation protocols for each subject-code. In order to assess the efficacy of the blinding, we asked our participants to guess whether they received active or sham stimulation at the end of the experiment.

5.1.3 Brain Stimulation

In order to increase strength and focality of the tDCS intervention, we implemented a 4-by-1 ring arrangement of electrodes located over the left DLPFC. The anode was placed at location F3 and four cathodes were placed in a ring around it (locations C3, T7, FP1 and Fz). This arrangement, when used with a stimulation intensity of 2mA, produces stronger and much more focal electric fields when compared to classical montages (see Figure 3) (Boayue et al., 2019). The used electrodes were PISTIM EEG&tCS Ag/AGCl electrodes (12 mm diameter) powered by a Startstim Neckbox (Startstim tCS, NE Neuroelectrics) and attached to the scalp using an electrode cap and conductive gel.

For comparison, we simulated both our target HD-tDCS setup and the montage used by Axelrod et al. (2015) using a set of publically available, high-resolution, realistic head models of healthy adults (Boayue, Csifcsák, Puonti, Thielscher, & Mittner, 2018). The simulation pipeline was based on the pre-released version of SimNIBS 2.1 (Saturnino et al., 2019). Conductivities for different tissue compartments were set as reported in our previous work (Boayue et al., 2018; Csifcsák et al., 2018): 0.465 S/m (skin), 0.01 S/m (skull), 0.5 S/m (eyeballs), 1.654 S/m (cerebrospinal fluid), 0.275 S/m (gray matter), 0.126 S/m (white matter). For the montage used in Axelrod et al. (2015) and Boayue et al. (2019), individual head models were fitted with electrodes with circular connectors (diameter: 0.5 cm) at the middle of the electrode pads (anode - F3: 4 x 4 cm and cathode - right supraorbital (RSO) area: 7 x 5 cm, both with a thickness of 1mm with 2.5mm sponge pocket). Stimulation intensity was set at 1 mA. For the HD-tDCS montage, electrode thickness was set to 1 mm + 2.5 mm gel thickness (anode: F3, cathodes: C3, T7, Fp1, Fz). Stimulation intensity for the anode was set to 2 mA, with equal distribution of return currents for the 4 cathodes (0.5 mA for each). The electrodes were placed according to the international 10/20 system.

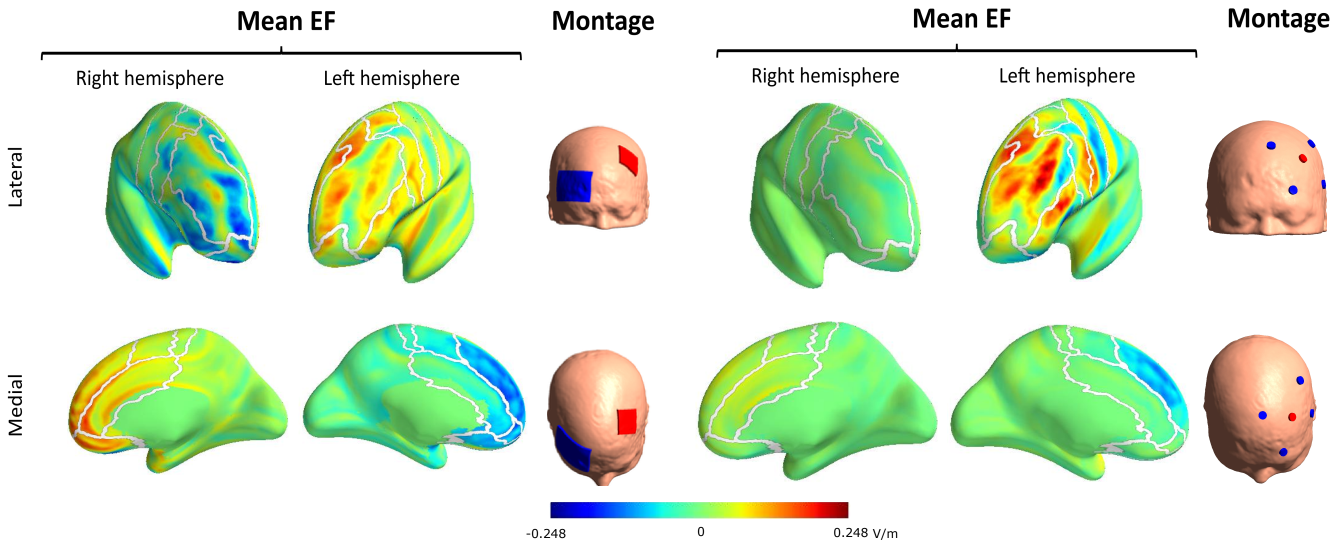

Figure 3. Simulation of the normal component of the electric field induced by Axelrod, Rees, Lavidor, and Bar (2015)'s setup (left) and our new protocol (right) averaged over N=18 individual datasets. While the traditional protocol features a broad and non-focal distribution of the electric field including both strong anodal and cathodal currents across both DLPFCs (left), our HD-tDCS protocol is both stronger and more focal.

We simulated both stimulation protocols for each of the subjects in our reference dataset (Boayue et al., 2018) and extracted the component of the electric field that is perpendicular to the cortical surface (normal component; Csifcsák et al., 2018). This normal component is believed to be the effective component of the E-field and it takes negative values for inward-going (cathodal) currents and positive values for outward-going (anodal) currents. This normal component was then averaged across the individual brains in order to account for inter-individual anatomical variability that has been shown to be an important determinant of the strength of the electric field (Opitz, Paulus, Will, Antunes, & Thielscher, 2015).

5.1.4 Procedure

Data were collected by two experimenters (authors IF and AEV) working together. The maximum total duration of the experiment was 90 minutes. Participants were required to set their mobile phones into flight-mode and to read and sign the informed consent form. Before continuing with the experiment, the experimenters measured the circumference of the head of the participant and selected a stimulation cap of the corresponding size. Using this cap, the locations of the five stimulation electrodes were located on the scalp and marked with a pen. These locations (F3, Fp1, Fz, C3 and T7) where then treated with a local anaesthetic cream (EMLA). During the time the local anesthetic needed to achieve full efficiency (20-30 minutes), subjects received instructions and performed the baseline session of the FT-RSGT (10 minutes).

We collected demographic information (age and sex), occupation as well as degree of experience with any musical instrument, because we assumed that musical training could impact our participants' ability to rhythmically respond to the ongoing metronome in the FT-RSG task. Participants were then presented with the explanation of what constitutes a "random sequence" using the flipping of a coin as an example used in studies 1 and 2. This was followed up by answering any questions the participants might have about randomness in the task. The participants received instructions on the FT-RSGT through the experimental software and then went through a training session that lasted for about 30 seconds. Finally, our subjects filled in a "mini-quiz" where they were asked to answer seven simple questions that were designed to measure whether they had understood the instructions with respect to randomness, mind wandering and the metronome. Wrong answers were followed up on and discussed before the participants were allowed to continue with the baseline session of the task.

After finishing the baseline session, any remaining EMLA cream was removed from the scalp and the electrode-locations cleaned with alcohol. PISTIM EEG&tCS electrodes were placed in positions F3, Fp1, C3, T7 and Fz on the cap and filled with conductive gel (Signa Gel, Parker Laboratories Inc., USA) before the cap was positioned on the participants' head. Next, electrodes where connected to the Startstim Neckbox (Startstim tCS, NE Neuroelectrics) which was fastened to the back of the cap. A connection to the stimulation computer was established through Bluetooth using the NIC software (version 2.0). It was ensured that all electrodes had impedances below 10 kΩ and the exact impedances were recorded for each participant and electrodes. In case one or several electrodes had too high impedances, the experimenters attempted to bring down impedance by pressing down the cap and/or inserting more gel through the top of the electrode. Once electrode preparation was finished, the stimulation protocol on the stimulation PC was activated (either sham or active, depending on the randomized subject-specific protocol used) and the main task started (total duration 20 minutes). After 20 minutes, the stimulation protocol turned off by itself.

After the end of the task, our participants were asked to fill out the Norwegian version of the Mindfulness Awareness Scale (MAAS; Brown & Ryan, 2003). Finally, the stimulation electrodes were removed, our participants interviewed about their experiences during the task and debriefed. All materials used in this study and all raw data are available from our study repository at https://osf.io/nm2sz/.

5.1.5 Pre-Registration

Before conducting the study, we pre-registered the study plan, experimental materials and an analytic strategy targeted towards distinguishing between the executive function (e.g., Smallwood & Schooler, 2006) and the executive failure views (e.g., McVay & Kane, 2010) of mind wandering in a public repository at https://osf.io/4hvdf. This pre-registration does not cover the effect of brain-stimulation on mind wandering presented in the current study and the corresponding analyses are therefore exploratory.

The idea of the pre-registered analysis plan was as follows: The two dominant views of how executive functions are related to mind wandering, the executive function view (EFu; Smallwood & Schooler, 2006) and the executive failure view (EFa; McVay & Kane, 2010) make opposite predictions how an additional availability or shortage of executive resources should impact mind-wandering propensity: While the EFu view posits that an increase in the availability of executive resources should manifest in increased mind wandering, the EFa view predicts the opposite (i.e., fewer mind-wandering episodes). Based on that distinction, we wanted to 1) change the availability of executive resources using brain stimulation and 2) relate that change to increases or decreases in mind-wandering propensity.

When pre-registering these hypotheses we made the overly simplistic assumption that an increase/decrease in the availability of executive resources would directly translate into the randomness of the generated sequences (i.e., either increase or decrease the AE of the generated sequences). We failed to take the possibility into account that additional resources could just as easily be diverted to MW instead of task-performance. As a consequence, our pre-registered analyses hinged completely on the ability of the HD-tDCS protocol to manipulate the AE of the sequences generated during stimulation, i.e., we hypothesized that the group receiving real stimulation should show higher or lower AE than the group receiving sham stimulation during the online sessions. We further constrained that should AE neither be increased nor decreased (i.e., tDCS was ineffective with respect to this measure), all further hypotheses relating to the relationship between MW and AE could not be tested. As reported in the results, tDCS did not change the randomness of the generated sequences and the pre-registered plan is therefore void. For the full set of hypotheses, please refer to the pre-registration document.

5.2 Results and Discussion

5.2.1 Blinding efficacy

In order to check whether blinding was effective, we asked our subjects to guess whether they received active or sham stimulation at the end of the experiment. Of the 30 subjects receiving sham stimulation, 20 guessed incorrectly that they had received active stimulation. Correspondingly, 19 out of 30 subjects receiving real stimulation correctly guessed that they received real stimulation. We calculated contingency table Bayes factors using an independent multinomial sampling plan (Morey & Rouder, 2018) and a prior concentration of $a = 1$ to assess the evidence for the hypothesis that the counts in the contingency table differed substantially. The Bayes-factor provided support for the null-hypothesis that the counts did not differ $\mathrm{BF}_{01} = 3.3$ (traditional χ^2-test: $\chi(1)^2 = 0.00, p = 1$). We conclude that blinding was effective for our novel protocol as opposed to the traditional protocol used in previous studies (Axelrod et al., 2015; Boayue et al., 2019) that has been shown not to be blinded effectively (Turi et al., 2019).

5.2.2 Pre-registered results

Our pre-registered analysis plan required us to first test, with a two-tailed t-test, whether application of the tDCS protocol would change recruitment of executive resources as reflected in the approximate entropy (AE) measure. Since we did not specify whether we would directly compare the groups' AE scores during stimulation or their respective changes from the preceding baseline session, we conducted both of these analyses. The two groups did not differ in the AE scores during stimulation, $\mathrm{BF}_{10} = 0.40$ ($\mathrm{M}_{\mathrm{sham}} = 3.0$, $\mathrm{M}_{\mathrm{real}} = 3.3$, $t(56.7) = 0.99, p = .32$). Neither did the comparison of the change in AE from baseline to stimulation session differ between the two groups, $\mathrm{BF}_{10} = 0.34$ ($\mathrm{M}_{\mathrm{sham}} = -0.26$, $\mathrm{M}_{\mathrm{real}} = -0.07$, $t(56.7) = 0.77, p = .44$).

Since our pre-registered analysis plan clearly specified that the other hypotheses were contingent on a significant difference between the stimulation groups in the AE measure, we did not conduct any of the other pre-registered analyses. However, we conducted further exploratory analyses using ordered probit regression models as described above (Boayue et al., 2019).

5.2.3 Effect of HD-tDCS on mind wandering

To analyze the impact the stimulation had on our participants' rate of mind wandering, we applied hierarchical ordered probit models treating the ordinal responses to the mind-wandering probes as dependent variable and using combinations of the following predictor variables: BV, AE ($m = 2$), trial, part (baseline vs. stimulation), stimulation (sham vs. real) and their interactions. All models had random intercepts per subject and for "part" (baseline vs. online) nested within each participant as each participant went through a baseline and a stimulation session, respectively. In total, 22 models of increasing complexity were tested (see Supplemental Figure 3 for a list).

We used the same model-selection procedure as in study 2. Both the BMA and the LOOIC-procedures agreed on the preferred model, which included main effects for AE, BV, part, stimulation and trial as well as the AE $\times$ BV interaction and the part $\times$ stimulation interaction (BMA: $p_{\text{BMA}} = 0.28$, next best model $p_{\text{BMA}} = 0.17$; LOOIC: $p_{\text{LOO}} = 0.42$, next best model $p_{\text{LOO}} = 0.32$). This last interaction is the crucial measure for how stimulation affected mind wandering: Because every participant went through an identical baseline session, the effect of stimulation should not manifest in a main effect of stimulation (which averages across baseline and stimulation sessions) but in a part $\times$ stimulation interaction which describes the differences in how participants' mind wandering changed from baseline to stimulation session separately for the sham and the real stimulation groups.

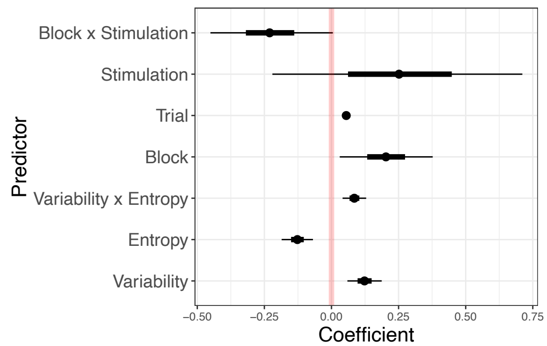

Figure 4. Model-coefficients of the winning model for study 3.

The winning model had a Bayesian R^2 (Gelman et al., 2019) of $R^2 = 0.44$ $[0.41, 0.46]$, see figure 4. As in study 2, the effect of BV was positive ($b = 0.12$ $[0.05, 0.20]$, $\text{ER}_+ = 799$) indicating that sequences just before mind-wandering had higher BV relative to those before probes that were responded to as "on-task". Similar to study 2, we found the opposite effect for AE ($b = -0.13$ $[-0.20, -0.06]$, $\text{ER}_- = 15999$), i.e., that sequences preceding mind-wandering probes were more random. We also replicated the positive interaction of AE and BV, $b = 0.09$ $[0.03, 0.14]$, $\text{ER}_+ = 799$ indicating that high BV is predictive of mind wandering when AE is increased, but less so when executive performance is compromised. Also as expected, we found clear time-on-task effects both between the two sessions (baseline vs. stimulation, $b = 0.20$ $[0.00, 0.41]$, $\text{ER}_+ = 33.2$) and within each of the sessions (trial: $b = 0.06$ $[0.04, 0.07]$, $\text{ER}_+ = \infty$). Furthermore, we found an inconclusive main effect of real vs. sham stimulation, $b = 0.25$ $[-0.32, 0.81]$, $\text{ER}_+ = 4.3$. Finally, the crucial part $\times$ stimulation effect was negative $b = -0.23$ $[-0.50, 0.05]$, $\text{ER}_- = 17.4$ indicating that mind wandering was reduced in the real relative to the sham stimulation group during the active stimulation session.

The main finding of this study was a relative reduction of self-reported mind-wandering during the stimulation block when comparing active to sham HD-tDCS. In order to test the robustness of this effect of tDCS on mind-wandering propensity, we calculated the regression coefficient for each of the 22 tested models that included the part $\times$ stimulation condition (a total of 12 models; see Supplemental Figure 4). For all models, the effect was negative with evidence-ratios ranging from 2.9 to 20.2 (mean $\text{ER}_- = 14.6$) indicating its robustness against analytical degrees of freedom.

6 Summary and Discussion

In a series of three studies, we developed a fast-paced experimental paradigm that allows the study of the dynamic interplay of mind wandering, executive control and behavioural variability within the course of an experimental session. We could show that our novel task is related to measures of executive control and that the extracted measures of approximate entropy and behavioural variability show the expected relationship to mind wandering propensity. In particular, in agreement with previous findings using different methods, behavioural variability was increased and randomness (indicating employment of executive resources) was decreased during periods of mind wandering relative to periods of focused attention (Seli et al., 2013; Teasdale et al., 1995).

Furthermore, we found evidence for the effectiveness of our HD-tDCS stimulation montage optimized to focally stimulate the left DLPFC, a region involved in the control of executive resources, in decreasing the propensity of mind wandering. In particular, subjects stimulated with real HD-tDCS reported lower mind wandering scores during stimulation than the group receiving sham stimulation. From a theoretical perspective, this result is inconclusive with respect to determining how DLPFC stimulation affected executive resources. Assuming that mind-wandering and the generation of random sequences both drew on the same executive resources, we might infer from the result that mind-wandering was decreased while entropy was unchanged as indicating that the available of executive resources was *reduced* relative to sham: Participants might simply not have had enough resources to mind-wander as much while ensuring high entropy of the generated sequences. On the other hand, we could just as well argue that reduced mind-wandering is in itself a feat of *improved* executive control as subjects were better able to keep their task-focus when receiving real stimulation. In that case, the failure to observe improved entropy could be a measurement problem. Both of these interprations seem equally plausible and we have to postpone a conclusion to future studies designed to distinguish between the opposing interpretations.

However, we acknowledge that our analysis purporting to [decreased MW during stimulation of the DLPFC] were not pre-registered and we therefore have to concur with our previous evaluation that "[...] it is important to replicate any [...] positive effects [of tDCS on mind wandering] before accepting them as facts" (Boayue et al., 2019). Pending the results of a high-powered, pre-registered study currently in progress in our group, the results reported here should therefore be taken as an encouraging but not definite finding that mind wandering can be decreased with HD-tDCS over the left DLPFC. Should the result prove to be replicable in a pre-registered study design, our finding could open up exciting possibilities for the treatment of psychiatric conditions that are characterized by maladaptive mind wandering (e.g., depression or ADHD; Hoffmann et al., 2016; Seli, Smallwood, et al., 2015; Van den Driessche et al., 2017).

The finding of reduced mind wandering during anodal tDCS above the left DLPFC might seem to be a surprising result, given previous work either pointing towards an effect in the opposite direction (Axelrod et al., 2015; Axelrod et al., 2018) or reporting a null-finding (Boayue et al., 2019). However, these studies applied less focal bipolar tDCS montages with the return electrode placed above the contralateral (right) supraorbital area, most likely resulting in strong stimulation-induced electric fields outside the target region, including medial prefrontal structures (see Figure 3). Therefore, tDCS protocols with bipolar electrode placement could have inadvertently modulated activity in the default-mode network (DMN; Andrews-Hanna, Reidler, Sepulcre, Poulin, & Buckner, 2010) via medial prefrontal stimulation, confounding the putative causal link between left DLPFC activity and the occurrence of task-unrelated thoughts. In this respect, our study provides more straightforward evidence for the involvement of the left DLPFC in the onset of mind-wandering episodes because the DLPFC was stimulated more focally. However, since we did not include an active control stimulation, it is still possible that other stimulation-related variables rather than stimulation of DLPFC directly may be responsible for the observed effects. A further difference between our current and previous protocols in the study of MW is an increase in total current stimulating the target area. Nonlinear effects of stimulation intensities on observed behaviour are not uncommon (Batsikadze, Moliadze, Paulus, Kuo, & Nitsche, 2013) and can be part of the explanation for our divergent results.

Since the DLPFC is a key hub in the frontoparietal control network (FPCN; Christoff et al., 2016), we anticipated that active tDCS would also influence executive performance in our task, and thus, enable the distinction between EFa vs. EFu theories of mind wandering. Even though the AE measure was not influenced by tDCS in our study, reduced mind-wandering propensity together with unchanged performance in the real stimulation group provides some support for the EFa view. Here, we speculate that improved executive control via anodal tDCS could have prevented involuntary shifts of attention towards mind wandering, while maintaining randomness of movement sequences. This outcome is incompatible with the EFu view, because if mind wandering and executive performance share resources, tDCS-associated enhancement in FPCN activity would have resulted in more task-unrelated thoughts without hindering task performance.

We also found evidence for an interaction between behavioural variability and entropy when predicting mind wandering. The interpretation of this novel finding is that the positive relationship between behavioural variability and mind wandering was strongest when approximate entropy (executive control) was also high and weaker in periods of low executive control. This finding resonates well with theories describing the dynamical evolution of mind wandering: When entropy is high, executive resources are being used to produce high-entropy sequences – in other words, subjects are concentrating on the task and perform well on it. An increase in BV is sensitive indicator of subjects losing their attentional focus (Seli et al., 2013) and can be seen as an early sign of a departure from a full task-focus and can occur with only minor or even no deterioration of task performance otherwise ("tuning out"; Cheyne et al., 2009; Smallwood et al., 2007). However, even these initial and often brief departures from focused processing are usually accessible to introspection (Seli, Jonker, Cheyne, Cortes, & Smilek, 2015; Cheyne et al., 2009), hence we can expect a strong relationship between BV and self-reported mind wandering when AE is high. Values of sequence-entropy at the lower-end of the scale, however, might signal a more severe disconnection from the ongoing task ("zoning out"). In this state, subjects are hypothesized to be actively engaged in mind wandering (i.e., following task-unrelated trains of thoughts) which would be reflected in severely decreased performance measured in both behavioural variability and entropy and a weaker relationship between behavioural variability and mind wandering. In fact, it is even possible that behavioural variability could decrease in such a deeper state of mind wandering (resulting in a reversal of the BV–MW relationship) given that this state is governed by "autopilot"-like behaviour (Hawkins, Mittner, Forstmann, & Heathcote, 2019). This novel effect could only be studied because of our innovative design that allows to simultaneous assess the dynamic allocation of executive control and behavioural variability and it provides exciting opportunities for further investigations.

Speculatively, the finding that AE and BV interact in predicting mind wandering may point towards the existence of distinct types of mind wandering as proposed by Mittner et al. (2016). These authors propose on neural grounds that there should be at least two different mental states when losing focus from the ongoing task. The first of these states, labeled “off-focus”, is supposedly characterized by its transient and subconscious nature. In this state, the narrow focus of attention applied to the current task is periodically broaded to allow the consideration of alternative behaviours, such as mind wandering. The off-focus state has been characterised as “explorative” in the sense that it allows to explore whether redirecting attention to other cognitive processes may be beneficial in the current situation. From that off-focus state, attention can be redirected into a full-blown mind wandering state. Compared to the transient off-focus state in which task-performance can be relatively unaffected, performance in full mind wandering is more severely impacted. Crucially, similar to the distinction between an initial “tuning-out” and a full “zoning-out” (Cheyne et al., 2009), that model describes the dynamical switching between on-task and mind wandering to be governed by the transition throught the off-focus state in a bi-directional way.

Our results can be interpreted in the framework of this model as follows: In the off-focus state, behavioural variability is increased relative to the on-task state but executive resources are still being fully allocated to the task at hand and the entropy of the sequences is therefore not impaired. We therefore find a regime in which there is a strong relationship between BV and mind wandering while AE is high (transition between on-task and off-focus states). During full mind wandering, on the other hand, executive resources are allocated to following internal trains of thoughts and hence the entropy of the generated sequences is reduced. In this state, BV is also generally increased but the transition between mind wandering and off-focus states is not characterized by changes in BV as performance is largely determined by autopilot-like behaviour.

Of course, without direct access to neural sources of information, this argument remains speculative. Future studies could therefore focus on bringing the reported experimental paradigm into an fMRI setting. Technically, employing the task in an fMRI design is not too challenging as the task was already designed to conform to standard fMRI requirements. For example, the reduced number of possible digits from nine to two allows to use the task with just two response-buttons commonly available in fMRI settings. Studying these effects in the fMRI has several benefits: First, the availability of brain contrasts can be used to validate the assumption that executive resources are increasingly being employed when sequences are more random by investigating whether brain regions involved in executive control show increased activity. Second, the brain signature of the proposed three-state configuration of mind states can be investigated directly. The neural model of mind wandering makes concrete assumptions about how various fMRI measures should change across the three states (Mittner et al., 2016). Identifying the three states using the behavioural signature developed in the current study therefore allows to directly validate whether these states conform to the predictions made by this model. For example, dynamic functional connectivity (Thompson et al., 2013) would be expected to be stronger in the off-focus state compared to both on-task and mind wandering and different subnetworks of the DMN should show distinct activity patterns. As such, this approach could contribute to our understanding of the neural signature of mind wandering.

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Data availability statement

All materials used in this study and all raw data are available from our study repository at https://osf.io/nm2sz/.

Author contributions statement

NB: designed study, analysed data, drafted paper; GC: designed study, commented on paper draft; IK: contributed to study design, collected data, commented on paper draft; CS: contributed to study design, collected data, commented on paper draft; IS: contributed to study design, collected data, commented on paper draft; AV: contributed to study design, collected data, commented on paper draft; MM: designed study, analysed data, drafted paper, funding;

Conflict of interest statement

The authors declare no conflict of interest.

List of abbreviations

MW mind wandering

BV behavioural variability

AE approximate entropy

EFa executive failure

EFu executive function

BF Bayes Factor

HDI Highest-density interval

HMC Hamiltonian Monte-Carlo

ER evidence ratio

LOOIC leave-one-out cross-validation information criterion

DLPFC dorso-lateral prefrontal cortex

fMRI functional magnetic resonance imaging

DMN default-mode network

FPCN frontoparietal control network

tDCS transcranial direct-current stimulation

HD-tDCS high-definition tDCS

RNGT random number generation task

FT-RSGT finger tapping random-sequence generation task

MRT metronome response task

SART Sustained Attention to Response Task

ISI inter-stimulus interval

ITI inter-tap interval

MAAS Mindfulness Awareness Scale

EF electric field