**Intentionality of Mind-Wandering as Reflected in Measures of Executive Control and Behavioral Variability: a TMS Study**

**Abstract**

1. **Introduction**

Humans spend a substantial amount of their waking lives engaged in spontaneous, self-generated thoughts that are decoupled from an ongoing activity or the current surroundings (Killingsworth & Gilbert, 2010; Seli, Beaty, et al., 2018). This mental phenomenon has been studied under the umbrella term of “mind-wandering” (MW) (Kane et al., 2007; Killingsworth & Gilbert, 2010; Klinger & Cox, 1987). Over the past two decades, cognitive neuroscientists have increasingly gained interest in elucidating the basic neurocognitive mechanisms and physiological underpinnings of MW (Callard et al., 2013). Interestingly, whilst MW has been associated with future planning and creative problem-solving (Mooneyham & Schooler, 2013), it has also been shown to interfere with task performance (Smallwood & Schooler, 2015) and negatively impact emotional well-being (Hoffmann et al., 2016).

Despite the ubiquity of MW in daily life, its operationalization constitutes a challenge for the field in virtue of its complexity. Recently, the family-resemblance framework for MW was put forth (Seli, Kane, Metzinger, et al., 2018; Seli, Kane, Smallwood, et al., 2018) which views MW as a heterogenous construct graded along multiple dimensions (e.g. task-relatedness, intentionality (Seli et al., 2016), metacognition (Christoff et al. (2009) etc.). Although, all the dimensions suggested are of interest to MW research, it is not feasible to investigate all of them at once. However, we deem intentionality particularly worth investigation since it has been attributed great explanatory power for MW states (Golchert et al., 2017; Robison et al., 2020; Seli, Beaty, et al., 2019; Seli, Schacter, et al., 2019). Intentional MW typically occurs when the task at hand isn’t compelling or does not require an individual’s full attention. Under these circumstances the person may decide to engage in task-unrelated thoughts intentionally or a spontaneously arising train might win the competition for attention (Murray et al., 2020). Although there exists a consensus that executive control plays a role in the onset and maintenance of MW, it remains unclear whether MW is a result of failure of executive control or a competition for the same resources (McVay & Kane, 2010). In this study, we will investigate the relationship between MW and executive control with respect to intentionality.

Another line of work closely related to the present study is on neuromodulation of MW. To this day, several studies have attempted to influence the propensity to mind-wander by means of transcranial direct current stimulation (tDCS). The yielded results are inconclusive: whilst some studies reported that anodal (excitatory) tDCS over left dorso-lateral prefrontal cortex (dlPFC) induced an increase in MW (Axelrod et al., 2015, 2018), others reported the same effect for cathodal (inhibitory) tDCS over the same region (Filmer et al., 2019), yet others showed no effect of anodal tDCS on MW likely caused by the weak modulatory effect of brain polarization procedures modulating regional excitability rather than operating on brain rhythms (Nya Mehnwolo Boayue et al., 2019). Here, we aim to elucidate the relationship between non-invasive brain stimulation (NIBS) and MW by testing transcranial magnetic stimulation (TMS) to modulate MW states. To our knowledge, our study is the first in MW research to use TMS. We will attempt to answer the following questions: Can TMS over left dlPFC modulate MW propensity and, by extension, task performance? Can it reduce the propensity to engage in MW? Is there a causal relation between executive control and spontaneous MW, underpinned by activity in the dlPFC ?

Thus, the objective of the project is two-fold. Firstly, we will attempt to entrain theta-band oscillatory activity in the left DLPFC and probe the causal relation between the entrained oscillations and MW. Secondly, we aim to dissociate intentional and spontaneous MW by demonstrating that only the former draws on executive resources. To this end, will conduct an online TMS study involving the finger-tapping random sequence generation task (FT-RSGT) designed and validated by (Nya M. Boayue et al., 2021).

With this study, we will test the following hypotheses:

* H1. Based on the correlation of fronto-medial theta oscillations with sustained attention (Clayton et al., 2015) and cognitive control (Cavanagh & Frank, 2014), we expect participants to mind-wander less when subjected to active rhythmic TMS compared to arrhythmic control TMS, sham and baseline. Quantitatively, we expect a positive effect of active rhythmic TMS on task scores (a higher score corresponds to less MW) as reflected in the coefficient value within the fitted model.
* H1.1. By extension, we expect subjects to more accurately emulate the rhythm of the metronome with with finger taps during active rhythmic TMS compared to other conditions. This would reflect in lower behavioral variability (BV).
* H2. We hypothesize an increase in executive control during active rhythmic TMS compared to other conditions. Quantitatively, this would manifest in an increase in approximate entropy (AE).
* H2.1. As an extension of hypothesis 2, building upon the literature linking higher executive control and intentional MW (Golchert et al., 2017; Seli, Kane, Smallwood, et al., 2018), we hypothesize lower rates of spontaneous MW during active rhythmic TMS compared to other conditions. On the computational level, we would expect a positive effect of active rhythmic TMS on intentionality scores whereby a higher intentionality score stands for higher intentional control of one's attention.

The outcome measures, experimental design and operational definitions are outlined hereunder. This study was preregistered on OSF platform: <https://osf.io/2wszr>.

**2. Methods**

***2.1. Participants***

We conducted an a-priori power analysis for a repeated-measure, within-factor ANOVA using G\*Power (also implemented in Gouraud et al., 2018). To reach the minimum acceptable power of 0.8 and to detect a medium effect (f = 0.25), a sample of 21 participants would be required (N of measures = 5). However, due to feasibility concerns and time constraints, we ran the analyses on a subset of subjects.

Our target population is in good health, right-handed, aged between 18 and 65 years old, affiliated to a social security scheme or beneficiary of such a regime (unless authorized by the ethical committee), fluent in written French or English and eligible according to MRI and TMS international safety guidelines.

However, we will not include people to whom at least one of the following pertains:

* currently participating in another study (< 24 hours or 1 week for studies involving brain stimulation or any other intervention affecting brain excitability);
* presenting or having a history of a psychiatric or neurological disorder or evolutive disease that interferes with the study tests;
* reported consumption of psychotropic substances (except nicotine and caffeine);
* taking central nervous medications (e.g. antidepressants, antiepileptic drugs) under benzodiazepines, anticonvulsants or neuroleptics treatment;
* pregnant, breastfeeding or has recently given birth;
* presenting a contra-indication to MRI (such as claustrophobia, pacemaker, cochlear implant, prosthesis, metal fragment injuries, or any other metallic implant, important black tattoo, permanent make-up etc.);

In addition, we shall exclude people who ask to stop the experiment or fail to cooperate and/or comply with the procedures during the experiment.

***2.2. Behavioral Task***

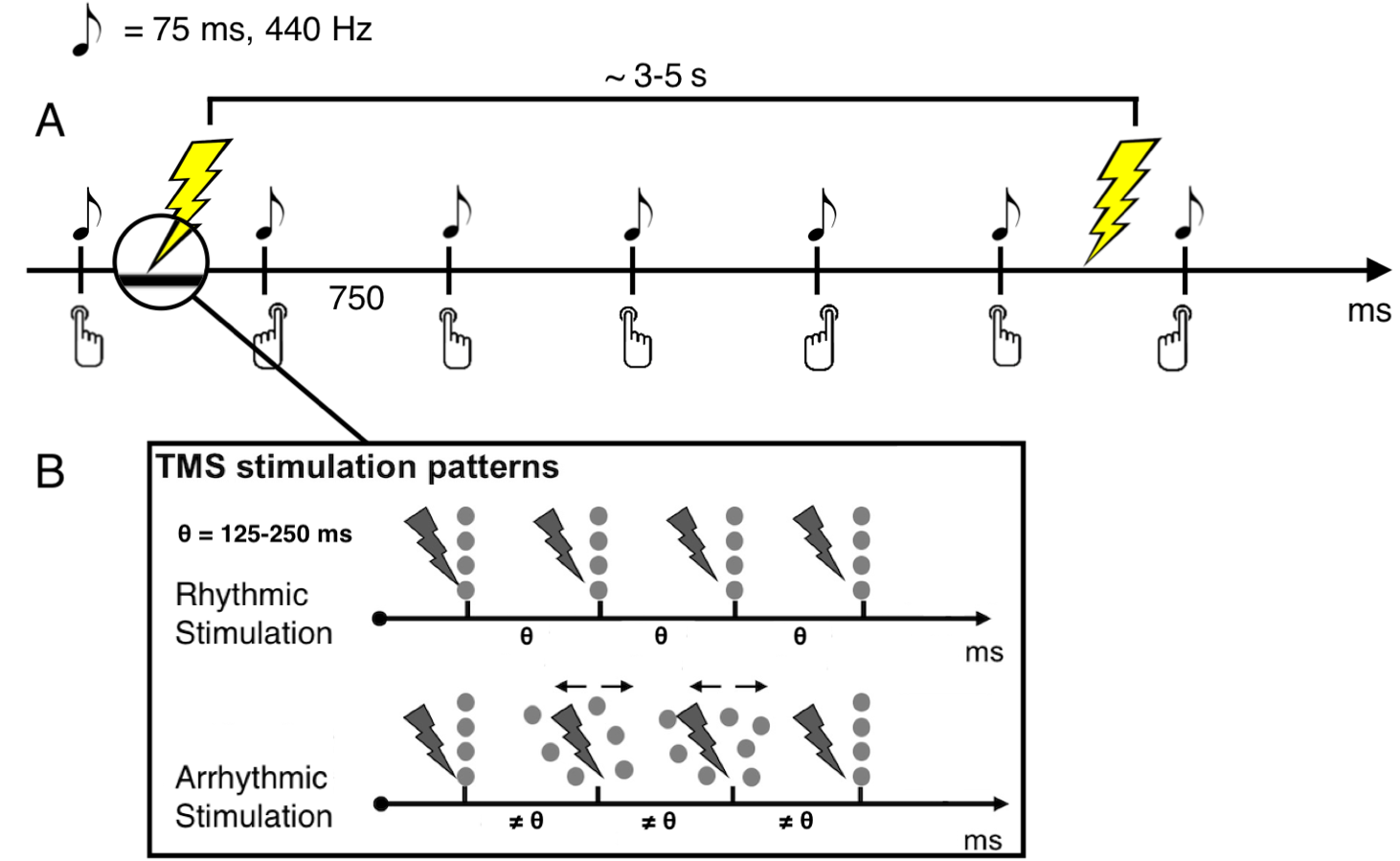
This study involves a novel task – the Finger-Tapping Random Sequence Generation Task (FT-RSGT: Boayue et al., 2021). FT-RSGT is a combination of a modified version of the random generation task (Baddeley et al., 1998; Towse, 1998) and a finger-tapping task (Kucyi et al., 2016; Seli et al., 2013). This task consists of two sub-tasks: i. rhythmic finger-tapping in response to an ongoing metronome and ii. the generation of irregular sequences by pressing one of the two available response-buttons (“S”, left key and “L”, right key). The subject was instructed emulate the rhythm of the metronome as accurately as possible with their finger taps and, simultaneously, to try and render every button press as unpredictable for the external observer as possible. To ensure that the participants understand the task, we provided ample examples of how an irregular sequence would compare to a regular sequence (e.g. “right-left-right-left” is more regular than “right-right-left-right”) and emphasized that each press must be difficult to predict for an external party. The subjects also underwent a training upon which they were asked to retrospectively assess the press sequences they had produced and to provide examples thereof.

Given that the generation of irregular sequences draws heavily on executive resources, the randomness of the generated sequence is related to their deployment. This has been confirmed by the finding that sequences generated during MW are typically less random (Boayue et al., 2020; Teasdale et al., 1995). In addition, the behavioral variability as measured by deviation of the taps from the on-going metronome in the finger-tapping studies have been shown to be an indicator of MW (Kucyi et al., 2016; Seli et al., 2013).

***2.3. Experimental Procedure***

Participants were seated in a comfortable chair, with their head resting on a chinrest at a distance of 57 cm from the screen. The task script ran on PsychoPy. The same script was used to trigger TMS pulses. The task began with instructions during which participants were encouraged to ask questions if anything was unclear. Participants were instructed to place their index fingers on two keyboard keys (“S” and “L”) and to fixate the cross in the centre of the screen throughout the entire experiment.

Each trial began with a tone of 440 Hz lasting for 75 ms. The tone repeated every 750 ms (= inter-stimulus interval; ISI) until the appearance of a thought-probe (see methods). The ISI of 750 ms was validated by Boayue et al. (2019) whereby they demonstrated that this interval was long enough for the executive control to be deployed, but also short enough so that the attention is maintained. The schematic representation of the task is depicted in figure 1 (A). The experiment consisted in two visits whereby the subject completed 14 blocks of FT-RSGT in total. The following section provides a detailed overview of the block design.



**Figure 1.** **A**: FT-RSGT: participants are instructed to press the right (L) or left (S) key in an irregular order simultaneously with the rhythm of the metronome. The tone of the metronome has a frequency of 440 Hz and its duration is 75 ms. TMS is administered every 3 to 5 s. **B**: Every TMS burst consisted of four pulses. Two stimulation patterns were implemented: rhythmic (rhTMS, top) and arrhythmic (arrhTMS, bottom). The inter-pulse interval (IPI: θ) was set based on the frequency of pulses. The latter was determined for each subject separately: an individual theta-peak frequency was extracted from the EEG recording of the first baseline. As a result, the IPI fell in the range of 125-250 ms (4-8 Hz). In the case of the arrhTMS, the IPI ≠ θ, but the total duration of the burst (3 \* θ) was identical for both patterns. However, IPI was always greater than 20 ms.

One task block lasts for 15 mins and includes 1200 trials. The experiment will comprise 2 blocks which correspond to different TMS conditions: rhythmic and control TMS. Participants will rest for 5 minutes between blocks. The order of blocks will be counterbalanced: half of the participants will start with the rhythmic block.

We chose arrhythmic TMS over sham as a control condition for several reasons. First, arrhythmic TMS allows to control for the frequency of the oscillation and keep the side-effects accompanying active TMS: possible muscle twitching, noise etc. The arrhythmic control condition thus allows to isolate the variable of interest (theta oscillations) and to preserve participant blinding. Second, it has been argued that sham lacks specificity to be regarded as a full-fledged control condition (Duecker & Sack, 2015). Furthermore, we will also collect EEG data during the experiment. However, these data will not be analyzed in the context of this study. For more details on the stimulation parameters, refer the following section.

***2.4. Stimulation Protocol***

The participants were subjected to 5 conditions in total over the course of two visits: baseline, sham rhythmic TMS (rhTMS), sham arrhythmic TMS (arrhTMS), active rhTMS and active arrhTMS. The subjects were sequentially randomized and assigned to either the rhythmic or the arrhythmic group. The rhythmic group was exposed to rhTMS during the first visit and to arrhTMS during the second visit. The order was reversed for the arrhythmic group. The experimental protocol is outlined in table 1.

*2.4.1. ROI Definition*

Prior to the experimental procedure, all participants will undergo a structural MRI scan. The resulting T1-images will be used to locate left DLPFC in every participant. The locate the ROI, we will use MNI coordinates which resulted from the seed-based parcellation performed by Groot et al., (2020): x = -37, y = 41, z = 22. We will use a frameless stereotactic system (*Brainsight TMS Navigation*) to identify the cerebellar location and to minimize any deviations of the coil from the targeted sites.

*2.4.2. rhTMS Parameters*

Repetitive TMS will be applied over the target areas with a biphasic rTMS device (Magstim Super Rapid) equipped with a figure-of-eight coil (Double 70-mm Alpha Coil; The Magstim Company Ltd, UK). All TMS applications will follow the updated safety guidelines and recommendations of the international TMS community (S. Rossi et al., 2021).

Two types of rTMS protocols will be used: rhythmic TMS and arrhythmic (control) TMS. The experiment has a repeated-measures design, that is, all participants will be subjected to both conditions during the task. Arrhythmic control TMS is used to control for placebo effects as well as to isolate the effect of the entrained oscillations. We will use a fixed intensity of 55% of the machine stimulator output (MSO, Magstim rapid 2,70 mm figure of eight coil) to account for the time that the TMS machine requires to recharge and deliver pulses at full intensity (Veniero et al., 2010).

Rhythmic TMS will be delivered during the first or second block at the stimulation frequency within the theta (3-8 Hz) band. It will consist of short bursts of 4 pulses at a given frequency (e.g., 4 Hz corresponding to 250 ms of inter-pulse interval within the burst). The inter-stimulation delay will vary from 3 to 5 seconds throughout the experiment to avoid carry-over effects. For the control arrhythmic TMS the onset timings of the 1st and the 4th pulse within the burst and total burst duration (e.g., 300 ms for 10 Hz stimulation) will be kept identical to those of rhythmic patterns. However, the 2nd and 3rd pulses will be randomly jittered before and after their exact onset timings in arrhythmic patterns (Figure 1, B).

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