On the neural substrates of mind wandering and dynamic thought: A drug and brain stimulation study

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Abstract

The impact of mind wandering on our daily lives ranges from diminishing productivity, to facilitating creativity and problem solving. There is evidence that distinct internal thought types can be modulated by transcranial direct current stimulation (tDCS), although little is known about optimal stimulation parameters or the mechanisms behind such effects. In addition, recent findings suggest changes in dopamine availability may alter the effect tDCS on neural and behavioural outcomes~~, and this relationship may interact with stimulation intensity~~. Dopaminergic functioning has also been implicated in executive processes anticorrelated with mind wandering such as attention and working memory, however the neurochemical mechanisms involved in internal thoughts are largely unknown. Here, we investigate the role of dopamine, and tDCS~~ intensity~~, on internal thought processes. Specifically, using an attentional control task, we test whether ~~, using an attentional control task if~~ dopamine availability (levodopa or placebo) mediates the effects of online high definition tDCS ~~across different stimulation intensities~~ (~~1mA,~~ 2mA, or sham). The role of dopamine in mind wandering, during an attentional control task, would be supported by an increase or decrease in dynamic thought with levodopa, and a brain stimulation ~~dosage~~ interaction with drug would support the influence of dopamine on tDCS outcomes.

Keywords: *mind wandering, dynamic thought, dopamine, levodopa, tDCS, task unrelated thought, prefrontal cortex*

Cognitive control and mind wandering represent the "yin and yang" of executive function. Mind wandering – the direction of thoughts towards self-generated, internally orientated representations – is a complex phenomenon, and this heterogeneity has been recently characterised in the dynamic framework (Martel et al., 2019). This hypothesis suggests there are three dynamic thought types – deliberately constrained thoughts, automatically constrained thoughts and freely moving thoughts (Kam et al., 2021; Martel et al., 2019; Seli et al., 2018). Currently, little is known on the neural substrates underlying these distinct thought types, however neuroimaging has indicated that similar neural networks underlie ~~underly~~ mind wandering and cognitive control operations, particularly those implicated in maintaining focus on goal directed representations (Christoff et al., 2016; Fox et al., 2015; Groot et al., 2021). However, the underlying causal neural mechanisms which drive a shift from task focussed towards internally oriented thoughts remain poorly understood.

Non-invasive brain stimulation approaches – such as transcranial direct current stimulation (tDCS) – can be applied to understand the causal neural substrates associated with mind wandering and attentional control. tDCS works by passing a weak electrical current (typically between 0.5mA and 4mA) between electrodes which are placed on the scalp (Filmer et al., 2014, 2020). High definition (HD) tDCS (see Figure 1), uses small electrodes, typically arranged in a 4 x 1 ring montage, to pass the current from the central anodal electrode to the four surrounding reference cathodes (Datta et al., 2009; Villamar et al., 2013). Consistent with imaging research, tDCS studies have causally implicated the prefrontal cortex (PFC) in mind wandering (Axelrod et al., 2018; Boayue et al., 2021; Filmer et al., 2019). However, an early research finding that 1mA anodal tDCS applied to the left PFC increased mind wandering (Axelrod et al., 2015, 2018) has failed to replicate in a high-powered replication study which found strong evidence against a stimulation effect (Boayue et al., 2020). ~~There is evidence to suggest the stimulation dosage may moderate the effects of tDCS on mind wandering, such that an optimal dosage is required to affect the frequency of task unrelated thoughts . However~~Furthermore, studies applying 2mA HD-tDCS to the PFC have also shown both support for (Boayue et al., 2021) and against (Alexandersen et al., 2022) modulations to mind wandering. Regarding the dynamic framework, we recently found, in a high-powered registered report, that freely moving thoughts were reduced by 2mA HD-tDCS stimulation being applied to the left PFC and deliberately constrained thoughts were reduced by stimulation to the right inferior parietal lobule (IPL; Rasmussen et al., 2023). These findings suggest dynamic thought types can be modulated by HD-tDCS and have potentially distinct neural substrates; however, the mechanisms behind such modulations remain unclear.

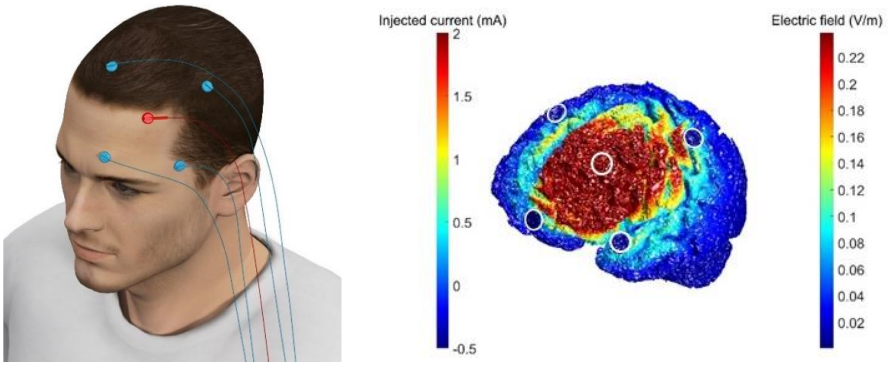

Figure 1. HD-tDCS montage and current modelling. Display of electrode placement over the left PFC, with the anode at F3 and cathodes placed at F7, C3, Fz and Fp1 (left image) and current modelling for this 4 x 1 ring HD-tDCS montage (right image).

Brain stimulation has been found to directly affect the excitability of various neurochemical mechanisms, including inducing changes in the concentration of dopamine neurotransmitters in cortical and subcortical regions (Bunai et al., 2021; Fonteneau et al., 2018; Fukai et al., 2019; Meyer et al., 2019). The importance of the dopaminergic system in cognitive control has been consistently highlighted, whereby dopamine manipulations have been shown to exert a dosage-dependent, inverted U-shaped effect, on attention and working memory processes (Cools, 2016; Cools & D'Esposito, 2011; D'Ardenne et al., 2012). Furthermore, there is evidence to suggest effects of PFC brain stimulation on cognitive control processes are related to changes in dopamine concentrations. For example, research has found tDCS induced improvements in the accuracy component of an executive functioning task were correlated with an increase of dopamine released in the right ventral striatum, which is linked to PFC through the meso-cortical-limbic system (Bunai et al., 2021; Fukai et al., 2019). There is also evidence to suggest this dopamine-tDCS interaction may directly influence behavioural outcomes (Borwick et al., 2020; Leow, Jiang, et al., 2023; Leow, Marcos, et al., 2023)~~, and moreover this influence may interact with tDCS intensity (Leow, Jiang, et al., 2023)~~. This research highlights the influence of dopamine on brain stimulation outcomes, ~~and suggests these effects may be dependent on the stimulation dosage. Hh~~however, no research to date has investigated the causal role of dopamine in internal thought processes.

The present study

The current study will employ an anodal HD-tDCS protocol, applied to the left PFC, in conjunction with a levodopa manipulation, designed to increase dopamine availability, to

explore the interaction between dopamine and stimulation effects on mind wandering, during an attention control task. Table 1 provides a full summary of the study design.

This research first aims to replicate the effect of PFC stimulation on freely moving ~~thought in the PFC~~ found ~~in~~ by Rasmussen et al. (2023), whereby we hypothesise that 2mA anodal HD-tDCS to the left PFC will reduce freely moving thought, relative to the sham group, across participants in the placebo drug condition (H_{1a}). While there have been contrasting findings on the effect of tDCS on task unrelated thought, there is evidence to suggest that stimulation can also reduce these thoughts (Boayue et al., 2021), thus we hypothesise that 2mA anodal HD-tDCS will reduce task unrelated thought, relative to the sham group, across the placebo drug groups (H_{1b}). ~~Given research has also found a dosage dependent effect of tDCS on mind wandering propensity , we aim to investigate the relationship between tDCS dosage (1mA and 2mA) and individuals' propensity to mind wander. Specifically, we predict that there will be a difference between the effect of the 1mA and 2mA active HD-tDCS conditions on freely moving thought, across the placebo drug conditions (H_{2a}). In addition, we predict that there will be a difference between the effect of the 1mA and 2mA active HD-tDCS conditions on task unrelated thought, across the placebo drug conditions (H_{2b}).~~

To understand the neurochemical mechanisms underlying mind wandering and the dynamic thought types, this research also aims to investigate whether the changes in mind wandering and dynamic thought, while completing a cognitively demanding task, are being driven ~~solely~~ by changes in dopamine availability. We hypothesise that there will be an effect of increasing dopamine availability via levodopa, compared to the placebo group, on freely moving thought (a) and task unrelated thought (b), across the sham stimulation conditions (H_{23}). Finally, because there is evidence that levodopa may mediate the effects of tDCS on performance outcomes (Leow, Jiang, et al., 2023; Leow, Marcos, et al., 2023)~~, and that this effect may be dependent on the stimulation dosage (Leow, Jiang, et al., 2023),~~ we also aim to investigate how the interaction between tDCS ~~dosage~~ and dopamine affects internal thought types in PFC. Thus, we predict there will be a difference in the effect of ~~1mA and~~ 2mA HD-tDCS~~,~~ in combination with levodopa on freely moving thought (a) and task unrelated thought (b), relative to the active ~~(1mA and 2mA)~~ placebo groups (H_{43}).

Research question	Hypotheses	Sampling plan	Analysis plan	Rationale for deciding test sensitivity	Interpretation given different outcomes	Theory that could be shown wrong by the outcomes
Does HD-tDCS affect freely moving and task unrelated thought?	2mA anodal HD-tDCS to the left PFC will reduce freely moving thought, relative to the sham group, across participants in the placebo drug condition (H_{1a}). 2mA anodal HD-tDCS will reduce task unrelated thought, relative to the sham group, across the placebo drug groups (H_{1b}).	Bayesian sampling approach. Testing will continue until: (a) Bayes Factor $(BF)_{10} > 6$, or $BF_{01} > 6$, for H_{1a} and H_{34} is reached, or (b) 240 (640 participants per group) is reached. See participants section for more detail.	**Hypothesis testing analyses** (1) Hierarchical order probit modelling for both thought types using 2mA vs sham, with placebo condition, as key stimulation comparison. (2) Bayesian independent samples t-tests: 2mA active vs sham stimulation, across placebo groups – for freely moving and task unrelated thought. Note: the t-test for freely moving thought is one of the two stopping rule tests	**For all hierarchical order probit modelling analyses:** If the credible intervals (CIs) do not cross 0, this will be interpreted as a meaningful effect. **For all other tests:** $BF_{10} > 6$ or $BF_{01} > 6$ ~~for stopping rule~~will be interpreted as~~is~~ enough evidence to establish a meaningful result. ~~For all tests~~	(1) If the winning LOOIC model includes a meaningful stimulation effect, this would indicate 2mA HD-tDCS affects the respective thought type. (2) $BF_{10} > 6$ for freely moving or task unrelated thought, suggests 2mA anodal stimulation affects the reporting of the respective thought type. $BF_{01} > 6$, indicates no effect of 2mA stimulation for the selected thought type.	An effect of 2mA tDCS on freely moving and/or task unrelated thought suggests tDCS can modulate mind wandering/dynamic thought types. Specifically, a reduction in these thoughts would support H_{1a} and H_{1b}. A null effect for task unrelated thought would align with literature suggesting a failure to alter thoughts using ~~2mA~~ HD-tDCS. A null effect or positive effect for freely moving thought would fail to replicate the Rasmussen et al. (2023) findings.
~~Does tDCS dosage (1mA and 2mA) affect individuals' propensity to mind wander?~~	~~There will be a difference between the effect of the 1mA and 2mA active HD-tDCS conditions for freely moving thought, across the placebo drug conditions (H_{2a}).~~ ~~There will be a difference between the~~		~~(1) Hierarchical order probit modelling for both thought types using 2mA vs 1mA active groups, with placebo condition, as key stimulation comparison.~~ ~~(2) Bayesian independent samples t-tests: 2mA vs 1mA active stimulation across placebo groups – for~~		~~(1) If the winning LOOIC model includes a meaningful stimulation effect, this would indicate a difference in the effect of 1mA and 2mA stimulation on the respective thought type.~~ ~~(2) $BF_{10} > 6$ for freely moving or task unrelated thought, suggests that there is a~~	~~If both H_{2a} and H_{2b} are supported, this provides evidence for dosage dependent differences in the effect of HD-tDCS on internal thought processes. If the dosage dependent changes are distinct for the two thought types, this supports theory that distinct internal thought types activate~~

	~~of 1mA and 2mA active HD-tDCS conditions for task unrelated thought (H_{2b}).~~		~~freely moving and task unrelated thought.~~	~~BF_{10} > 3 or BF_{01} > 3 is supported by the literature as enough evidence to establish a meaningful result. In addition, if the credible intervals (CIs) do not cross 0 for the probit modelling, this will be interpreted as a meaningful effect. BF > 3 provides meaningful evidence for an effect. BF > 6 or BF > 6 is supported by the literature as enough evidence to establish a meaningful~~	~~difference between the effect of 2mA and 1mA stimulation. BF_{01} > 6, indicates no difference between the effect of 2mA and 1mA stimulation.~~	~~different neural pathways. A null effect for either thought type would suggest there is no difference in the dosage effects on the thought type, irrespective of whether both dosages have an effect or not.~~
Are changes in dynamic thought being driven by dopamine availability?	There will be a difference in the effect of levodopa, relative to the placebo group, on freely moving thought (a) and task unrelated thought (b), across the sham stimulation conditions (H_{2}~~3~~).		**Hypothesis testing analyses** (1) Hierarchical order probit modelling for both thought types using levodopa vs placebo as the key predictor. (2) Bayesian independent samples t-tests: levodopa vs. placebo across sham groups – for freely moving and task unrelated thought.		(1) If the winning LOOIC model includes a meaningful drug effect, this indicates levodopa affects the frequency of the select thought type. (2) BF_{10} > 6 for either thought type, indicates levodopa affects the frequency of the respective thoughts. BF_{01} > 6, suggests no effect of levodopa on the thoughts.	Support for H_3 would provide direct evidence for the dopaminergic system being recruited during internal thought processes, in the context of the cognitively demanding task. A null effect would suggest that dopamine concentrations are not directly facilitating or inhibiting freely moving or task unrelated thought.
Does the interaction between tDCS ~~dosage~~ and dopamine differentially affect internal thought types?	There will be an interaction between levodopa and tDCS ~~dosage~~, specifically there will be a difference between the effect ~~of 1mA and 2mA~~of active stimulation group~~s~~ with and without levodopa, on freely moving thought (a) and task unrelated thought (b)		**Hypothesis testing analyses** ~~(1) 3 (stimulation: 2mA, 1mA, sham) x 2 (levodopa, placebo) Bayesian ANOVA – for freely moving and task unrelated thought.~~ (1~~2~~) Hierarchical order probit modelling for both thought types using ~~1mA levodopa vs 1mA placebo and 2mA~~active levodopa vs ~~2mA~~ active placebo as key comparison groups.		~~(1) BF_{incl} > 6 for stimulation x levodopa interaction term would indicate a dosage dependent effect of stimulation and dopamine.~~ (1~~2~~) If the winning LOOIC models for both ~~analyses~~ thought types include evidence for a stimulation x drug effect, this would suggest specific stimulation~~ dosage~~, combined with dopamine affects the respective thought	If the ~~ANOVA~~ probit modelling or t-tests show~~s~~ a meaningful interaction, this supports research proposing a ~~dosage dependent~~ interaction between stimulation and dopamine affecting behavioural outcomes – expanding on this to understand ~~the optimal dosage for~~how tDCS and dopamine combined may facilitat~~e~~~~ing~~ or inhibit~~ing~~ the dynamic thought types. ~~If there is meaningful~~

	(H_{43}).		(23) ~~2~~ Bayesian independent samples t-tests: ~~1mA levodopa vs 1mA placebo and 2mA~~active levodopa vs ~~2mA~~ active placebo – for freely moving and task unrelated thought. Note: the t-test for freely moving thought is one of the two stopping rule tests	~~result. If the CIs do not cross 0 for the probit modelling, this will also be taken as a meaningful effect.~~	type. (32) BF_{10} > 6 for select thought type, indicates there is a difference between levodopa and placebo with stimulation~~at the respective tDCS dosage~~. BF_{01} > 6, suggests no effect of levodopa and stimulation interaction on each thought type~~ at each dosage~~.	~~evidence for an effect at either dosage, this would indicate that specific dosage combined with dopamine affects the respective thought type, however this analysis does not allow for comparison between dosages as the ANOVA does.~~
Does dopamine have any physiological effects?	We predict there will be no change in heart rate, blood pressure or mood with the administration of levodopa.		**Control analyses** (1) 2 (Time: before drug, 2 hours after taking drug) x 2 (Drug: levodopa, placebo) Bayesian ANOVAs – for blood pressure, BL-VAS scores, and heart rate		BF_{excl} > 63 for the interaction term will evidence for a null effect and BF_{incl} > ~~3~~6 would be evidence for an adverse effect of levodopa.	If there is evidence of adverse effects, any effect of dopamine may have been influenced by these adverse effects (manipulation check). A null effect would suggest no adverse effects were present.
Are relevant individual traits balanced between conditions?	We hypothesise there will be no difference in relevant traits between the six groups.		**Control analyses** (1) One-way ANOVAs with the scores for BIS-11, Morningness-Eveningness, Adult ADHD Self-Report Scale, Rumination Response Scale, and MAAS as the DV, respectively, and the six conditions as predictors. (2) ~~3~~2 (Stimulation: 2mA~~, 1mA,~~ sham) x 2 (Drug: levodopa, placebo) Bayesian ANOVA on baseline data.		BF_{excl} > ~~3~~6 will indicate moderate evidence for no meaningful differences between the groups, and thus the null hypothesis will be accepted. BF_{incl} > ~~3~~6 would be evidence for a difference between groups.	If there are any group differences found then this would draw into question the conclusiveness of the respective effects of stimulation, dopamine, or an interaction between these outcome variables on mind wandering or task performance (manipulation check). A null effect would suggest that there are no meaningful differences in these traits between the four groups. ~~A null effect would indicate there~~

						~~are no group differences which may be influencing the results.~~
Are the groups blinded appropriately?	We predict participants will be unable to correctly identify if they are sham or placebo condition, relative to the active or levodopa condition.		**Control analyses** (1) Proportion of correct guesses for people in; active vs. sham stimulation; ~~high vs. low dosage;~~ and levodopa vs. placebo drug.		We will interpret a BF_{excl} > ~~3~~6 as moderate evidence for there being no meaningful differences between the groups and thus the null hypothesis would be accepted. BF_{incl} > ~~3~~6 would be evidence for subjective beliefs influencing mind wandering.	If participants are highly accuracy at rating themselves correctly in the sham or placebo group, this would indicate that the blinding was not effective for the respective factor. Furthermore, this indicates individuals' belief about their respective group may be influencing their reporting of each thought type (manipulation check).
Are there any effects of stimulation and dopamine on deliberately and automatically constrained thoughts?	There may be a difference in the effects of stimulation, ~~stimulation dosage~~ and dopamine, relative to the sham and placebo control conditions for deliberately or automatically constrained thoughts. Furthermore, we predict the interaction between dopamine and stimulation ~~dosage~~ may affect the reporting of these thought types.		**Exploratory analyses** (1) Run probit models for deliberately and automatically constrained thought. (2) Run all t-tests ~~and ANVOAs~~ (same structure as freely moving and task unrelated thought analyses) with deliberately and automatically constrained thought as DV.		(1) If the winning LOOIC model includes a meaningful effect for the key predictor, this would suggest that factor affects the frequency of the respective thought type. (2) BF_{10} > 6 or BF_{incl} > 6 for deliberately constrained or automatically constrained thought, indicates the respective factor of interest affects the frequency of the respective thought type. BF_{01} > 6 or BF_{excl} > 6, suggests there is no effect of the respective factor on the selected thought type.	Any effect of stimulation~~,~~ ~~stimulation dosage~~ or dopamine on deliberately or automatically constrained thought would provide preliminary evidence for these thoughts being affected by the specified factor in the PFC. If the effects found for these thought types are distinct from those found for freely moving and task unrelated thought, this would support the heterogeneity of internal thought processes, and would suggest these distinct thought types recruit different neural pathways.

Methodology

Ethics approval

This research was approved by The University of Queensland Human Research Ethics Committee (Clearance ID: 2009000335). Participants will be recruited through the paid participant pool, the School of Psychology first-year volunteer pool at The University of Queensland, or flyers. Compensation will be either $20 per hour or course credits. All participants will be required to provide informed consent to be eligible to participate in the study.

Design

Each participant will complete a single session, which will consist of either 2mA active ~~(1mA or 2mA)~~ or sham HD-tDCS, in conjunction with a dopaminergic manipulation (levodopa or placebo drug). The stimulation will be delivered in conjunction with the Finger-Tapping Random-Sequence Generation Task (FT-RSGT), which is designed for participants to generate random sequences in time to a metronome tone. This study will employ a between subjects' design, whereby participants will be pseudo-randomly allocated to one group according to the following variables: drug (Levodopa, Placebo) x~~,~~ stimulation condition (anodal HD-tDCS, sham HD-tDCS~~), and stimulation intensity (1mA, 2mA~~). Thus, the conditions will be: (1) sham HD-tDCS and placebo; (2) sham HD-tDCS and levodopa; ~~(3) 1mA anodal HD-tDCS and placebo; (4) 1mA anodal HD-tDCS and levodopa;~~ (3~~5~~) 2mA anodal HD-tDCS and placebo; (4~~6~~) 2mA anodal HD-tDCS and levodopa. A between-subjects approach is most appropriate for this study as it will help preserve the integrity of the stimulation and dopamine blinding. Further, it reduces the likelihood of practice effects in the task or any inter-session changes, which are associated with within-subjects designs.

The session will begin with participants completing a demographic questionnaire which will be used to pseudo-randomly allocate participants into demographically balanced groups. This will be conducted in a double-blinded manner via a MATLAB allocation script. This method is also designed to reduce the likelihood of group-related confounds in the between-groups design. They will then receive training on the FT-RSGT task and the four thought probes that will be presented throughout, before completing a 10-minute baseline block on the task (see Figure 2). The levodopa or placebo drug will then be crushed and mixed with orange juice for participants to consume and administered by an alternative experimenter, while the HD-tDCS electrodes are set up. This is to ensure the drug manipulation is blinded for both the participants and experimenter. During this period, participants will also complete some trait-based questionnaires. After 40 minutes has passed since the drug administration, participants

will complete a 30-minute stimulation block, consisting of the FT-RSGT in conjunction with online active ~~(1mA or 2mA)~~ or sham stimulation. Once they have completed the task, an end of session questionnaire will be administered, and participants will be debriefed on their participation in the study.

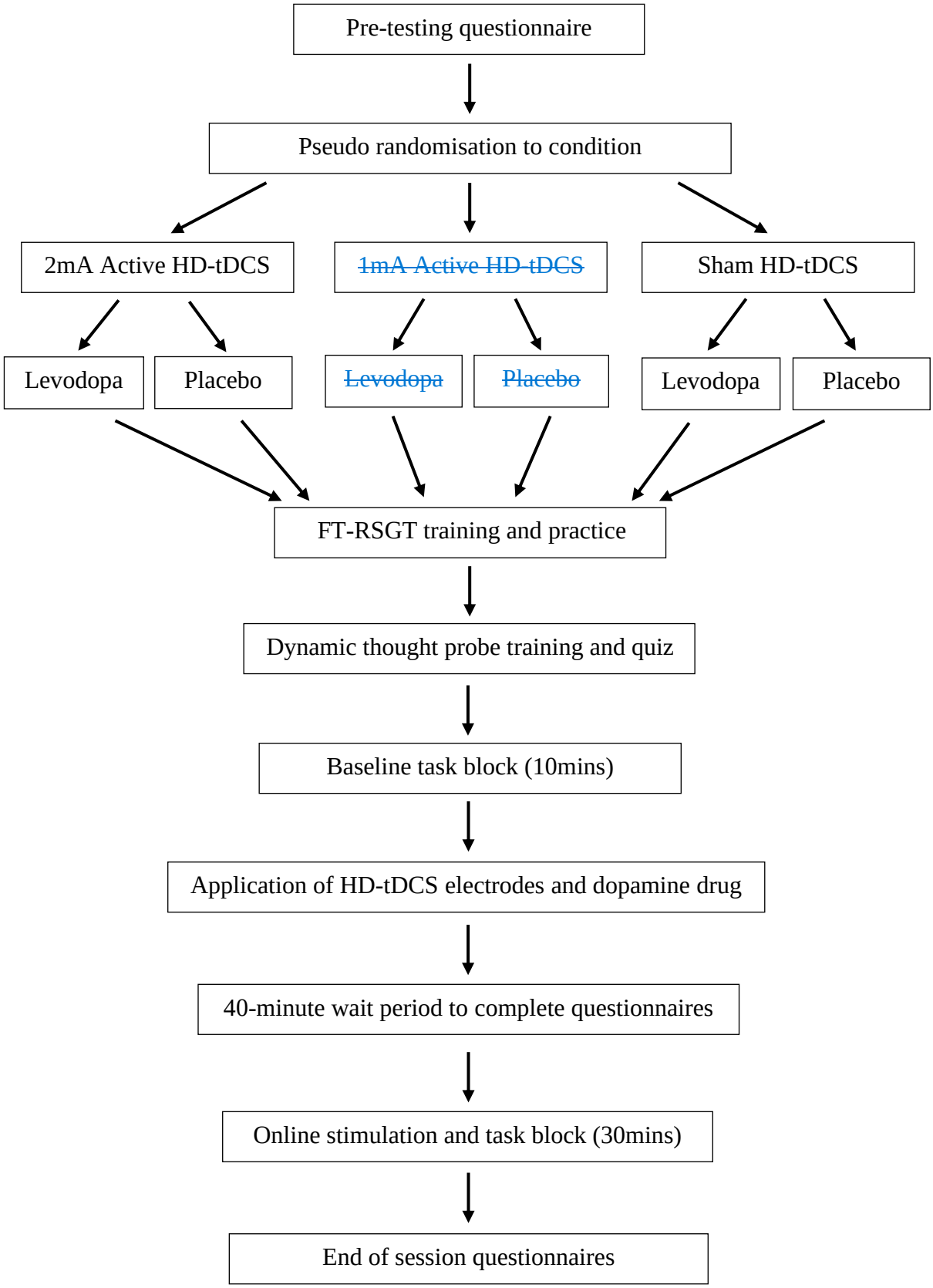

Figure 2. Experimental procedure. The sessions will begin with a pre-screening and pseudo random allocation to one of ~~six~~ four stimulation and drug groups, which is followed by training and a 10-minute baseline block. The electrodes will then be applied, in conjunction with the

dopamine drug manipulation. After a 40-minute wait period, participants will then complete a 30-minute online stimulation block and finally an end of session questionnaire and debriefing on the experiment.

Participants

Bayesian sampling plan

There will be no pre-determined sample size for this study, as it will employ a Bayesian sampling approach. Participants will continue to be recruited until a Bayes Factor $(BF)_{10} > 6$ or $BF_{01} > 6$ has been reached for the ~~critical~~ selected hypothesis tests (see above), or until the maximum sample size of 240 complete datasets (6~~4~~0 participants per group; the maximum number dictated by resource constraints) is reached. This is larger than the sample size which has been used previously to find meaningful results (Rasmussen et al., 2023) and we believe inconclusive results in the ~~critical~~ chosen tests at this sample size will still offer an important contribution to the literature. The stopping rule will be first checked after 15 participants in each group have been tested, and for every 5 participants per group thereafter. The first ~~critical~~ selected hypothesis test is that freely moving thought will be reduced with ~~2mA~~ active HD-tDCS, relative to sham group, for the placebo conditions. Specifically, we will run a Bayesian independent samples t-test which compares the ~~2mA~~ active group to the sham stimulation group, for participants in the placebo condition. This will be run on the stimulation block data alone, with average freely moving thought responses as the dependent variable. This test has been selected to replicate the effect found by Rasmussen et al. (2023), whereby 2mA HD-tDCS to the PFC decreased freely moving thought relative to sham. The ~~second~~ additional ~~critical~~ selected hypothesis test is that there will be an interaction between levodopa and tDCS ~~dosage~~, specifically there will be a difference between the effect of ~~1mA and 2mA~~ active stimulation groups with and without levodopa, on freely moving thought. This will be assessed using a ~~3 (Stimulation: 2mA active, 1mA active, sham) x 2 (Drug: levodopa, placebo) Bayesian between-subjects ANOVA~~Bayesian independent samples t-test which compares the active levodopa group to the active placebo group on the stimulation block data alone, with the average freely moving thought responses as the dependent variable. This additional test has been selected as there is evidence levodopa may mediate the effects of tDCS on performance outcomes (Leow, Jiang, et al., 2023; Leow, Marcos, et al., 2023)~~that the effect of dopamine on tDCS outcomes may be dependent on the stimulation intensity~~, thus we believe finding an interaction between these factors would provide a meaningful contribution to the field.

Exclusion criteria

Participants (aged 18-40) must be right handed and meet the following criteria, in order to be included in the study: (1) English as their primary language; (2) No current use of psychiatric medication(s); (3) No current or previous psychiatric/neurological condition(s); (4) No current use of psychotropic drugs or blood pressure medication; (5) Not currently taking part in other tDCS studies and they must meet the tDCS safety screening questionnaire criteria (see supplementary materials; e.g. no implanted medical device or metal in the head). Participants will also be excluded and replaced in the data collection phase if they cannot understand the thought probes after training and additional clarification from the experimenter. After completing the screening and training on the task, participants will then be pseudo-randomly allocated to demographically balanced groups using a MATLAB script, which allows for the double-blinding of each subject's condition. This script will account for participants age, sex, time spent playing video games and musical instruments, hours of sleep from the previous night and whether their sessions are before or after 12:00pm (i.e., AM or PM).

Participants will also be excluded from the study and replaced during the testing phase if their responses to the end of session questionnaire suggest that the participant did not understand how to correctly generate random number sequences. Specifically, if participants cite that they used the same pattern throughout which repeated more than twice at a time (e.g. *z,z,z,m,m,z,z,z,m,m*) or if they state that they only alternated from one key to the other in the same order throughout, with one or more taps at a time on each key (e.g. *z,z,z,m,m,m,z,z,z,m,m,m*, or *z,m,z,m*), they will be excluded. ~~An example which would suggest the task has not been completed correctly would be if the participant cites a specific pattern that they used to approach the task (e.g., they repetitively used z,z,z,m,m,m,z,z,z,m,m,m to generate the sequences).~~ Finally, participants will be excluded and replaced during the testing phase if they do not comply with all instructions throughout the experiment or if there is any misfunctioning in the stimulation equipment during the session. This will also include if participants report any discomfort from the stimulation or if the Nurostym device identifies that the electrode impedances are too high and self-terminates the stimulation. Participants who meet any of the above exclusion criteria will be removed before the experimenter is unblinded to the data and they will be replaced during the data collection phase.

Behavioural assessments

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

The FT-RSGT task requires participants to respond in a random sequence to an ongoing metronome tone by pressing one of two response-buttons at a time (see Figure 3). This task has been selected to replicate the methodology used by Rasmussen et al. (2023) and because it is designed to be a more reliable test for detecting periods of mind wandering due to the large number of trials and more sensitive measures of task performance (Alexandersen et al., 2022; Boayue et al., 2021). The two response buttons correspond to two separate keys (‘z’ for left-hand and ‘m’ for right-hand). The metronome tone will be presented at 440Hz for 75ms, with a 750ms inter-stimulus interval and participants will be instructed to time their taps with the tone as accurately as possible. During the task, participants will be asked to maintain their focus on a white (RGB 255 255 255) fixation cross in the centre of the screen with a grey (RGB 128 128 128) background.

The task will be presented on a 24-inch LED monitor, with a refresh rate of 100 Hz. Participants will sit approximately 70cm away from the monitor and will use a standard Macintosh keyboard and mouse to respond. The auditory tone will also be presented through CREATIVE GigaWorks T40 Series II speakers. There will initially be 20 practice trials in the training block, which can be completed twice to consolidate participants understanding of the task. Participants will then complete training on the thought probes, followed by another 20 practice trials, including an example of the four thought probes after the final trial. There will then be a baseline block that consists of 720 trials, running for approximately 10 minutes, before participants are administered with levodopa or a placebo and have a 40-minute wait preceding the stimulation block. The stimulation block will include 2160 trials, which will run for approximately 30 minutes, including a 30 second break after approximately 15 minutes.

Figure 3. Finger-Tapping Random-Sequence Generation Task. Illustration of the two keys participants will use to generate the random sequences (on the left) and the display screen (on the right).

There will be two measures of task performance: the randomness of the sequence and participants variability in the timing of their responses. The randomness of participants sequences will be determined by a measure of approximate entropy, which is designed to calculate the predictability of the next item in a sequence, based on a specified number of previous items, *m*. This study will employ an $m = 2$, which replicates the *m* value used by Rasmussen et al. (2023). This measure was selected as there is evidence for a relationship between executive functioning and randomness, such that directing more executive resources towards the FT-RSGT, will result in more random sequences (Boayue et al., 2021). Thus, a smaller ApEn score indicates more repetitive patterns in the data and a larger score represents greater randomness in the patterns, which can be used to infer participants are more focused on the task. Participants performance will also be measured through behavioural variability, which is the deviation in their responses from the metronome tone. This will be calculated using the 20 trials prior to each set of mind wandering probes, where the standard deviation of the difference between the tone and response for these trials will be included in the analyses.

Mind wandering probes

There will also be four thought probes presented throughout the task, which are designed to assess the contents of participants thoughts. The four probes will appear together each time and they will be pseudo-randomly presented every 45 to 75 seconds during the baseline and stimulation blocks. Thus, there will be a total of 10 probes in the baseline block and 30 probes in the stimulation block. The four questions will be: (1) Before the probe, were you thinking about something other than the random sequence generation task; (2) Before the probe, was your mind wandering around freely; (3) Were you actively directing your thoughts; and (4) Was your mind stuck on something. The questions are designed to ask participants about their thoughts in the 10-15 seconds before the probes are presented. Participants will respond to each question on a 7-point Likert scale which ranges from “Not at all” (1) to “Very much” (7), with the middle point (4) labelled “Moderately”. These responses will be made using to 1-7 keys on the keyboard, and there will be no time constraints to respond.

Participants will be trained on the four thought probes at the beginning of the session, going through detailed explanations of the four types of thoughts, alongside example scenarios where they could occur. These explanations are based on Kam et al. (2021), however they are designed to replicate Rasmussen et al. (2023). Participants will then be tested on their understanding of the four questions by explaining their responses for each thought probe in the context of four example scenarios. The full description of the probes and examples can be

found in the supplementary materials. The thought probe information will be presented in the centre of a grey background (RGB 128 128 128) in white Arial font (visual angle = 1.1°).

Levodopa protocol

Each participant will begin the session with their blood pressure and heart rate being measured. After training on the task and a baseline block of the FT-RSGT, they will then receive either levodopa (Madopar® 125 tablet: Levodopa 100mg/ Benserazide Hydrochloride 25mg) or a placebo tablet (Centrum® for women multivitamin). The Madopar table combines levodopa and benserazide hydrochloride to prevent the immediate uptake of the drug, as the benserazide component is unable to cross the blood-brain barrier which inhibits the early conversion of levodopa to dopamine (Contin & Martinelli, 2010). To double blind the main experimenter and participant to the drug condition, an additional experimenter who is not otherwise involved in the testing sessions will oversee the drug protocol. Participants will then be required to wait approximately 40 minutes after the drug administration before completing the stimulation block, to ensure the task is undertaken when the plasma concentration is around its peak (Contin & Martinelli, 2010). At the end of the session, participants and the experimenter will be asked to select which dopamine drug manipulation group they were in (levodopa, placebo), to assess the efficacy of the drug manipulation blinding. They will again be assessed on their confidence in this decision, asking "How confident are you in your judgement of your dopamine drug condition?". The responses will be rated on a 7-point Likert scale, ranging from "Not at all confident" (1) to "Extremely confident" (7), with the midpoint as "Moderately confident" (4). This data will be used to compare the proportion of correct guesses across both conditions, whereby a lower proportion of correct guesses across the two groups would indicate that the blinding was effective for these conditions.

Stimulation protocol

Each participant will receive 2mA anodal or sham HD-tDCS over the left PFC ~~at either 1mA or 2mA~~. The stimulation will be delivered online, in conjunction with the FT-RSGT, with each participant receiving one of ~~three~~ two stimulation protocols in conjunction with either the levodopa or placebo drug (~~4~~6 groups in total). Whether stimulation is active or sham will be double-blinded. ~~However, it is not possible to blind the experimenter to the tDCS intensity, as this must be manually entered for each session.~~ At the end of the session, participants and the experimenter will be asked whether they received active or sham stimulation~~, and whether this~~

~~was at a high or low dose~~, to assess the effectiveness of the blinding. Participants and the experimenter will also be asked to rate their confidence in their decisions, asking, "How confident are you in your judgement of your stimulation condition?". ~~They will also be asked "How confident are you in your judgement of your stimulation dosage?". Both~~ This question~~s~~ will consist of a 7-point Likert scale, ranging from "Not at all confident" (1) to "Extremely confident" (7), with the mid-point labelled as "Moderately confident" (4).

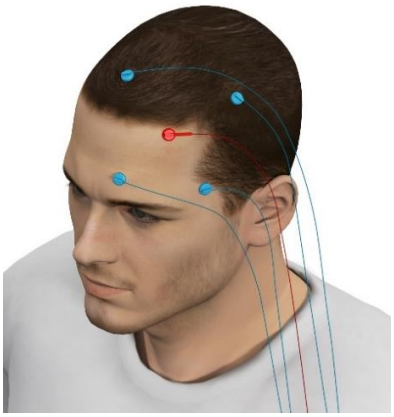

Figure 4. HD-tDCS montage. The PFC arrangement, with the target electrode at F3 and the surrounding four cathodes.

HD-tDCS montage

The electrode placement will be determined using the International 10-20 EEG system, with the anode placed over F3 and the four surrounding reference cathodes at F7, Fp1, C3 and Fz (see Figure 4). This is designed to replicate the PFC montage used by Rasmussen et al. (2023). The HD-tDCS will be administered at ~~either 1.0mA or~~ 2.0mA current intensity, with ~~0.25mA or~~ 0.5mA to each of the four reference electrodes, respectively. The stimulation will be delivered using a Nuerostym stimulator, with a 4 x 1 ring electrode arrangement. The electrodes will be 12mm Ag/AgCl electrodes which are secured to the scalp using a cap and conductive gel. The stimulation will last for 30 minutes, including a 30 second ramp up and down period. The sham stimulation will be delivered for 75 seconds, with the same ramp up and ramp down times. ~~Half the sham participants will have stimulation delivered at 1.0mA and half will have stimulation delivered at 2.0mA, equally balanced across the levodopa and placebo groups.~~ All participants will first complete a 10-minute baseline block of the FT-RSGT, before completing 30-minutes of ~~1mA or~~ 2mA~~,~~ active or sham stimulation in conjunction with the task. ~~The stimulation will be immediately terminated if participants report experiencing any discomfort, or if there are any technical difficulties, including if Nurostym device identifies that the electrode impedances are too high, and self-terminates the stimulation.~~

Self-report questionnaires

Given the FT-RSGT requires participants to respond accurately in time to a metronome tone, it is important to account for any influence of video game or musical training on participant's response variability. Thus, at the beginning of the session, participants will be asked how many hours they spend playing video games and musical instruments each week, and this information

will be entered into the randomisation script to ensure these two variables are balanced across the four groups (see supplementary materials). Measures of heart rate, blood pressure and mood will also be taken at the beginning and at the end of the session. Mood will be assessed via the Bond-Lader Visual Analogue Scale (BL-VAS; Bond & Lader, 1974), which is a sixteen-item scale, with each element rated on a 10-point analogue scale. The total score will be calculated across all the items.

During the HD-tDCS electrode set up, participants will also be given two tests, designed to measure trait impulsivity and participants' morningness and eveningness predisposition. This is because there is evidence to suggest that individual's attentional impulsiveness is correlated with variation in dopamine D2 and D3 receptor availability (Buckholtz et al., 2010; Taylor et al., 2018). Furthermore, individuals' circadian arousal rhythms, measured via their disposition as a morning or evening person, have also been found to be correlated with cognitive control functions (Anderson et al., 2014) and an individual's propensity to mind wander (Carciofo et al., 2013, 2014). The Barratt Impulsivity Scale (BIS-11) is a 30-item questionnaire, which rates each item on a 4-point Likert scale from "Rarely/Never" (1) to "Almost always/always" (4). It is designed to assess three factors which predict impulsive personality traits: attentional (attention and cognitive instability impulsiveness), motor (motor and perseverance), and non-planning (self-control and cognitive complexity). The Morningness-Eveningness questionnaire (Horne & Ostberg, 1976) will be used to assess participants activity and alertness across different times of day. There are 19 items, consisting of both Likert and time-scale questions, which are totalled to obtain a global score. This is converted into a 5-point scale, designed to categorise the different circadian rhythms across participants.

In addition, mind wandering has been found to be associated with individual's trait mindfulness abilities and with pervasive negative thoughts, or ruminative thoughts (Jonkman et al., 2017; Mrazek et al., 2012). Furthermore, there is evidence to suggest that ADHD symptomology is predictive of mind wandering (Franklin et al., 2017; Jonkman et al., 2017) and deficits in dopamine concentrations have also been found in clinically diagnosed ADHD patients (Mehta et al., 2019). Thus, there will be three questionnaires given at the end of the session to control for any individual differences in these variables between the experimental conditions. These questionnaires include the Mindful Attention and Awareness Scale (MAAS), the Rumination Response Scale and the Adult ADHD Self-Report Scale (see supplementary materials for questionnaire details). The MAAS assesses how present participants are in their daily lives via 15 items which are rated on a 6-point scale ranging from "Almost Always" (1)

to “Almost Never” (6). Participants scores are calculated via the mean of the 15 items, with higher levels of mindfulness being represented by higher scores. The Rumination Response Scale will be included to assess how often participants engage in different ruminative thoughts when they are feeling down, sad, or depressed. Participants will rate each of the 22 items on a 4-point Likert scale from “Almost never” (1) to “Almost always” (4) and the scores will be added together. Greater ruminative thoughts will be represented by higher total scores. Finally, the Adult ADHD Self-Report Scale is made up of 18 questions which are designed to capture the frequency that participants exhibit symptoms associated with ADHD. All questions are rated on a 5-point Likert scale, ranging from “Never” (1) to “Very Often” (5), with the total score calculated by totalling all the ratings together and higher scores indicate a greater number of ADHD tendencies.

The end of session questionnaire will also include a detailed assessment of participants involvement with video games and musical instruments, alongside questions addressing participants perspective on their task performance and their experience with the drug and stimulation. Finally, participants will be asked to rate their motivation to complete the task on a 7-point Likert scale ranging from “Not at all motivated” (1) to “Extremely motivated” (7). This question will ask participants, “How motivated were you to perform well in this task?” (Seli et al., 2015). Motivation levels have been linked to task performance outcomes (Brosowsky et al., 2020) and there is evidence to suggest dopamine levels are linked to motivation (Mohebi et al., 2019), thus it is important to assess the motivation levels between the ~~six~~ four groups to ensure there are no differences which may be influencing the results. For the full end of session questionnaire, refer to the supplementary materials.

Proposed analyses

Overview

At the end of each participants session, all raw data files will be uploaded to The University of Queensland Research Data Manager cloud storage. All analyses will be completed using a combination of JASP and RStudio, specifically employing the *brms* (Bayesian Regression Models using Stan; Bürkner, 2017) and *BayesFactor* packages (Mulder et al., 2021). There is currently no previous research investigating the effect of dopamine concentrations and stimulation ~~intensity~~ on individuals’ propensity to mind wander, thus this study will employ a default Jeffreys-Zellner-Siow prior of r = 0.707, centred around 0 (Rouder et al., 2009). All analyses will assess whether the results are more likely under the null or ~~alterative~~ alternative model, which will be interpreted by BF_{10} and BF_{01}. Here, we will use a conservative approach

to interpret BF values, with BF_{10} > 6 and BF_{01} > 6 taken to represent meaningful evidence for an alternative or null effect, respectively. ~~Consistent with the standard interpretation of Bayes Factors, BF_{10} of 1-3 or BF_{01} of 1-3 will be considered anecdotal evidence for the alterative or null hypothesis, respectively. BF_{10} of 3-10 or BF_{01} of 3-10 will be considered moderate evidence in for the respective hypothesis, and BF_{10} > 10 or BF_{01} > 10 will be considered strong evidence for the alterative or null hypothesis, respectively~~ (Lee & Wagenmakers, 2013)~~.~~ The analyses will primarily focus on the effects of stimulation and dopamine on freely moving thought and task unrelated thought, as these thought types have previously been shown to be modulated by tDCS applied to the left PFC (Boayue et al., 2021; Filmer et al., 2019; Rasmussen et al., 2023), however the effects on deliberately and automatically constrained thought will also be investigated in a more exploratory manner.

Post-study data exclusion

The post-study exclusion criteria for participants will replicate the criteria used by Rasmussen et al. (2023) and will be employed once data collection is completed, thus these participants will not be replaced in the final sample. Firstly, across all participants in the baseline block, individuals who score more than 3 standard deviations above or below the sample mean for their approximate entropy and behavioural variability scores will be excluded from the study. Furthermore, in the stimulation block, participants will be removed if they score more than 3 standard deviations above or below their respective group's mean for their approximate entropy or behavioural variability scores, or their mean responses to any of the four thought probes. Finally, to ensure that extreme outliers during the task do not skew any time on task effects, individual trials which are greater than 3 standard deviations above or below the mean for each group's approximate entropy and behavioural variability scores will also be removed from the analyses.

Applying modelling to investigate the dynamic thought types

This study will primarily employ hierarchical order probit modelling to investigate the effects of HD-tDCS and dopamine on the dynamic thought types (Alexandersen et al., 2022; Boayue et al., 2021; Rasmussen et al., 2023). This analysis technique treats the thought probe responses as ordinal data, which allows for investigation into time on task effects and individual's response variability across the duration of the task (Rasmussen et al., 2023). Participants thought probe responses will be entered as the dependent variable into the models and there will be several predictor variables, relating to the measures of task performance (behavioural

variability and approximate entropy), block and trial data, alongside their interactions, however participants stimulation condition (2mA active~~, 1mA, or~~ vs. sham) or dopamine condition (levodopa vs. placebo) will be entered in as the key predictor for the respective analyses~~,~~. The specific predictors employed in each probit model are ~~which are~~ explained in detail below. The model weights will be interpreted using two methods. The first method is by calculating the pareto smoothed importance sampling leave-one-out cross-validation scores (PSIS-LOO; Vehtari et al., 2017, 2022) and then comparing the LOO information criterion values (LOOIC; Vehtari et al., 2017) using a stacking procedure (Vehtari & Gabry, 2018; Yao et al., 2018). The second method is applying pseudo-Bayesian model-averaging (pseudo-BMA; Vehtari & Gabry, 2018; Yao et al., 2018).

In analyses where the LOOIC and pseudo-BMA winning models do not agree on a preferred model, the winning LOOIC model will be interpreted, as this method has been found to have greater predictive accuracy when the true model is not in the model list, by selecting the model with the best predictive distribution (Vehtari & Gabry, 2018; Yao et al., 2018). This is consistent with the analysis practices used by Rasmussen et al. (2023). Where there are inconsistencies in model interpretations, they may be driven by differences in the amount of data for the baseline (10 probe sets) and stimulation (30 probe sets) phases. Thus, where needed to address model discrepancies, the model comparisons will be re-run on the stimulation data alone.

The effect of HD-tDCS on task unrelated and freely moving thought

We hypothesise that 2mA anodal HD-tDCS to the left PFC will reduce freely moving thought, relative to the sham condition (H_{1a}). We also hypothesise that 2mA anodal HD-tDCS will reduce task unrelated thought, relative to the sham condition (H_{1b}). We will first employ the hierarchical order probit modelling to investigate the effect of ~~2mA~~ anodal stimulation on both thought types, alongside the effects of stimulation on task performance. This will consist of comparing 23 models, increasing in complexity, which include the following predictor variables and their interactions: stimulation (~~2mA~~ active vs. sham), behavioural variability, approximate entropy, trial, and block (baseline vs. stimulation). There will be one probit model assessing the effects on freely moving thought, and the other assessing the effects on task unrelated thought.

In addition, to investigate the direct effect of ~~2mA~~ stimulation on both freely moving and task unrelated thought, we will employ a Bayesian independent samples t-test for both thought types. The t-test will compare ~~to 2mA~~the active anodal HD-tDCS group to the sham

group, for participants who are in the placebo drug condition. While tests will be conducted for both thought probes, the results from the freely moving thought t-test is one of the two ~~critical~~ tests used for the stopping rule in~~for~~ this study, as there was evidence for 2mA anodal stimulation reducing freely moving thought found by (Rasmussen et al., (2023).

~~**The effect of HD-tDCS dosage on task unrelated and freely moving thought**~~

~~We are also interested in the how HD-tDCS dosage (1mA vs. 2mA) affects the frequency of the distinct thought types. Specifically, we predict that there will be a difference between the effect of the 1mA and 2mA active HD-tDCS conditions on freely moving thought (H_{2a}). We also predict there will be a difference in the effect of 1mA and 2mA active HD-tDCS on the frequency of task unrelated thoughts (H_{2b}). Thus, we will employ the hierarchical order probit modelling approach to compare the effect of 2mA and 1mA stimulation on both freely moving and task unrelated thoughts, alongside any meaningful effects on task performance. For both thought types, this will involve comparing 23 models of increasing complexity which include the following predictor variables and their interactions: stimulation (2mA vs. 1mA), behavioural variability, approximate entropy, trial, and block (baseline vs. stimulation).~~

~~Furthermore, we will use two Bayesian independent samples t-tests to investigate the direct dosage effects. There will be one test for freely moving thought responses and the other for task unrelated thought responses, with both comparing the 2mA anodal HD-tDCS group to the 1mA anodal HD-tDCS group, for participants who are in the placebo drug condition.~~

The effect of dopamine on task unrelated and freely moving thought

As there is evidence hinting at a relationship between dopamine and mind wandering (Cools, 2008; O'Callaghan et al., 2021), we are also interested in investigating the direct effects of dopamine on freely moving and task unrelated thoughts. We hypothesise that there will be an effect of levodopa, relative to the placebo drug, on freely moving and task unrelated thought (H_{3}~~$_2$~~). To assess these effects, we will use two hierarchical order probit models – one with freely moving thought as the outcome variable and the other assessing the effects on task unrelated thought responses. Each probit model will consist of 23 models of increasing complexity, which include the following predictor variables and their interactions: pharmacological manipulation (levodopa vs. placebo), behavioural variability, approximate entropy, trial, and block (baseline vs. stimulation). For both thought types, we will also assess the direct effect of dopamine by applying a Bayesian independent samples t-test, comparing

the levodopa condition to the placebo condition, for participants who are allocated to the sham group.

The interactive effects of dopamine and stimulation on the dynamic thought types

Given findings that suggest the effects of tDCS on behavioural outcomes may be mediated by individuals' dopamine concentration (Leow, Marcos, et al., 2023)~~, alongside the dosage that the stimulation is delivered at~~ , this study predicts there will be a difference in the effect of ~~1mA and~~ 2mA HD-tDCS, in combination with levodopa on freely moving thought and task unrelated thought, relative to the active stimulation with placebo group~~s~~ (H_{43}). This will first be analysed using ~~a 3 (Stimulation: 2mA active, 1mA active, sham) x 2 (Drug: levodopa, placebo) Bayesian between-subjects ANOVA, to assess the interaction between HD-tDCS dosage and levodopa. This ANOVA will be employed for both freely moving and task unrelated thought, however the freely moving thought analysis will be the second critical test for this study. This test has been selected, as we believe a meaningful interaction between stimulation dosage and dopamine will contribute to our understanding the neurochemical mechanisms underlying mind wandering.~~

~~We will also employ~~ hierarchical order probit modelling to assess the combined effect of stimulation and dopamine~~, at each stimulation dosage~~. There will be ~~two~~ a probit model~~s~~ run ~~each~~ for both freely moving and task unrelated thought, with 23 models included in ~~the four analyses~~each. ~~The first two probit models will include the following predictors and their interactions: drug-stimulation combination (1mA active stimulation with levodopa vs. 1mA active stimulation with placebo), behavioural variability, approximate entropy, trial, and block (baseline vs. stimulation). The second two probit models~~Specifically, they will include the ~~alternative drug-stimulation combination as the~~ key predictor as: (~~2mA~~ active stimulation with levodopa vs. ~~2mA~~ active stimulation with placebo), alongside the additional predictors – behavioural variability, approximate entropy, trial, and block (baseline vs. stimulation).

~~Finally~~Furthermore, there will be ~~two~~ a Bayesian independent samples t-tests employed for both freely moving and task unrelated thought, to assess the effect of stimulation in conjunction with dopamine ~~at each HD-tDCS dosage~~. ~~The first t-tests~~They will compare the ~~1mA active HD-tDCS in conjunction with levodopa group to the 1mA active HD-tDCS with placebo group for each thought type and the second tests will compare the 2mA~~ active HD-tDCS with levodopa condition to the ~~2mA~~ active HD-tDCS with placebo condition for each thought type. Importantly, the freely moving thought t-test will also be used to determine the stopping rule for this study. This test has been selected, as we believe a meaningful interaction

between stimulation dosage and dopamine will contribute to our understanding the neurochemical mechanisms underlying mind wandering.

Control analyses

The application of levodopa can occasionally result in side effects including nausea (Chen et al., 2020) and changes in mood state (Beaulieu-Boire & Lang, 2015). Thus, to ensure that there are no changes in blood pressure, mood, or heart rate due to the drug administration, we will run three 2 (Time: before drug administration, ~2 hours after drug administration) x 2 (Drug: levodopa, placebo) Bayesian between-subject ANOVAs, with blood pressure (diastole and systole), BL-VAS scores and heart rate as the dependent measures, respectively. We will interpret a BF_{excl} > ~~3~~ 6 for the interaction term as moderate evidence for there being no meaningful differences between the groups and thus the null hypothesis would be accepted.

Testing for baseline differences

To investigate any group differences in participants' responses in the self-report measures, we will use five one-way between-subjects ANOVAs. This will include responses for the BIS-11, the Morningness-Eveningness questionnaire, the Adult ADHD Self-Report Scale, the Rumination Response Scale, and the MAAS, as the respective dependent measure for the five ANOVAs. The ~~six~~ four stimulation conditions will also be included as the predictor variable in each analysis (sham HD-tDCS with placebo; sham HD-tDCS with levodopa~~; 1mA anodal HD-tDCS with placebo; 1mA anodal HD-tDCS with levodopa~~; ~~2mA~~ anodal HD-tDCS with placebo and ~~2mA~~ anodal HD-tDCS with levodopa). If there are any meaningful differences found between the groups for any ANOVA, these will be followed up using t-tests, and any measures with meaningful group differences will also be included as a covariate in the modelling analyses.

To ensure there are no differences between the groups in their baseline responses to the thought probes, we will also rerun the ~~3~~2 (Stimulation: ~~2mA~~ active~~, 1mA active~~, sham) x 2 (Drug: levodopa, placebo) Bayesian between-subjects ANOVA on the baseline data alone, for both freely moving thought and task unrelated thought. We will interpret a BF_{excl} > ~~3~~ 6 for the interaction term as moderate evidence for there being no meaningful differences between the groups and thus the null hypothesis would be accepted.

Assessing blinding

We will be assessing the effectiveness of the blinding for ~~both~~ the stimulation ~~condition and stimulation dosage, alongside the~~and pharmacological conditions that participants are allocated to. For each of these factors, we will assess the proportion of correct guesses between the two groups – the active and sham stimulation conditions; ~~the high and low dosage conditions;~~ and the levodopa compared to placebo conditions. This will be assessed for both the participants and the experimenters.

Exploratory investigation into deliberately and automatically constrained thought

In addition to assessing the effects of HD-tDCS and dopamine on freely moving and task unrelated thought, we will also assess these effects on deliberately constrained and automatically constrained thought. As there is no evidence to date for these thought types being modulated via tDCS to the PFC (Rasmussen et al., 2023), these analyses will be exploratory. We will run the same hierarchical order probit analyses used in the central analyses above, employing 23 models of increasing complexity, with the key predictor alternating between stimulation, ~~dosage,~~ and drug, to assess these effects on each thought type. We will also include the following predictors and their interactions in all the probit models: behavioural variability, approximate entropy, trial, and block (baseline vs. stimulation). However, to investigate the effect of ~~2mA~~ stimulation, we will employ one probit model for each thought type, including stimulation (~~2mA~~ active vs. sham) as the additional predictor. ~~We will then run one model for both deliberately and automatically constrained thoughts using stimulation dosage (2mA vs. 1mA) as the additional predictor of interest.~~ In addition, we will run two models, one for both thought types, which include the dopamine condition (levodopa vs. placebo) as the added key predictor. Finally, to investigate the interactive effect of stimulation and dopamine we will run ~~two~~ one model~~s~~ for both deliberately and automatically constrained thoughts. ~~One pair of models will include 1mA active stimulation with levodopa vs. 1mA active stimulation with placebo as the predictor of interest and the second~~This pair of models will include ~~2mA~~ active stimulation with levodopa vs. ~~2mA~~ active stimulation with placebo as the key predictor.

In addition to the modelling analyses, we will employ the same Bayesian independent samples t-tests which are applied in the main analyses. Each t-test will be run for both deliberately constrained thoughts and automatically constrained thoughts. We will first compare the ~~2mA~~ anodal HD-tDCS group to the sham group, for participants who are in the placebo drug condition. ~~We will then assess the effect of stimulation dosage by comparing the 1mA anodal HD-tDCS group to the 2mA anodal HD-tDCS group, for participants in the placebo drug condition. In addition~~We will then~~, to~~ assess the effect of dopamine alone, ~~we~~

~~will compare~~by comparing the levodopa group to the placebo group, for participants in the sham condition. Finally, we will run ~~two~~ a t-test~~s~~ for each thought type, to assess the combined effect of stimulation and dopamine on the frequency of each thought probe. ~~The first pair of t-tests will compare 1mA HD-tDCS with levodopa to 1mA HD-tDCS with placebo and the second pair~~Each will compare ~~2mA~~ active HD-tDCS with levodopa to ~~2mA~~ active HD-tDCS with placebo. ~~To further explore the interactive effects, we will also run the 3 (Stimulation: 2mA active, 1mA active, sham) x 2 (Drug: levodopa, placebo) Bayesian between subjects ANOVA for each thought type.~~

~~Finally, to assess the effects of 1mA stimulation alone, we will run a Bayesian independent samples t-test for each of the four thought types, whereby the 1mA anodal HD-tDCS group will be compared to the sham group, for participants in the placebo drug condition. The effect of 1mA stimulation is not a critical investigation for this study, however it is important to also measure the independent role of this stimulation condition in modulating the reporting of the dynamic thought types. This analysis will allow a comparison between effects of the two stimulation conditions and will provide further insight into the potentially differential role of the two stimulation intensities on mind wandering and dynamic thought.~~

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