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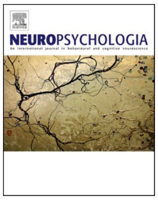

Increasing mind wandering with accelerated intermittent theta burst stimulation over the left dorsolateral prefrontal cortex

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A R T I C L E I N F O

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A B S T R A C T

Mind wandering (MW) is the intentional or unintentional experience of attending to internal task-unrelated thoughts while being occupied with an external task. Even though maintaining task focus is assumed to require executive functions (EF), it is not clear how and to what extent MW and EF interact. Research has found that activity in the dorsolateral prefrontal cortex (DLPFC) is associated with EF and MW. To understand the causal role of the DLPFC in relation to MW and EF, researchers have turned to non-invasive brain stimulation. Thus far, most studies have used transcranial direct current stimulation, but the results have been inconclusive. To further elucidate the relationship between the DLPFC, EF and MW, we conducted a pre-registered, sham-controlled, triple-blinded within-subject experiment by combining intermittent theta burst stimulation (iTBS) interleaved with a recently developed MW-EF task. In contrast to our expectations, participants reported significantly more MW following real iTBS as compared to sham stimulation. However, at the same time, psychomotor precision and EF improved, indicating that participants were able to engage in resource-intensive MW while simultaneously performing well on the task. We argue that iTBS enhanced the underlying executive resources that could be used to increase both MW and task performance in line with the resource-control view of MW. This finding opens exciting avenues for studying the complex interplay between MW and EF and provides empirical support for the utility of iTBS in improving executive performance during a demanding cognitive task.

Mind wandering (MW) is a mental state in which humans engage in internally generated thoughts that are unrelated to the current task (Smallwood and Schooler, 2015). For instance, while you are driving home from work, you might find yourself starting to think about plans for the weekend or which meal you are going to prepare for dinner. Despite being engaged in the largely automatized activity of driving, your conscious thoughts are not related to the current activity. Research indicates that MW is a pervasive phenomenon, accounting for between 25 and 50 percent of our waking life (Killingsworth and Gilbert, 2010). Still, MW is typically associated with reduced performance on most cognitive tasks (Alexandersen et al., 2022; Groot et al., 2021; Smallwood and Schooler, 2015; but see Vékony et al., 2023). Critically, MW can be dangerous during tasks such as driving because it interferes with maintaining attention to rarely occurring but critical events (Yanko and Spalek, 2013, 2014). These insights prompted enquiries into the relationship between MW and executive functioning (EF).

Some researchers have theorized that MW occurs due to a failure of EF to maintain task focus and to prevent engagement in MW (executive failure account; McVay and Kane, 2010). Other researchers (Smallwood and Schooler, 2006) have posited that MW might rather rely on the same underlying executive resources as the primary task, implying a continuous balance of whether to engage in the primary task or MW (executive use account). Both theories predict less MW with increasing task demands (Seli et al., 2018b). However, the two theories predict opposite effects on MW regarding changes in EF: If more executive resources are available, the executive use theory would predict MW to increase, while the executive failure theory would predict MW to decrease, as more resources are available to prevent MW from intruding. One possibility to disambiguate between these theories is the application of non-invasive brain stimulation (NIBS) to modulate EF.

Studies employing NIBS in the field of MW have typically applied transcranial direct current stimulation (tDCS) over the prefrontal cortex (PFC). The main motivation to target prefrontal areas and particularly the dorsolateral PFC (DLPFC) is its known relation to executive functions (e.g., Cole et al., 2010; Mansouri et al., 2009) and its involvement in MW (Christoff et al., 2009; Fox et al., 2015; Groot et al., 2021). However, a

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recent meta-analysis aggregating the results from the existing literature concluded that tDCS over the DLPFC does not seem powerful enough to reliably influence MW (Nawani et al., 2023). A key reason for the lack of a consistent effect of tDCS on MW may be its low intensity (Guidetti et al., 2022) and lack of focality (Boayue et al., 2018). Here, we used repetitive transcranial magnetic stimulation (rTMS), which is a stimulation method that induces a strong peak electric field (~100 m V/mm; Turi et al., 2021) in a more focal manner compared to tDCS (Priori et al., 2009; Rossini et al., 2015). These features make rTMS a more suitable method to investigate the causal relationship between activity in the left DLPFC, EF performance and MW propensity. We implemented intermittent theta burst stimulation (iTBS), which has been found to increase neural excitability (Huang et al., 2005; Klimesch et al., 2003; Li et al., 2017) and improve cognitive performance (Wu et al., 2021; Xu et al., 2023) in a manner that may accumulate over several stimulation rounds (Tse et al., 2018; Yu et al., 2020).

To investigate the relationship between EF and MW, the cognitive task must reliably draw on executive functions. However, the vast majority of research on MW has used the sustained attention to response task (SART; Robertson et al., 1997), which is a low-demand, monotonous and repetitive task requiring response inhibition to rarely occurring cues. These features of the SART can foster MW, which is typically measured by so-called thought probes, i.e., brief questions enquiring the attentional state of the participants presented throughout the experiment. However, due to the low EF demand of the SART, it may not be suitable to investigate the relationship between MW and EF. Therefore, Boayue et al. (2020) created the finger-tapping random sequence generation task (FT-RSGT) that strongly relies on EF while being monotonous and repetitive. In the FT-RSGT, participants respond to a rhythmic metronome, which enables measuring behavioural variability (BV), a behavioural marker sensitive to fluctuations of attention (Kucyi et al., 2016; McVay and Kane, 2012; Seli et al., 2013). Moreover, participants are required to generate random sequences of left and right taps, which draws heavily on EF (Baddeley et al., 1998) and is sensitive to stimulus-independent thoughts (Teasdale et al., 1995). Thus, the FT-RSGT enables the measurement of EF while retaining features that foster MW, which is necessary to investigate the relationship between MW and EF.

Based on the above, we hypothesized that iTBS targeting the left DLPFC would decrease MW relative to sham stimulation, while improving performance as measured by randomness of the tapping sequences and BV. The rationale behind this hypothesis was that, in line with the executive failure account of MW, we expected real stimulation to enhance the availability of executive resources, which, in turn, would allow for more effective shielding of task-focus.

1. Method

1.1. Study design

The experiment has been approved by the regional ethical committee in Norway (REK #285811). Our study was pre-registered at OSF (https://osf.io/2g8nz) and the data and all study materials are publicly available (https://osf.io/txpu2/). We implemented an accelerated, offline iTBS procedure interleaved with blocks of the FT-RSGT. The design was a triple-blinded sham-controlled 2 (stimulation session: sham vs. real) x 4 (blocks: B0-B3) within-subject (crossover) design (see Fig. 1a).

1.2. Participants

We pre-registered a sample size of 40 participants, powered to find a small-to-medium effect size of $\eta^2 = 0.044$, with 80% power at $\alpha = .05$. We recruited 46 right-handed, rTMS-naïve participants in Tromsø, Norway between March 2022 and May 2023. All participants were informed about the experiment and gave written consent before joining. Two participants had to be replaced due to not following the protocol. Four participants dropped out at the familiarization stage due to discomfort with the stimulation protocol. This left us with a final sample of 40 participants (25 females) with an average age of 23.3 years (SD = 3.29). Participants were compensated for their time with a gift card of 500 NOK (approximately 50 Euros) at a local mall. Participants had to be 18–50 years old, right-handed, no previous or current psychiatric/neurological disorder and no first degree relative with epilepsy (see Supplemental Methods for more details).

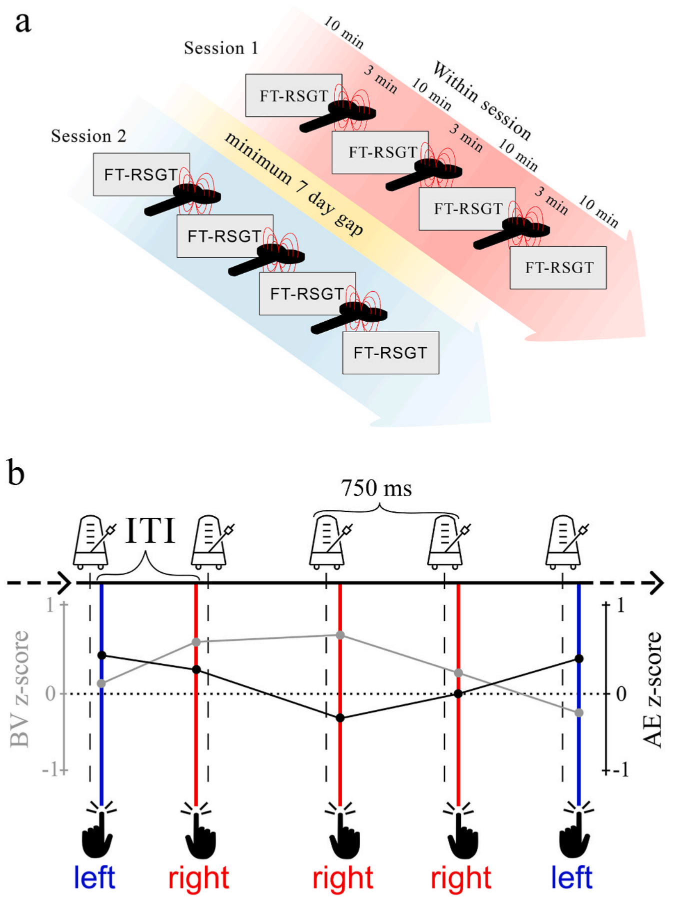

Fig. 1. Overview of the experimental procedure and the finger tapping random sequence generation task.
Note: (a) Overview of the experimental procedure. (b) Schematic overview of how the behavioural indices, approximate entropy (AE) and behavioural variability (BV), are tracked through the finger-tapping random sequence generation task (Figure by Aasen, S. R., 2024; available at https://doi.org/10.6084/m9.figshare.25471960.v1 under the CC-BY 4.0 licence). ITI = inter-tap-interval.

1.3. The FT-RSGT

The task required the participants to generate a random sequence of taps using their two index fingers, while closely matching the beat of a metronome (beeps at 440 Hz presented for 75 ms with an inter-stimulus interval of 750 ms; see Fig. 1b). Each block of the FT-RSGT lasted approximately 10 min, contained 11 pseudo-randomly presented thought-probes prompted every minute on average (randomly between 40 and 80 s). At each probe, participants had to answer three consecutive questions, which were always presented in the same order; the first related to the participant's general attention: "To what degree were you focused on the task right before this question?", answered on a 1–4 Likert scale (1: not at all focused; 4: completely task focused). The other two questions related to the content of thought and intention of participants (these are not further analysed here, see Supplemental Methods and Results).

BV was calculated by taking the standard deviation of the inter-tap intervals of the last 25 taps preceding each thought-probe, which was log-transformed and z-scored (using the grand mean and standard-deviation across all subjects and sessions). Approximate entropy (AE; Pincus and Kalman, 1997) is a measure of sequence irregularity that estimates the probability that similar subsequence's of a length $m = 2$, when augmented by one position, will remain similar. This statistic was calculated over the 25 taps preceding each probe. The raw AE value was transformed according to $-\log\left(\log(2) - AE\right)$ to and z-transformed using the grand mean and standard deviation (Boayue et al., 2020).

1.4. *iTBS protocol*

The iTBS protocol consisted of 50 Hz bursts of three TMS pulses, repeated at 5 Hz for 2 s and followed by a break of 8 s. This sequence was repeated 20 times, resulting in a total of 600 pulses (total duration approximately 3 min; Fig. 2a). We used a MAG & More PowerMAG lab 100 with the Double coil PMD70-pCool active coil and the Double coil PMD70-pCool-Sham sham coil (MAG & More GmbH, Germany). To target the left DLPFC, we used a Localite TMS Navigator system (version 3.0.72; Localite GmbH, Germany). No individualized magnetic resonance imaging (MRI) scans were collected, and therefore, we relied on the MNI template brain co-registered to our participants' head anatomy. The coil was positioned at a 45° angle in posterior-lateral orientation relative to the midline. The stimulation protocol resulted in an electric field that was focused on the left lateral prefrontal cortex (Fig. 2b).

1.5. *Procedure*

We equipped participants' right hands with three Ag/AgCl electrodes: The ground was placed on the dorsum of the hand, the reference was placed on the lateral surface of the proximal interphalangeal joint of the 5th finger, while the active electrode was placed on the abductor digiti minimi muscle. The electrodes were connected to a Brain Vision V-amp 8 digital DC amplifier (Brain Vision, LLC, the United States).[1] Participants' heads were co-registered to the MNI anatomy, and we continued with determining the resting motor threshold (RMT). We navigated to the predetermined MNI coordinate corresponding to the primary motor cortex ($x = -40$, $y = -20$, $z = 52$) and started the hotspot hunting followed by determination of the motor threshold. Participants then proceeded with the first round of the FT-RSGT (baseline, B0), while experimenters set up the blinding procedure that ensured that the experimenter was unaware of the coil used for stimulation. In both sessions (conducted on two different visits), real or sham iTBS was delivered 3 times at 80 % RMT (Fig. 1a). To target the DLPFC ($x = -44.23$, $y = 29.48$, $z = 21.62$) we used the Localite neuronavigator. Before the first stimulation round, participants were familiarized with a 1-s sequence of the stimulation procedure. After the last task-block, participants answered general questions regarding the experiment, questions regarding the efficacy of the blinding procedure, and a TMS checklist about possible side effects (Brunoni et al., 2011). In total, each session lasted approximately 2 h (see Supplemental Methods for details).

1.6. *Statistical analysis*

Our main analysis complied with our pre-registered protocol (OSF; https://osf.io/2g8nz). We conducted 3 separate 2x4 repeated measures analysis of variance (rmANOVA) tests, with dependent variables MW (i.e., answers to the first probe question about being on-task or engaged in MW), BV and AE, and within-subject factors Stimulation (real vs. sham) and Block (B0, B1, B2, B3). Efficacy of the blinding protocol was assessed with nonparametric tests, separately for participants' and researchers' guesses at each session.

1.6.1. *Bayesian exploratory analysis*

In addition to our pre-registered models, we also carried out a set of more targeted analyses that included the important task-on-time effect and provided a more detailed view on the temporal evolution of EF, BV and MW with task progress in the real vs. sham iTBS conditions. These analyses were not pre-registered and should therefore be considered as exploratory, even though the hypotheses being tested remain pre-registered.

Utilizing standard linear modelling for ordinal data poses several issues (Boayue et al., 2019; Liddell and Kruschke, 2018), and to address these concerns we used ordinal regression models implemented in a hierarchical Bayesian framework. More specifically, we used a Bayesian ordinal probit model (Bürkner and Vuorre, 2019), that has already been used successfully to analyse changes in MW following NIBS (Alexandersen et al., 2022; Boayue et al., 2019, 2020). Furthermore, we report two additional analyses where AE and BV served as the dependent variables in hierarchical Bayesian linear regression models, set to evaluate changes in these two behaviour measures following real vs. sham iTBS.

We estimated the effects of the predictors Trial number (z-transformed), Block (B0, B1, B2, B3) and Stimulation (sham vs. real) on self-reported MW and the behavioural indices AE and BV. We used Hamiltonian Monte-Carlo algorithms implemented in the Stan software (Stan Development Team, 2024; via package cmdstanr; Gabry et al., 2023) to sample from 6 parallel chains with 3000 samples each, discarding the first 1500 samples of each chain. Convergence of all models was confirmed visually and all $\widehat{R}$-values were confirmed to be lower than 1.05. We used the default priors implemented in the brms-package (Bürkner, 2017) that are non-informative for coefficients corresponding to fixed effects and weakly informative for the intercept and standard-deviation parameters (Student-t prior with 3 df, mean = 0 and SD = 2.5). For each coefficient, we report its posterior mean b and 95% highest-density interval (HDI). In addition, for directed effects, we report the probability of the effect to be positive (p^+) or negative (p^-) as well as the evidence ratio for a positive (ER^+) or negative effect (ER^-). The ER quantifies how much more likely the effect is to be in the expected compared to the opposite direction. Additionally, based on these models, we calculated the effect of repeating the stimulation 3 times per session (i.e., whether there was evidence for effect accumulation) by comparing the sham vs. real stimulation effect of each block to the previous block.

2. Results

2.1. *Blinding efficacy and side effects of the stimulation*

Regarding the blinding (Table S2, Table S3), neither the participants ($X^2(1, N = 20) = 0.1$, $p = .747$, $BF_{10} = 0.66$) nor the researchers ($X^2(1, N = 20) = 0$, $p > .999$, $BF_{10} = 0.57$) managed to guess the stimulation in session 1 above chance level. Similar results were obtained in session 2 (participants: $X^2(1, N = 20) = 0$, $p > .999$, $BF_{10} = 0.56$; researchers: $X^2(1, N = 20) = 0.9$, $p = .343$, $BF_{10} = 1.18$), indicating successful blinding of both participants and experimenters. Participants reported very few side effects (Supplementary Results; Table S6 and Fig. S1), and only "trouble concentrating" was elevated for real stimulation relative to sham stimulation ($M = 0.33$, $t(39) = -2.48$, $p = .018$, $BF_{10} = 2.56$)

2.2. *Pre-registered analyses*

The pre-registered rmANOVA for MW indicated a significant main effect of Block ($F(3,117) = 2.91$, $p = .037$, $\eta_p^2 = 0.07$) and Stimulation (F

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[1] Approximately half-way through data collection, the V-amp device malfunctioned, and we replaced it with a Brain Vision Quickamp (Brain Vision, LLC, the United States).

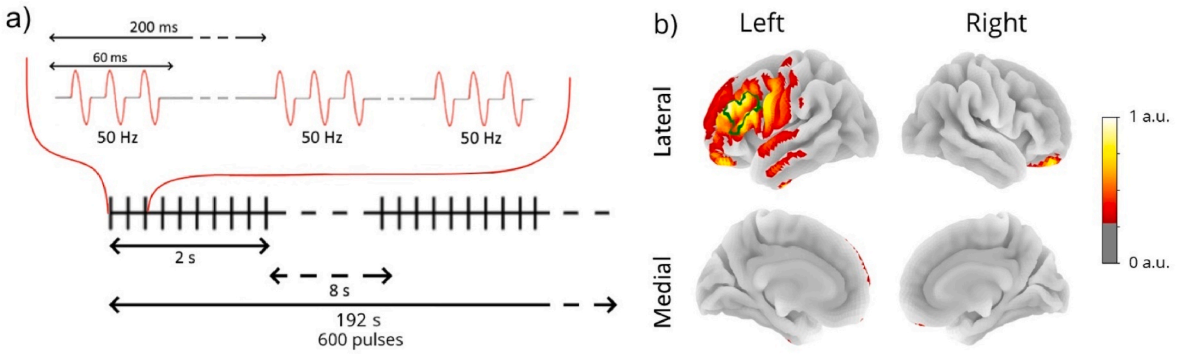

Fig. 2. Simulation of stimulation intensity over the left dorsolateral prefrontal cortex and the intermittent theta burst stimulation protocol.
Note. (a) Visual overview of the intermittent theta burst stimulation protocol. (b) Simulation of the electric field generated (Supplemental Methods) by the stimulation, created using simNIBS (Saturnino et al., 2019). Figure by Aasen, S. R., 2024; available at https://doi.org/10.6084/m9.figshare.25472026.v1 under the CC-BY 4.0 licence.

$(1,39) = 4.79$, $p = .035$, $\eta_p^2 = 0.11$), but no interaction ($F(3,117) = 1.1$, $p = .353$, $\eta_p^2 = 0.03$), suggesting that MW increased over blocks and also increased with real stimulation. The corresponding analysis for BV did not reveal a main effect of Block ($F(3,117) = 1.59$, $p = .195$, $\eta_p^2 = 0.04$), Stimulation ($F(1,39) = 1.3$, $p = .29$, $\eta_p^2 = 0.03$), or an interaction ($F(3,117) = 1.01$, $p = .389$, $\eta_p^2 = 0.03$). Regarding executive control (i.e., the AE measure), we found a significant main effect of Block ($F(3,117) = 4.57$, $p = .005$, $\eta_p^2 = 0.10$), but no main effect of Stimulation ($F(1,39) = 0.49$, $p = .487$, $\eta_p^2 = 0.01$) or an interaction ($F(3,117) = 0.62$, $p = .601$, $\eta_p^2 = 0.02$), suggesting that AE generally decreased over blocks (see Table S1). In accordance with our pre-registration protocol, we did no follow-up analyses as the interactions in these rmANOVAs were not significant.

2.3. Exploratory analyses

2.3.1. Effects of stimulation on MW

Results of the Bayesian ordered probit model for MW (see Table S9) indicate that MW increased within blocks as a function of Trial ($b = 0.20, [0.17, 0.24], p^+ = 1.00, \mathrm{ER}^+ = \infty$). Compared to baseline (B0), in the sham condition, MW was not changed in the first block (B0 to B1: $b = 0.02, [-0.12, 0.17], p^+ = .614, \mathrm{ER}^+ = 1.59$), but there is some evidence suggesting that MW increased in the second block (B0 to B2: $b = 0.12, [-0.03, 0.27], p^+ = .947, \mathrm{ER}^+ = 17.9$). This increase returned to baseline levels in the third block (B0 to B3: $b = 0.03, [-0.11, 0.18], p^+ = .671, \mathrm{ER}^+ = 2.04$). Compared to sham stimulation, some evidence suggests that real stimulation increased MW in the first (stimulation × B1: $b = 0.14, [-0.07, 0.34], p^+ = .901, \mathrm{ER}^+ = 9.07$), the second (stimulation × B2: $b = 0.21, [-0.01, 0.4], p^+ = .973, \mathrm{ER}^+ = 36.5$), and the third block (stimulation × B3: $b = 0.16, [-0.04, 0.36], p^+ = .932, \mathrm{ER}^+ = 13.7$), see Fig. 3a.

2.3.2. Effects of stimulation on task performance

In terms of the performance indices, BV increased over time within blocks ($b = 0.11, [0.08, 0.13], p^+ = 1.00, \mathrm{ER}^+ = \infty$; see Table S10 for all regression coefficients). Compared to baseline (B0), in the sham condition, BV did not appear to change in the first block (B0 to B1: $b = 0, [-0.11, 0.1], p^+ = .48, \mathrm{ER}^+ = 0.92$), but evidence was found for an increase

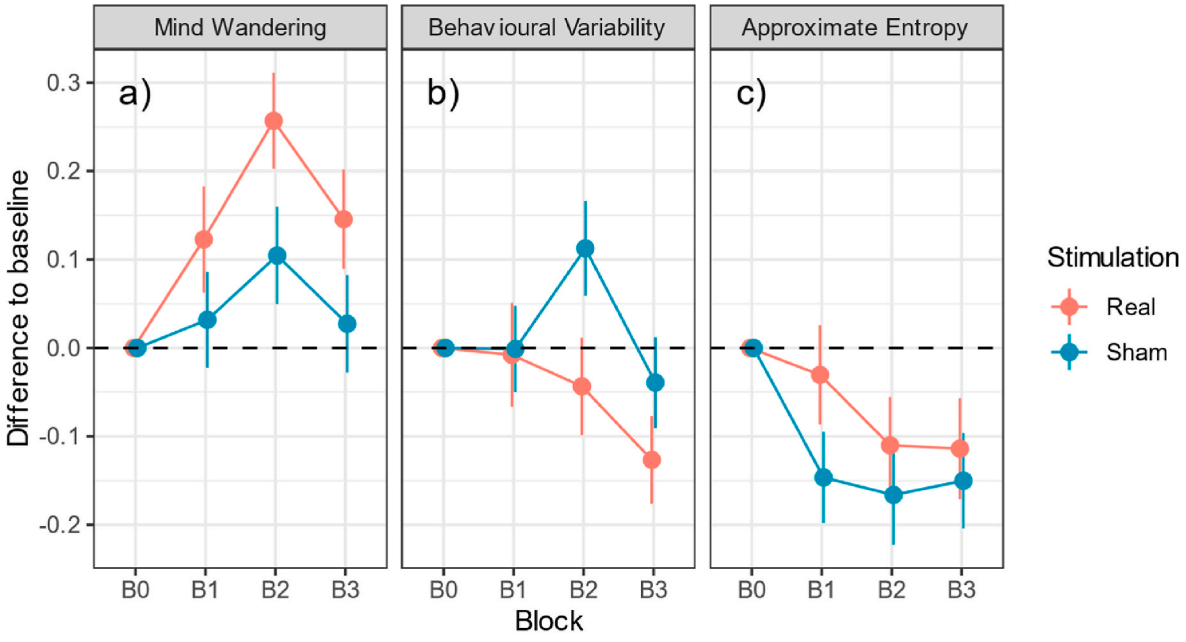

Fig. 3. Mind wandering, approximate entropy and behavioural variability over block and stimulation.
Note. Error bars represent standard error of the mean. Figure by Aasen, S. R., 2024; available at https://doi.org/10.6084/m9.figshare.25472137.v1 under the CC-BY 4.0 license.

in the second block (B0 to B2, $b = 0.11, [0.01, 0.23], p^{+} = .975, \mathrm{ER}^{+} = 38.6$). This increase returned to baseline levels in the last block ($b = -0.04, [-0.15, 0.07], p^{-} = .765, \mathrm{ER}^{-} = 3.26$). Compared to the sham stimulation, real stimulation did not influence BV in the first block (stimulation × B1: $b = 0, [-0.16, 0.15], p^{-} = .525, \mathrm{ER}^{-} = 1.11$), but evidence was found for a decrease in the second block (stimulation × B2: $b = -0.15, [-0.31, 0], p^{-} = .975, \mathrm{ER}^{-} = 39.4$). This decrease returned to baseline levels in the third block (stimulation × B3: $b = -0.09, [-0.24, 0.06], p^{-} = .865, \mathrm{ER}^{-} = 6.43$), see Fig. 3b.

Regarding the entropy of the tap sequences, AE did not show a clear relationship with trial ($b = 0.01, [-0.02, 0.04], p^{+} = 0.79, \mathrm{ER}^{+} = 3.67$). Compared to baseline, in the sham stimulation, AE was reduced in the first (B1: $b = -0.14, [-0.25, -0.03], p^{-} = .995, \mathrm{ER}^{-} = 199$), the second (B2: $b = -0.17, [-0.27, -0.06], p^{-} = .998, \mathrm{ER}^{-} = 599$), and the third block (B3: $b = -0.15, [-0.26, -0.04], p^{-} = .997, \mathrm{ER}^{-} = 359$). Compared to the sham stimulation, some evidence suggests that real stimulation increased AE in the first block (stimulation × B1: $b = 0.11, [-0.04, 0.28], p^{+} = .921, \mathrm{ER}^{+} = 11.6$), but this increase returned to baseline levels in the second (stimulation × B2: $b = 0.05, [-0.1, 0.21], p^{+} = .753, \mathrm{ER}^{+} = 3.04$) and third blocks (stimulation × B3: $b = 0.03, [-0.12, 0.18], p^{+} = .666, \mathrm{ER}^{+} = 2$), see Fig. 3c.

2.3.3. *Accumulating effect of the iTBS protocol*

We did not find strong evidence that the effect of stimulation on MW accumulated in the second (B2-B1: $b = 0.07, [-0.13, 0.27], p^{+} = .745, \mathrm{ER}^{+} = 2.92$) or third (B3-B2: $b = -0.05, [-0.25, 0.15], p^{-} = .683, \mathrm{ER}^{-} = 2.15$) block. However, for BV, we found evidence that the effect accumulated in the second block (B2-B1: $b = -0.15, [-0.30, 0.01], p^{-} = .970, \mathrm{ER}^{-} = 32.6$) but not in the third block (B3-B2: $b = 0.07, [-0.09, 0.22], p^{+} = .806, \mathrm{ER}^{+} = 4.16$). As for AE, we did not observe any accumulating effects for either the second (B2-B1: $b = -0.06, [-0.21, 0.09], p^{-} = .780, \mathrm{ER}^{-} = 3.54$) or third (B3-B2: $b = -0.02, [-0.17, 0.13], p^{-} = .602, \mathrm{ER}^{-} = 1.51$) block (see Table S7).

3. Discussion

We investigated whether three rounds of iTBS targeting the left DLPFC in an accelerated protocol would decrease the tendency to engage in MW while maintaining or improving task-performance in the FT-RSGT. In contrast to our hypotheses, we found that real stimulation actually increased MW relative to sham stimulation. This was further corroborated by reports of heightened difficulty in concentrating during the real stimulation condition. In addition, exploratory Bayesian analyses further revealed that BV and AE were slightly improved in some blocks, and otherwise remained comparable to the sham condition.

While our results do not support the executive failure view of MW, which predicted decreased MW because of an increased capacity to avoid distracting thoughts due to iTBS, they are in line with the executive use view of MW (Smallwood and Schooler, 2006). This account posits that executive resources are shared between the task at hand and MW, and thus, higher MW propensity leads to reduced availability of executive resources and impaired cognitive performance. Accordingly, if the general pool of executive resources available is increased via an experimental manipulation such as iTBS, participants can potentially employ these extra resources to engage in more MW while maintaining or even improving performance on the FT-RSGT. This is precisely the pattern of results observed in our study, and we therefore cautiously interpret our results in support of that theory.

The apparent conflict between the executive use and failure accounts is resolved when considering the resource-control account of MW (Thomson et al., 2015). This theory distinguishes between executive control and executive resources and proposes that executive resources typically remain constant, while executive control decreases over time as fatigue sets in (Thomson et al., 2015). In that view, executive control is responsible for delegating and shielding executive resources allocated to the task and preventing engagement in MW. Therefore, as executive control decreases during the task, more of executive resources become available for MW. In relation to our results, if we assume that iTBS targeting the left DLPFC increased the pool of executive resources while not affecting executive control, our results seem to support this theory: As the pool of executive resources is increased, the capacity to MW also grows while maintaining the ability to perform the task at an acceptable level. The improvement in behaviour might occur because the optimal distribution of task resources increases due to the larger pool of executive resources. Moreover, given that we did not find iTBS to influence the ratio of deliberate vs. spontaneous episodes of MW (see: Supplementary Results), here we also propose that any iTBS-induced change in the redistribution of executive resources did not depend on participants' deliberate control. Lastly, we found a significant time-on-task effect indicating that task performance decreased over time, which suggests that executive control is unaffected by the stimulation protocol.

One aspect of our design related to the repeated application of the stimulation protocol (i.e., iTBS) to investigate a possible accumulation of the effect over blocks. Previous research has suggested that the after-effects of rTMS on neuronal excitability may accumulate with repeated stimulation rounds, particularly when using an inter-stimulation-interval of around 15–30 min (Nettekoven et al., 2014; Tse et al., 2018; Yu et al., 2020), though this is not uncontested (see Bakulin et al., 2022; Chung et al., 2018; Thomson et al., 2019). Our exploratory results on the accumulating effects of rTMS can be partially interpreted in support of this claim. Specifically, we only found an accumulating effect for BV in B2 (i.e., after the second stimulation), but we did not find any significant accumulating effect for either MW or AE. Thus, it seems possible that repeated iTBS may affect cognitive processes supporting stable responding (e.g., BV), but not others (e.g., MW and AE). However, rather than being conclusive evidence of accumulating effects of the stimulation, our results can also be interpreted in terms of the increasing fatigue over blocks, which may have made the brain more susceptible to iTBS. Unfortunately, our current study cannot distinguish between these possibilities, and it will be up to future research to elucidate on this issue.

Our results indicate a general improvement in performance and a decrease in MW reports on the last block (B3) relative to the preceding blocks in both the sham and the real stimulation sessions. We believe this "end-of-session" effect is related to motivational factors (Bengtsson et al., 2009; Locke and Braver, 2008; Seli et al., 2018a) initiated by the participants' realization that they were close to the end of the long and exhausting experiment (Emanuel et al., 2022). In support of this idea, recent research indicates that implementing a continuous task progression feedback improves performance relative to not providing such feedback (Katzir et al., 2020). Other studies suggest that task motivation follows a U-shape curve, where effort is the highest at the start and end of a task (Emanuel, 2019). In addition, MW reports have been found to follow an inverse U-shape pattern in a task with predictable task demands: MW reports were less frequent at the start and end of a task run, but increased around the middle of the task run (Seli et al., 2018a). Participants in our study were instructed in advance about the number of blocks and were also reminded by the experimenters before starting their last block, and hence, our results are in line with previous research reviewed above.

The DLPFC has been proposed as a region crucial for allocating resources to neural networks relevant for either off-task or on-task cognition (Turnbull et al., 2019a). Similarly, this cortical area is part of the fronto-parietal control network (FPCN), which has also been related to switches in mental content (Christoff et al., 2016; Smallwood et al., 2012; Turnbull et al., 2019b). As a consequence, increased activity in the DLPFC induced by iTBS could have improved the efficiency of reallocating resources between brain networks, and optimize attentional switching between MW and on-task (e.g., Mittner et al., 2016). For instance, the DLPFC has been found to directly modulate activity within the DMN (Deck et al., 2023; Spreng et al., 2013), which in turn has been repeatedly linked to both MW (Christoff et al., 2009; Deck et al., 2023; Fox et al., 2015) and stable task performance (Esterman et al., 2014; Groot et al., 2022; Kucyi et al., 2017). In addition, the DLPFC is a key region in integrating and maintaining task-related information (Cole et al., 2010, 2016; Kim et al., 2015), and thus, it is possible that modulating neural excitability within the DLFPC could have optimized between-network dynamics, leading to changes in both MW propensity and task performance. Ultimately, more research is needed to elucidate the precise mechanisms by which the DLPFC modulates attentional focus and task performance, respectively.

Limitations of our current study include our reliance on standardized MNI coordinates. Optimally, individual MRI scans in combination with functional MRI (fMRI) could be applied to improve targeting the DLPFC. There is, however, evidence that more elaborate scalp measurements, and even the international 10–20 system is not necessarily inferior to individualized MRI or fMRI-based targeting approaches (Xu et al., 2023). Furthermore, even though we implemented a sham-controlled design, we did not include an active control condition (i.e., active stimulation of a presumably unrelated brain area). Future studies may want to include the stimulation of a control region (e.g., an occipital site) in addition to the sham-control to assess the specificity of the experimental protocol in terms of cortical targeting.

Our results open intriguing avenues for future research. We found that applying an excitatory iTBS protocol over the left DLPFC increased MW, reduced BV and improved AE. Future research may want to investigate whether using continuous TBS (cTBS), a rTMS protocol commonly believed to reduce the neuronal excitability of the stimulated area (Huang et al., 2005), might induce the opposite effects, namely reduce MW, increase BV, and improve AE.

Furthermore, targeting alternative brain regions that have been shown to be involved in MW, such as the inferior parietal lobe (Nawani et al., 2023; see also Drevland et al., 2024), might help to better understand the intricacies of MW and its relationship to various brain regions. Additionally, the right DLPFC is often overlooked in favour of the left DLPFC, but research suggests that the right DLPFC is related to randomness generation (Groot et al., 2022). Therefore, the right DLPFC should be an additional target for future studies attempting to provide insight into the specific relationship between the brain, randomness generation and MW. Moreover, future studies could use dual-coil stimulation protocols targeting the DLPFC (or the angular gyrus; Drevland et al., 2024) bilaterally to investigate whether MW and performance could be further improved.

Furthermore, despite the negative effects of MW in sustained attention tasks, MW might be beneficial for creative problem solving (Baird et al., 2012), and future studies could stimulate the left DLPFC with iTBS, to increase MW, to investigate whether increased MW leads to improved (creative) problem solving. Finally, MW is a multifaceted phenomenon, and it might be necessary to incorporate multiple methodological approaches (Mittner et al., 2014), such as simultaneous fMRI-EEG (Groot et al., 2022) and pupillometry (Groot et al., 2021), to study the effects of brain stimulation protocols on the delicate interplay between EF and MW.

In summary, we found that repeated application of an iTBS protocol over the left DLPFC withing a single experimental session increased experiences of MW while retaining or even improving psychomotor precision and EF (i.e., randomness generation) relative to the sham condition. Our results are in general agreement with previous research, indicating that rTMS over the DLPFC can improve cognitive functions, such as faster response times, increased accuracy (Xu et al., 2023), improved working memory and cognitive flexibility (Wu et al., 2021) relative to sham stimulation in a way that may accumulate with repeated stimulations (Nettekoven et al., 2014; Tse et al., 2018; Yu et al., 2020). We argue that iTBS increased the pool of executive resources (e.g., Smallwood and Schooler, 2006) in light of the resource-control view of MW (Thomson et al., 2015).

Data and material availability

The raw data and all used materials are publicly available at https://osf.io/txpu2/.

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CRediT authorship contribution statement

Steffen Rygg Aasen: Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Ragnhild Nicolaisen Drevland:** Writing – review & editing, Resources, Methodology, Investigation, Conceptualization. **Gábor Csifcsák:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Matthias Mittner:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuropsychologia.2024.109008.

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