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The role of the left dorsolateral prefrontal cortex in the interplay between metacontrol and mind-wandering. Evidence from a HD-tDCS study

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Abstract

The metacontrol framework claims that cognitive control operates along a continuum between persistence and flexibility. While spontaneous mind-wandering is often considered a failure of control, emerging evidence suggests that different types of mind-wandering, intentional versus unintentional, may reflect distinct metacontrol dynamics. We examined how high-definition transcranial direct current stimulation (HD-tDCS) over the left dorsolateral prefrontal cortex modulates the interplay between metacontrol strategies and mind-wandering, using a global-local task combined with intermittent thought probes. Ninety-two participants completed a global-local task while receiving either anodal or sham HD-tDCS at 1.5 mA over the left dorsolateral prefrontal cortex. Mind-wandering episodes were assessed using thought probes, distinguishing between intentional and unintentional mind-wandering. Metacontrol tendencies were inferred from global precedence effects observed in response accuracy and latency. HD-tDCS selectively enhanced accuracy in the local condition during the second half of the task, suggesting an increase in persistence-oriented control. Intentional mind-wandering was positively associated with cognitive flexibility (greater global precedence), while unintentional mind-wandering correlated with persistence. However, stimulation did not directly affect mind-wandering rate. Our findings support a double dissociation between types of mind-wandering and metacontrol styles. They provide causal evidence that HD-tDCS over the left dorsolateral prefrontal cortex can promote persistence without altering spontaneous thought frequency, thereby validating and extending the metacontrol framework.

Introduction

When individuals engage in cognitive control to complete tasks, their performance can be characterized by two meta-control styles that vary along a continuum, from extreme persistence to extreme flexibility (Hommel, 2015; Hommel & Colzato, 2017; Hommel, Colzato and Beste, 2024; Mekern et al., 2019). These styles dictate whether an individual maintains a focused and sustained approach to the task at hand (persistence) or fluidly shifts attention between various approaches, tasks, ideas, and thoughts (flexibility). Variations in these control styles have been observed both within individuals (Ashby et al., 1999; Colzato et al., 2012, 2017; Fischer & Hommel, 2012) and between different individuals (Colzato et al., 2008, 2014; Colzato, van Beest, et al., 2010; Colzato, Waszak, et al., 2010; McKone et al., 2010; Stock et al., 2014). This adaptability allows humans to adopt different control styles based on specific tasks, challenges, cultures, religions, moods, or genetic factors.

Despite the human mind's capacity for complex cognitive tasks, it frequently experiences lapses in concentration, known as mind-wandering (hereafter MW). These episodes involve shifting attention away from the current task towards unrelated thoughts and internal reflections (Smallwood & Schooler, 2015). This phenomenon underscores the brain's dual capacity for intense focus and spontaneous diversion, reflecting a delicate balance between maintaining attention and engaging in introspective or imaginative thought. Consequently, mind-wandering not only exemplifies occasional lapses in focus but also highlights the intricate interplay between external task engagement and internal cognitive

processes (Martínez-Pérez et al., 2023; Thomson et al., 2015). Emerging evidence suggests that mind-wandering can occur spontaneously (unintentional) or deliberately (intentional) (Seli et al., 2015) and studying the triggers of mind-wandering reveals significant distinctions (Martínez-Pérez et al., 2021, 2023; Seli et al., 2016, 2018). For instance, monotonous tasks like the Psychomotor Vigilance Task (PVT) tend to produce a higher rate of intentional mind-wandering compared to more demanding tasks like the Sustained Attention to Response Task (SART) (Martínez-Pérez et al., 2021), which are associated with higher rates of unintentional mind-wandering (Martínez-Pérez et al., 2021; Seli et al., 2016).

Understanding the interplay between cognitive control styles (persistence-flexibility) and MW propensity is crucial, though rarely studied. The latter involves voluntary or involuntary shifts in attention from the task to self-generated thoughts and unrelated mental content, potentially influencing task performance depending on the predominance of persistence or flexibility. One can thus hypothesize that a tendency towards flexibility is linked to a higher propensity for MW or, more specifically, that the nature of MW (spontaneous or voluntary) correlates with the metacontrol strategies employed for task performance. Furthermore, these associations could have identifiable neural correlates. Recent advances in neuroscience have identified the dorsolateral prefrontal cortex (DLPFC) as a key regulator of both MW (Andrews-Hanna et al., 2014; Christoff et al., 2009; Stawarczyk et al., 2011) and metacognitive strategies (Beaty et al., 2015; Botvinick et al., 2001). Non-invasive brain stimulation techniques, such as transcranial direct current stimulation (tDCS), have been instrumental in establishing causal links between DLPFC activity and cognitive control styles. Specifically, tDCS studies have shown that modulating DLPFC activity can influence individuals' propensity for MW (Axelrod et al., 2015, 2018; Boayue et al., 2021; Filmer et al., 2019, 2021; Martínez-Pérez et al., 2023; and Nejati et al., 2023 with tACS) and their tendency towards persistence or flexibility in cognitive control (Andrews et al., 2011; Mayseless & Shamay-Tsoory, 2015; Zmigrod, 2014).

Despite these insights, the temporal dynamics of MW and metacontrol strategies under DLPFC modulation remain poorly understood. Our objectives here were threefold. First, we aimed to investigate the temporal course of metacontrol strategies and MW within a single experiment. Second, we sought to assess the effect of high-definition tDCS (HD-tDCS) over the DLPFC on the propensity for MW and the development of persistence or flexibility strategies in task performance. Finally, we aimed to understand how these metacontrol tendencies correlate with one another, depending on whether MW is triggered intentionally or unintentionally, a distinction that is crucial to consider when investigating MW with transcranial electric brain stimulation (Chaieb et al., 2019).

As a key objective of the present study was to track changes in time-on-task, mind-wandering (MW) and global-local performance under online HD-tDCS, we implemented a single continuous task stream beginning at stimulation onset rather than adding a separate baseline block. This was to avoid the possibility that an additional pre-stimulation block could induce practice and strategy-setting effects that would carry over to the stimulation period and complicate the interpretation of time-on-task dynamics. However, we acknowledge that the absence of a within-session baseline restricts our ability to unambiguously attribute observed group differences to stimulation-induced change versus pre-existing

differences. Accordingly, we present stimulation-related findings as between-group differences expressed over time under randomized assignment, and treat mechanistic conclusions as tentative, pending replication with baseline and/or active-control montages.

To address these objectives, we designed a study that evaluates MW through thought probes, in which participants are intermittently asked whether they are focused on the task or thinking about something else. Specifically, we incorporated thought probes at pseudo-random intervals to capture the temporal evolution of MW episodes. To examine metacontrol strategies, we used a version of the global-local task (Navon, 1977). We posited that people would tend to react more quickly to the broader global aspects compared to the smaller local details, a phenomenon referred to as the global precedence effect (GPE). Furthermore, this effect is more pronounced in certain individuals than in others and has been observed to vary within the same individual based on the circumstances. This variability has been linked to a flexible cognitive style, in contrast to a less prominent global precedence bias, which is associated with a more persistent and detail-oriented approach (Colzato, Hommel, et al., 2010; Colzato, van Beest, et al., 2010; Colzato, Van Hooidonk, et al., 2010; McKone et al., 2010). This approach allowed us to explore the effects of HD-tDCS over the DLPFC on the interplay between MW and metacognitive strategies within a single cognitive task.

Method

Participants

All participants were students at the University of Murcia who participated for course credits, and none of them had previously participated in any study on transcranial electrical stimulation. We used G*Power software (Faul et al., 2007) to determine the required sample size for achieving 80% power to detect a small effect (Cohen's d = 0.25) at an alpha level of 0.05. This calculation suggested that a sample of 46 participants would be sufficient to detect even a small effect of HD-tDCS on global-local task performance. However, given our additional interest in examining the effects of HD-tDCS on intentional and unintentional mind-wandering rates, we decided to collect data from a larger sample of 92 participants (mean age: 19.64, range: 18-29 years; 82 females), of which 45 were randomly assigned to the sham group and 47 to the stimulation (anodal) group.

The study was approved by the ethical committee of the University of Murcia, and all participants gave their informed consent before the experiment. The study adhered to the ethical principles outlined in the Declaration of Helsinki.

Apparatus and stimuli

Behavioral measures

The experiment was controlled using a Windows 10 equipped computer connected to a 22-inch TFT monitor with a resolution of 1920 × 1080 pixels, viewed at approximately 60 cm distance. Programming

and data analysis were conducted using E-Prime 3 software, and responses were recorded with a 5-button Chronos device from Psychology Software Tools. The task was adapted from Navon's (1997) global-local paradigm. Participants were instructed to identify a target stimulus in each trial, which consisted of the letters "A" or "L." These letters could be presented either as a large letter composed of smaller letters (global condition) or as the smaller letters themselves forming a larger letter (local condition).

Each trial began with a fixation point displayed for 1000 ms, followed by the target letter presented to the right or left of the fixation point for 150 ms. Participants then had 2000 ms to respond by pressing buttons 4 or 5 on the Chronos device. Feedback indicating the correctness of the response (correct/incorrect) was provided for 1500 ms. If no response was given within 2000 ms, it was recorded as an error, and the next trial commenced. Participants completed a total of 320 trials, encompassing 8 different combinations of global-local letters presented in randomized order, with the constraint that each combination occurred equally often within the entire session. For the global condition, we had 4 combinations: large A/small Ts, large A/small Hs, large L/small Ts, and large L/small Hs. For the local condition, we also had 4 combinations: small As/large T, small As/large H, small Ls/large T, and small Ls/large H. Participants ran 40 trials for each combination. As “Half” (first versus second) was a factor of interest, we also ensured that the distribution of trial types was balanced across halves, so that time-on-task effects could not be attributed to systematic changes in stimulus composition.

We assessed MW using intermittent thought probes, which were presented at fixed trial-count intervals. One probe occurred after every 16 trials, making 20 probes in total across 320 trials. Within this constraint, the probes were not dependent on task events or performance. A fixed interval was chosen to ensure comparable sampling density across participants and between the first and second halves of the session, a key factor of interest. The probe asked: 'Which of the following responses best characterizes your state of mind just before the presentation of this display?', with the following response options: “On-task”, “Intentional MW” and “Unintentional MW”. Participants received verbal and written instructions both for answering the thought probe questions and for the task itself. For the thought probes, participants were informed that "on-task" meant thinking about something related to the task (e.g., how difficult or boring it was or the buttons they had to press). They were provided with a definition of MW and a brief explanation of the difference between intentional and unintentional MW. Intentional MW referred to moments when they voluntarily thought about things unrelated to the task (e.g., a shopping list), while unintentional MW referred to involuntary thoughts about unrelated matters (e.g., a past event suddenly coming to mind). Participants were explicitly told that there were no right or wrong answers and were encouraged to respond honestly. They used buttons 1, 2, and 3 on the Chronos device to choose between the three response alternatives: on-task, intentional MW, or unintentional MW with unlimited time to respond.

HD-tDCS setup

The HD-tDCS was administered online using a Starstim 8 device and Sponstim sponge-based electrodes with a circular area of 8 cm², controlled through NIC v2.0.11.7 software (Neuroelectrics®, Barcelona). The target brain area for anodal stimulation was the left dorsolateral prefrontal cortex (l-DLPFC), located at F3 according to the 10-20 system. Three return electrodes, T7, Cz, and Fp2, were positioned in a triangular configuration, each with a 33% current return (Figure 1A, 1B), and the intensity was set at 1.5 mA. This form of high-definition montage has been demonstrated to enhance the focality of stimulation (Kuo et al., 2013), and it has proven effective in modulating the DLPFC in previous studies conducted in our laboratory (Martínez-Pérez et al., 2019, 2022, 2023). Stimulation was delivered online for 15 minutes from the start of the task, including a 30-second ramp-up/ramp-down period. Sham stimulation consisted of these ramp periods only, to mimic scalp sensations. The 15-minute duration was chosen to align with standard HD-tDCS protocols targeting the prefrontal cortex, while also minimizing participant burden and ensuring sufficient time for stimulation during the initial stages of the task. As the main objective was to determine whether increasing the excitability of the left dorsolateral prefrontal cortex (l-DLPFC) influences the control policy towards persistence, an anodal-versus-sham comparison was implemented.

The study employed a double-blind design, whereby neither the investigator nor the participant knew what type of tDCS stimulation was being delivered. This procedure was implemented using NIC2 software provided by Neuroelectrics to ensure that neither expectations nor biases influenced the outcomes. Importantly, after completing the task, participants were asked to complete a brief questionnaire about blinding, indicating whether they believed they had received active or sham stimulation. Their guesses did not differ from the level of accuracy expected by chance.

Procedure

After registering for the experiment via the university email distribution list, participants were scheduled to perform the experiment in situ, with sessions conducted between 10 AM and 4 PM. On the day of the experiment, participants were randomly assigned to either the sham or tDCS group using a double-blind design. Participants then performed the modified version of the global-local task in individual soundproof rooms. Upon completing the task, they were asked to finish the session by completing a brief transcranial electrical stimulation blinding efficacy survey. A detailed scheme of the procedure is depicted in Figure 1C.

>> Insert Figure 1 here <<

Statistical analyses

Data were analyzed using JASP 0.18.3, with a significance level set at $\alpha = 0.05$. The primary objective of this study was to investigate the temporal course (first vs. second half) of the global-local task and the thought probes and to determine whether participants modulated their global-local scores and MW rates as a function of HD-tDCS stimulation. Additionally, we examined correlations between MW and global-local measures using Pearson correlation analysis.

Three analyses of variance (ANOVAs) were conducted. The first ANOVA used MW rate as the dependent variable, while the other two utilized accuracy and response time (RT) in the global-local task as dependent variables. In the first analysis, Half (first half, second half) and MW Intentionality (intentional, unintentional) were the within-participant factors, and Stimulation (anodal, sham) was the between-participant factor. For the second and third ANOVAs, Half (first half, second half) and Target type (global, local) were the within-participant factors, with Stimulation (anodal, sham) as the between-participant factor. The Greenhouse-Geisser correction was applied to all tests, and further simple effects analyses were conducted only when interactions were significant. All post hoc tests were corrected using Tukey's method. Descriptive statistics were reported as the mean and standard error of the mean (SEM).

Results

Mind-wandering

The rate of both intentional and unintentional MW, measured as the proportion of each MW probes among all thought probes, showed that the rate of unintentional MW was significantly higher than the rate of intentional MW, $F(1, 90) = 69.06$, $p < 0.001$, $\eta^2 = 0.225$ (M = 0.082, M = 0.268, respectively). The Half factor was also significant, $F(1, 90) = 65.52$, $p < 0.001$, $\eta^2 = 0.048$, indicating a greater MW rate during the second half of the task (M = 0.218) compared to the first half (M = 0.132). Importantly, the Half × Intentionality interaction was also significant, $F(1, 90) = 7.145$, $p = 0.009$, $\eta^2 = 0.008$. The interaction analysis revealed that, although both intentional and unintentional MW increased significantly from the first to the second half of the task, unintentional MW exhibited a greater relative increase (all ps < 0.001, see Figure 2A). None of the other factors or their interactions reached statistical significance (all Fs < 1), indicating that the stimulation did not affect MW.

Global-Local task (RT)

The Half factor reached statistical significance, $F(1, 90) = 103.86$, $p < 0.001$, $\eta^2 = 0.069$, indicating that participants responded faster in the second half of the experiment (M = 422 ms) compared to the first half (M = 484 ms). The Target type factor was also statistically significant, $F(1, 90) = 267.98$, $p < 0.001$, $\eta^2 = 0.94$, with faster responses observed under the global condition (M = 417 ms) compared to the local condition (M = 489 ms). That is, we replicated the standard global precedence effect (GPE) (Navon, 1977) with this version of the global-local task. Additionally, the Half × Target type interaction was also significant, $F(1, 90) = 7.45$, $p = 0.008$, $\eta^2 = 0.006$. Post-hoc tests, corrected for multiple comparisons, revealed significant differences for all contrasts except the comparison between first-half-global and second-half-local responses. None of the other factors or their interactions reached statistical significance (all Fs < 1), indicating that tDCS did not affect global-local RTs.

Global-Local task (ACC)

The Half factor reached statistical significance, $F(1, 90) = 14.89$, $p < 0.001$, $\eta^2 = 0.012$, indicating that participants were more accurate in their responses in the second half of the experiment (M = 0.95) compared to the first half (M = 0.93). The Target type factor was also statistically significant, $F(1, 90) = 90.31$, $p < 0.001$, $\eta^2 = 0.17$, showing more accurate responses under the global condition (M = 0.96) compared to the local condition (M = 0.92). This outcome replicated the GPE in accuracy data, as observed with RTs.

Importantly, the Half × Target type × Stimulation interaction was also significant, $F(1, 90) = 9.81$, $p = 0.002$, $\eta^2 = 0.007$ (see Figure 2B). To further explore this interaction, we conducted separate ANOVAs for the sham and active anodal conditions. For the sham condition, significant main effects were observed for both the Half factor, $F(1, 44) = 6.5$, $p = 0.004$, $\eta^2 = 0.021$, and the Target type factor, $F(1, 44) = 41.89$, $p < 0.001$, $\eta^2 = 0.315$ (demonstrating the GPE). However, the Half × Target type interaction was not significant, $F(1, 44) = 1.94$, $p = 0.171$, $\eta^2 = 0.007$.

Conversely, in the tDCS condition, the ANOVA revealed a significant Half × Target type interaction, $F(1, 44) = 9.29$, $p < 0.001$, $\eta^2 = 0.315$. Inspection of Figure 2B suggests that, under anodal stimulation, accuracy for local targets increased from the first (M = 0.89) to the second half (M = 0.92) of the task, $t(46) = 3.78$, $p < 0.001$, Cohen's $d = 0.124$. This is consistent with improved maintenance of detail-oriented processing under increasing time-on-task demands. In contrast, anodal stimulation had no significant effect on accuracy in the global condition over time, $t(46) = 0.131$, $p = 0.89$, Cohen's $d = 0.085$ (M = 0.96, for the first and second halves).

Correlation between MW and Global-Local task

To explore the relationship between the propensity for MW and the biases toward persistence-flexibility, we constructed a Pearson correlation matrix encompassing measures of global intentional MW, unintentional MW, the Global Precedence Effect in response times (GPE-RT), and the Global Precedence Effect in accuracy (GPE-ACC). These analyses are exploratory and do not model either within-session temporal dynamics or group-specific coupling. Therefore, they should be interpreted as associations between participants rather than as evidence of co-fluctuations within individuals over time. The correlation matrix is presented in Figure 2-C (see Figure 2-D for illustrating the density graphs of those correlations). A positive correlation was observed between intentional MW and GPE-ACC ($\rho = .267$, $p = 0.01$), while unintentional MW showed a negative correlation with GPE-ACC ($\rho = -.210$, $p < 0.05$). None of the other correlation pairs reached statistical significance.

>> Insert Figure 2 here <<

Discussion

This study offers new empirical evidence for the dynamic interplay between metacontrol modes and MW, and how this interaction can be modulated through HD-tDCS over the l-DLPFC. This study examined: (i) how intentional and unintentional motor work (MW) evolves over time; (ii) how global–local performance indices relate to MW intentionality; and (iii) whether anodal high-density transcranial direct current stimulation (HD-tDCS) targeting the left dorsolateral prefrontal cortex (DLPFC) modulates these patterns. Three key findings emerged. Firstly, both intentional and unintentional mind wandering (MW) increased from the first to the second half of the task, with a relatively larger increase for unintentional MW. Secondly, anodal stimulation did not alter overall MW rates. Thirdly, we observed stimulation-related modulation of accuracy selective to local processing in the second half of the task.

Importantly, as the design did not include a pre-stimulation baseline block or an active-control stimulation site, we interpret the stimulation-related pattern as indicating a bias towards persistence-oriented processing under time-on-task demands according to the metacontrol framework proposed by Hommel and Colzato (2017). However, we refrain from making strong claims about region-specific mechanisms. Replication involving baseline measurements and an active control montage would strengthen anatomical and mechanistic inferences.

One of the key contributions of our study is the demonstration of a double dissociation between intentional and unintentional MW and their relationship to metacontrol tendencies. Specifically, we observed that intentional MW was positively correlated with the GPE in accuracy, an index of cognitive flexibility, whereas unintentional MW was negatively associated with the same measure, indicative of a more persistence-oriented style. These results align with previous studies by Hommel, Colzato, and colleagues showing that flexible cognitive styles are associated with greater responsiveness to global-level information and broader attentional scopes (Colzato et al., 2010; Hommel & Colzato, 2017).

This distinction further supports the view that intentional MW may reflect an adaptive form of internal cognition, akin to what Hommel and Colzato (2017) describe as the flexible mode of control, where internal thoughts are generated deliberately and may serve creative or future-oriented purposes (Smallwood & Schooler, 2015). In contrast, unintentional MW appears to emerge from lapses in metacontrol persistence, consistent with a loss of top-down regulation typical of a persistence-dominated control mode as time-on-task progresses (McVay & Kane, 2010; Seli et al., 2016).

Despite these clear associations, HD-tDCS did not significantly affect the overall frequency of either form of MW. This absence of a direct stimulation effect on spontaneous thought aligns with previous mixed findings in the literature (Axelrod et al., 2015; Filmer et al., 2019; Martínez-Pérez et al., 2023; Rasmussen et al., 2024) and suggests that modulating MW propensity may require broader network-level stimulation, including medial prefrontal and default mode regions. Nonetheless, HD-tDCS over l-DLPFC did significantly improve task accuracy under local processing conditions, but only in the second half of the task, when performance typically declines. This selective improvement suggests a facilitation of persistence, helping participants maintain attention to detail as fatigue sets in, again consistent with the persistence mode described by the metacontrol framework (Hommel & Colzato, 2017).

Stimulation was delivered online for 15 minutes from the start of the task, whereas the global-local task lasted approximately 25 minutes. Therefore, the accuracy benefit observed in the second half should not be interpreted as a strictly concurrent “online-only” effect when it emerges. Rather, it is consistent with delayed or sustained consequences of early stimulation (e.g., task-set maintenance that persists beyond stimulation offset), which become most apparent under increasing time-on-task demands. Additionally, the co-occurrence of increased MW rates with improved accuracy in the second half is not necessarily contradictory. Thought probes provide intermittent self-reports, whereas accuracy reflects continuous task performance. Thus, participants may report more off-task thoughts over time while still providing adequate task-set support on response-requiring trials. Furthermore, gains in stimulus-response mapping due to practice can improve accuracy even as subjective MW increases with fatigue. These interpretations remain tentative and highlight the value of future analyses that relate performance immediately preceding each probe to the reported mental state.

These findings provide novel causal support for the metacontrol model, particularly the idea that stimulation can bias control states depending on task demands and temporal dynamics. Our prior work has shown similar increases in MW over time (Martínez-Pérez et al., 2023), and the current study extends this by demonstrating that HD-tDCS may mitigate decline in performance by reinforcing persistence-oriented control.

Moreover, the observed increase in both intentional and unintentional MW across the session replicates our earlier findings (Martínez-Pérez et al., 2021, 2023), reinforcing the idea that time-on-task effects reflect shifts in cognitive resources and control modes. These temporal dynamics are central to the metacontrol perspective, which argues that persistence and flexibility are not static traits but adaptable states responsive to internal and external pressures (Hommel, 2015).

Limitations and future directions

Several limitations qualify the strength and specificity of the conclusions. Most importantly, the study did not include a pre-stimulation baseline block and did not include an active-control stimulation site. Consequently, stimulation-related effects are best interpreted as between-group differences expressed over time under randomized assignment, and the present design does not allow strong claims about region-specific mechanisms uniquely attributable to l-DLPFC modulation. These constraints are common in early-stage neuromodulation work, but they underscore the need for replication using baseline assessment and an active-control montage to strengthen anatomical and mechanistic inference.

A second set of limitations concerns measurement precision and temporal dynamics. MW estimates were derived from a limited number of probes per half, with fewer intentional than unintentional reports, reducing precision for fine-grained interaction tests involving intentionality. In addition, the stimulation window (15 minutes) was shorter than the overall task duration, which constrains inferences about the temporal locus of effects emerging in the second half; such effects may reflect delayed or sustained consequences of early stimulation rather than strictly concurrent online modulation. Future studies

should increase probe density, incorporate probe-locked/time-resolved analyses of performance, and more tightly align stimulation timing with the critical task epochs (or systematically vary stimulation timing) to clarify when and how neuromodulation influences control-policy expression.

Importantly, these limitations do not undermine the central contribution of the present work. The study identifies a theoretically diagnostic dissociation between intentional and unintentional mind-wandering in their relationship to global-local indices, and it provides initial evidence consistent with the idea that prefrontal neuromodulation can bias task-expressed persistence under increasing time-on-task demands. These findings sharpen testable predictions for future experiments designed to establish specificity while building on the diagnostic patterns observed here.

Overall, the present study identifies a dissociation relevant to metacontrol between intentional and unintentional MW, and provides evidence consistent with the view that these forms of mental engagement are related differently to persistence-flexibility in task performance. Additionally, while the design does not permit robust region-specific mechanistic inference, the observed stimulation-related pattern indicates that HD-tDCS targeting the left prefrontal cortex can modulate task-based control in a manner that selectively enhances persistence-oriented performance under escalating time-on-task demands. Together, these findings offer empirical support for key predictions of the metacontrol framework and generate clear, testable hypotheses for future neuromodulation studies incorporating baseline assessment, active-control stimulation, and time-resolved modelling to establish anatomical specificity and temporal dynamics.

Declarations

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Conflict of interest

The authors declare no competing interests.

Data availability statement

The datasets generated and analyzed during the current study are available from the first/corresponding author upon request.

Author Contributions

Víctor Martínez-Pérez: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. Lucía B. Palmero: Investigation, Methodology, Formal analysis, Writing – original draft. Guillermo Campoy: Investigation, Formal analysis, Writing – review &

editing. Lorenza Colzato: Conceptualization, Writing – review & editing. Bernhard Hommel: Conceptualization, Methodology, Writing – review & editing. Luis J. Fuentes: Conceptualization, Methodology, Writing – original draft, Writing – reviewing and editing, Funding acquisition.

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Figures

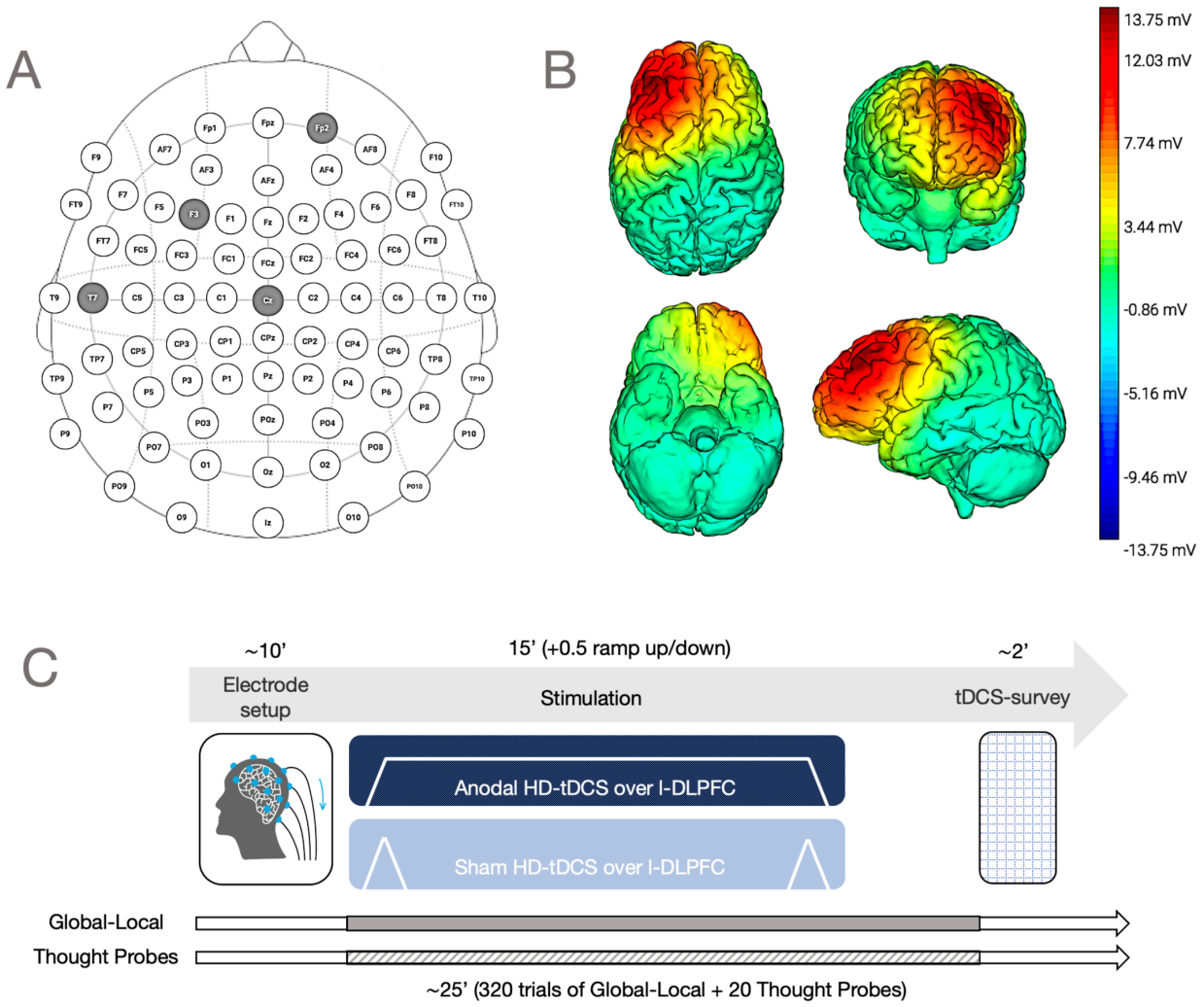


Figure 1

(A) Electrodes setup. (B) Resulting E-field stimulation. (C) Experimental procedure.

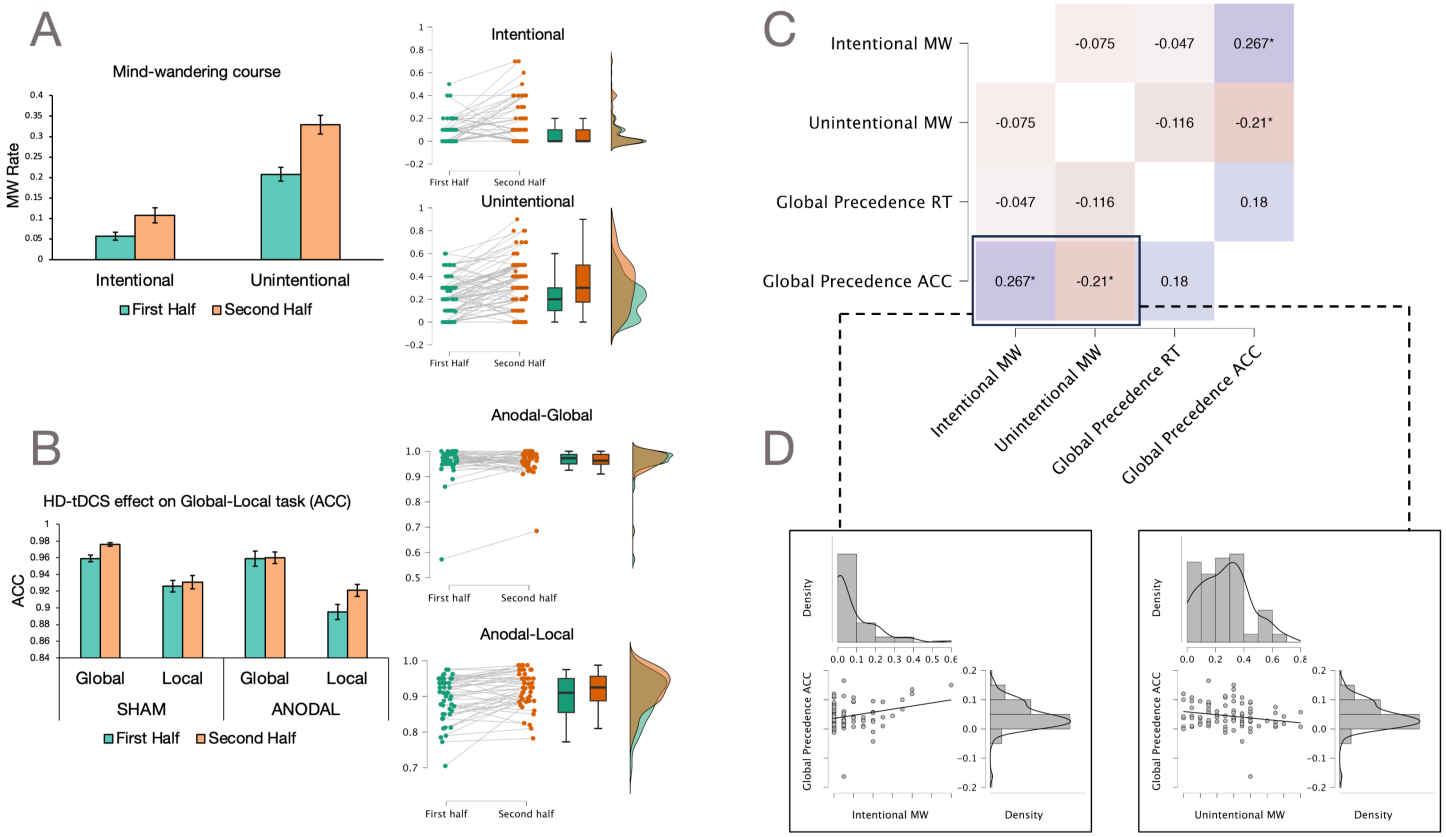


Figure 2

Results resume: (A) Temporal course of the MW over the task splitting by intentional and unintentional. (B) Temporal course of the Global-Local task (ACC) and its interaction with the HD-tDCS stimulation. (C) Matrix of correlations between Intentional/Unintentional MW, Global Precedence (RT) and Global Precedence (ACC). (D) Density graphs of significant correlations between Intentional MW and Global Precedence (negative correlation), and Unintentional MW and Unintentional MW and Global Precedence (positive correlation).