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Highlights

- Meta-analysis on transcranial direct current stimulation (tDCS) and mind wandering
- Risk of bias (RoB) and tDCS stimulation parameters heterogeneity controlled
- RoB strongest predictor of study outcomes
- Anodal tDCS of right inferior parietal lobule predicts reduced mind wandering
- Left dorsolateral prefrontal cortex stimulation did not modulate mind wandering

Modulation of mind wandering using transcranial direct current stimulation: A meta-analysis based on electric field modeling

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Abstract

Mind wandering (MW) is a heterogeneous construct involving task-unrelated thoughts. Recently, the interest in modulating MW propensity via non-invasive brain stimulation techniques has increased. Single-session transcranial direct current stimulation (tDCS) in healthy controls has led to mixed results in modulating MW propensity, possibly due to methodological heterogeneity. Therefore, our aim was to conduct a systematic meta-analysis to examine the influence of left dorsolateral prefrontal cortex (lDLPFC) and right inferior parietal lobule (rIPL) targeted tDCS on MW propensity. Importantly, by computational modeling of tDCS-induced electric fields, we accounted for differences in tDCS-dose across studies that varied strongly in their applied methodology.

Fifteen single-session, sham-controlled tDCS studies published until October 2021 were included. All studies involved healthy adult participants and used cognitive tasks combined with MW thought-probes. Heterogeneity in tDCS electrode placement, stimulation polarity and intensity were controlled for by means of electric field simulations, while overall methodological quality was assessed via an extended risk of bias (RoB) assessment.

We found that RoB was the strongest predictor of study outcomes. Moreover, the rIPL was the most promising cortical area for influencing MW, with stronger anodal electric fields in this region being negatively associated with MW propensity. Electric field strength in the lDLPFC was not related to MW propensity.

We identified several severe methodological problems that could have contributed to overestimated effect sizes in this literature, an issue that needs urgent attention in future research in this area. Overall, there is no reliable evidence for tDCS influencing MW in the healthy. However, the analysis also revealed that increasing neural excitability in the rIPL via tDCS might be associated with reduced MW propensity. In an exploratory approach, we also found some indication that targeting

prefrontal regions outside the lDLPFC with tDCS could lead to increased MW propensity.

Keywords

Mind wandering; Task-unrelated thought; tDCS; Electric field modeling; Risk of bias; Systematic review

1. Introduction

Mind wandering (MW) is a heterogeneous construct encompassing task-unrelated and stimulus-independent thoughts that can be both intentional or unintentional (Giambra, 1989; Seli et al., 2018; Smallwood & Schooler, 2015). MW has been reported to be detrimental to driving (He et al., 2011) and academic performance (Foulsham et al., 2013). Specific manifestations of MW are implicated in psychiatric conditions such as "mind blanking" in attention-deficit/hyperactivity disorder (ADHD; (Madiouni et al., 2020; Van den Driessche et al., 2017) and ruminative thoughts in major depressive disorder (MDD; (Demeyer et al., 2012). Based on these considerations, there is a need to develop methods that can modulate MW, primarily by reducing its frequency.

Transcranial direct current stimulation (tDCS) is a technique based on the non-invasive application of a constant electric field to the brain that elicits a low-voltage electric current in underlying cortical areas (1-2mA). The electrodes are placed on the scalp of the individual, and the current passes through different tissue types before reaching the cerebral cortex (Lefaucheur & Wendling, 2019). The direction of current flow is influenced by the polarity of the electrodes (anode or cathode), causing either depolarization or hyperpolarization of the neuronal membrane, which in turn modulates the frequency of action potentials (Fertonani & Miniussi, 2017).

After initially promising finding (Axelrod et al., 2015), several studies have attempted to modulate MW via tDCS. The evidence, however, is inconclusive with some studies reporting increased MW propensity (Axelrod et al., 2015; Axelrod et al., 2018; Filmer et al., 2019; Filmer et al., 2021), no effect (Boayue et al., 2020; Alexandersen et al., 2022) or decreased MW propensity (Boayue et al., 2021; Kajimura et al., 2019; Kajimura & Nomura, 2015) relative to sham stimulation. Some findings are more nuanced. For instance, while one study reported decreased MW following tDCS in men only (Bertossi et al., 2017), another found no effect of tDCS on MW propensity, but a shift in MW content with less emotionally negative, past-

oriented thoughts following real tDCS (Chou et al., 2020). These controversial findings are likely due to variability in tDCS protocols, a diversity in the applied cognitive paradigms and other methodological factors like blinding, risk of bias and (lack of) statistical power (Csifcsák et al., 2019).

The selection of target regions for tDCS is typically informed by neuroimaging studies, frequently highlighting the role of the default mode network (DMN) and the frontoparietal control network (FPCN) in MW (Christoff et al., 2016; Smallwood et al., 2012). Therefore, the majority of tDCS studies targeted either the left dorsolateral/lateral prefrontal cortex (lDLPFC/LPFC) within the FPCN, or the right inferior parietal lobule (rIPL) within the DMN in an attempt to interfere with MW propensity (Supplementary Figure 1). While initial studies found that anodal stimulation above the lDLPFC leads to increased number of MW self-reports (Axelrod et al., 2015; Axelrod et al., 2018), Kajimura et al. (Kajimura & Nomura, 2015) proposed that anodal stimulation of the rIPL and concomitant cathodal stimulation of the left LPFC reduces MW frequency. Due to the weak spatial focality of the typically used bipolar tDCS protocols, it was not possible to determine whether the stimulation of the rIPL, the lDLPFC, or the combination thereof was causally related to the observed effect in this study (Kajimura & Nomura, 2015). Other stimulation protocols aimed at stimulating cortical regions outside the lDLPFC/LPFC and rIPL: One study targeted the medial prefrontal cortex (mPFC; (Bertossi et al., 2017), while another study targeted the IPL bilaterally (Chou et al., 2020). However, the choice of target regions for tDCS is not straightforward. For example, in a meta–analysis of functional neuroimaging studies on MW, the right rather than left DLPFC was found to be associated with mind-wandering (Fox et al., 2015). Therefore, the issue of target region selection needs to be explored further.

In a typical conventional bipolar tDCS montage, two electrodes – one anode and one cathode – are placed on the scalp, with one electrode positioned above the target region, while the other (return) electrode placed either on a relatively distant scalp

location, or on the cheek or shoulder. As the current enters the head, the electric field (EF) is diffused by the skull and other intervening tissues before reaching the cortex. Often, the peak of EF falls outside the target area directly under the electrodes, compromising the focality of the stimulation (Csifcsák et al., 2018; Wischnewski et al., 2021). To overcome this limitation of low focality, high-definition (HD-tDCS) montages with multiple, but smaller electrodes have been used (Datta et al., 2009). Most commonly, HD-tDCS protocols utilize a ring-like electrode configuration, such as the 4 × 1 montage, where one anode is placed above the target region and is surrounded by four return electrodes (Boayue et al., 2021; Chou et al., 2020). In comparison with bipolar tDCS protocols, HD-tDCS typically increases the focality of stimulation, as the EF is more constrained (Datta et al., 2009; Edwards et al., 2013; Masina et al., 2021). However, even with HD-tDCS, to establish a causal link between changes in MW frequency and tDCS-induced electric fields (EF) in the target area, one needs to consider potential stimulation of other brain regions, since HD-tDCS montages are still not selective enough to constrain their effect to neural activity exclusively in the target region (Boayue et al., 2018; Csifcsák et al., 2018).

Currently, it is unclear which stimulation parameters influence the effect of tDCS on MW. In addition to electrode placement, the polarity of stimulation is of key importance. So far, some studies have used anodal tDCS above the lDLPFC (Boayue et al., 2020; Boayue et al., 2021; Clarke et al., 2020; Filmer et al., 2019; Filmer et al., 2021; Nord et al., 2017), while others have applied cathodal tDCS to the lDLPFC (Filmer et al., 2019; Filmer et al., 2021) and even, both anodal and cathodal polarities have been used above the LPFC (Kajimura & Nomura, 2015) or above the rIPL (Chou et al., 2020; Kajimura et al., 2019). Finally, studies have also utilized different stimulation intensities (Supplementary Figure 1; Filmer et al., 2019; Filmer et al., 2021). However, precise knowledge is still lacking on whether the increase in stimulation intensity supports greater neurophysiological or behavioural effects (Bestmann et al., 2015; Esmaeilpour et al., 2018), and the issue of individual dose

optimization for decreasing variability in outcomes still remains to be solved (Esmaeilpour et al., 2018).

A crucial methodological aspect of interventional studies is to minimize risk of bias (RoB) to improve the reliability of findings (Higgins et al., 2011). RoB includes aspects like proper randomization, blinding of participants and personnel, as well as post-session verification of blinding, with the final RoB score reflecting the estimated overall methodological quality of the study (Higgins et al., 2011). In the field of non-invasive brain stimulation, the issue of blinding is of special importance, as ineffective blinding can mask or exaggerate the behavioural findings and some of the most used stimulation protocols have been shown to result in ineffective blinding (Fassi & Cohen Kadosh, 2021; Turi et al., 2019). Identification of the stimulation condition (real vs. sham) by the participant can lead to changes in behaviour to match the expected outcome, which can be misinterpreted as a direct neural consequence of tDCS (Turner et al., 2021). Also, most studies do not follow a pre-registered analysis plan or publish their paper as registered reports. Lack of pre-registration carries the risk of overly flexible data analysis ("researcher's degrees of freedom") thereby invalidating tests of statistical significance (Silberzahn et al., 2018). The low adoption rate of the registered-report format (Chambers & Tzavella, 2022) in brain-stimulation studies reflects the possibility of strong publication bias. Together, these concerning methodological practices can lead to overestimated effect sizes, and ultimately, to irreproducible findings (Boayue et al., 2020; Chambers & Tzavella, 2022; Csifcsák et al., 2019).

Finally, studies aiming for modulating MW propensity via tDCS also differ in the cognitive tasks used, with predominantly monotonous tasks such as the sustained attention to response task (SART), the finger-tapping random sequence generation task (FT-RSGT), perceptual load tasks, the multisource interference task (MSIT), the choice reaction time (CRT) task, attentional distraction tasks and the intrusive

thoughts tasks (Supplementary Figure 2), all being used in conjunction with MW probes.

Traditional meta-analytic approaches have been used to study the effect of tDCS on cognition in many domains (Mendes et al., 2022; Schroeder et al., 2020), but due to the large heterogeneity in stimulation protocols (electrode placement, size, shape, polarity, stimulation duration and intensity) as well as in the cognitive tasks used, drawing firm conclusions can be extremely challenging. Recently, a novel approach has been introduced that aimed at accounting for the between-study heterogeneity in tDCS protocols by using computational modeling to extract tDCS-induced EFs across the cortex (Wischnewski et al., 2021). Arguably, this approach can help to abstract from the largely incidental methodological aspects of NIBS studies and to focus on the putative relevant aspect, i.e., the tDCS "dose" that is reflected by the strength of the EF. In their meta-analysis (MA), the authors successfully identified regions that contributed to the meta-analytic evidence for tDCS-associated improvements in working memory performance, which, surprisingly, were outside the most commonly targeted region (i.e., the DLPFC) in this cognitive domain (Wischnewski et al., 2021). In our study, we adopted a similar approach as Wischnewski and colleagues (2021) and used computational modeling to simulate the cortical distribution and strength of tDCS-induced EFs in a realistic head model for each tDCS protocol included in the MA. In the study by Wischnewski et al. (2021), the magnitude of the EF was estimated for each cortical locus irrespective of its spatial orientation (often referred to as “normfield”; (Wischnewski et al., 2021). However, in the present MA, we primarily focused on the strength of the “normal component” of EF at each brain location. The normal component is the part of the EF that is perpendicular to the cortical surface, either entering (positive values) or leaving (negative values) the cortex. Given that the normal component takes EF orientation into account, it has been associated with polarity-specific effects, leading to increases or reductions in neural excitability (herein referred to as “anodal” and “cathodal” effects; (Saturnino

et al., 2019). We chose to focus on the normal component, since we argued that, in addition to EF magnitude, the orientation of EF might also contribute to the modulation of MW by tDCS, and should be explored to reveal potential polarity-specific effects (Axelrod et al., 2018; Filmer et al., 2021; Kajimura et al., 2019; Kajimura & Nomura, 2015).

Based on the above, here we present the first MA of tDCS studies that aimed at modulating MW propensity in healthy adults, by quantifying the normal (and in an exploratory approach, also the normfield) component of the EF in *a priori* selected target regions, the lDLPFC/LPFC and the rIPL. This "targeted MA" approach allowed us to study tDCS-induced changes in MW propensity across a wide-variety of tDCS protocols reported in the literature, by focusing on their potential to modulate activity in the lDLPFC/LPFC and rIPL. We chose to extract both the anodal and cathodal peak EFs from these two regions for each tDCS protocol because we identified studies that found effects on MW when applying tDCS above these regions with both polarities (Axelrod et al., 2018; Filmer et al., 2021; Kajimura et al., 2019; Kajimura & Nomura, 2015). Hence, due to the general uncertainty of polarity-specific tDCS effects outside the motor cortex (Jacobson et al., 2012) and also extending to MW research, we wanted to clarify not only if these two regions contribute to changes in MW propensity via tDCS, but also, whether these effects are polarity-specific.

In addition to the targeted MA described above, in an exploratory approach we also extracted the EF in 300 parcels covering the entire cerebral cortex to identify regions that might be more potent predictors of the meta-analytic effect than the two most commonly targeted areas in this field, the lDLPFC/LPFC and the rIPL.

Finally, since research on the effect of tDCS on MW propensity is characterized by the presence of many controversial findings, we have also estimated the RoB of each study to account for factors related to study design, such as randomization, blinding of participants/personnel and post-session verification (Higgins et al., 2011).

Importantly, we extended the original RoB assessment with scores reflecting whether the studies followed a pre-registered analysis plan, and in an even more rigorous approach, whether the studies were published as registered reports, where the methods have passed peer-review before data collection began (Chambers & Tzavella, 2022).

2. Methods

Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) (Moher et al., 2009) and the Cochrane Handbook for Systematic Reviews (Higgins et al., 2011) guidelines were followed to structure this MA.

2.1. Search strategy

We searched the following databases until 1st October 2021: PubMed, Web of Science, PsycINFO (OVID), Open science framework (OSF) preprints and Google search (for articles not indexed elsewhere). The initial aim of the MA was to include all tDCS and TMS (transcranial magnetic stimulation) studies that aimed at modulating MW in healthy adults. Therefore, we used search terms ("mind wandering" OR "spontaneous thought" OR "task-unrelated thought" OR "unintentional thought" OR "stimulus-independent thought" OR “rumination”) AND ("non-invasive brain stimulation" OR “tDCS” OR "transcranial direct current stimulation" OR “TMS” OR "transcranial magnetic stimulation" OR “rTMS” OR "repetitive transcranial magnetic stimulation" OR “tACS” OR "transcranial alternating current stimulation" OR “tES” OR "transcranial electrical stimulation" OR “TBS” OR "theta burst stimulation"), and we also examined the review articles for additional empirical papers. The search strategy is available in Supplementary Table 1, and the search results can be found here (https://osf.io/9j7f4).

2.2. Selection criteria

The inclusion criteria for the studies were: healthy adult participants, studies assessing the effects of non-invasive brain stimulation, sham-controlled, MW probes

implemented during a cognitive task (intermittently asking participants whether their attention was on- or off-task), single-session tDCS-associated effect sizes either reported or could be calculated from descriptive data (presented in the results section, figures, tables, or supplementary material), published in a peer-reviewed journal in English language, with full-text availability. We excluded irrelevant studies by reading titles and abstracts. There were no TMS-related articles using a cognitive task with MW probes in healthy adults, and studies with a focus on rumination using rumination-specific questionnaires were dropped to make the MA more specific to MW assessed via thought-probes. The full text of the remaining studies were retrieved and screened for our inclusion criteria (Figure 1). We identified 15 eligible articles that we included in the MA.

2.3. Data extraction

For each included study, the following information was extracted: first author, year of publication, PubMed ID (pmid), type of montage (bipolar or HD-tDCS), contrast (whether effects of tDCS were evaluated online, offline, online relative to a baseline, or offline relative to a baseline), brain region of stimulation (i.e., scalp location of the anode/cathode above the targeted region), tDCS parameters (i.e., current intensity, polarity and duration of the stimulation), cognitive task used, study design (within- or between-subject), number of participants in the anodal, cathodal and/or sham tDCS groups. Effect sizes quantified as Cohen's *d* were determined by calculating tDCS-induced changes in MW propensity compared to a sham condition using the Campbell effect size calculator (campbellcollaboration.org) such that positives values reflect a tDCS-induced increase, whereas negative effect sizes indicate a tDCS-induced decrease in MW propensity. In papers with a baseline measurement present, the difference between baseline-corrected anodal or cathodal (post-test – pre-test) and baseline-corrected sham (post-test – pre-test) tDCS was calculated. For studies reporting both online and offline effects (i.e., behavioural effects measured during and after stimulation), effect sizes were calculated for each contrast separately.

We gathered data for effect size calculation from the result sections and tables, or, if the authors did not respond to our request for the raw data, we estimated effect sizes from figures using WebPlotDigitizer (https://automeris.io/WebPlotDigitizer/). A single value of Cohen's *d* was associated with each different tDCS protocol, contrast and/or study design. Each tDCS protocol was given a unique number if any of the parameters (electrode shape, size, position, placement, polarity, stimulation intensity) differed from any other protocol, resulting in 21 protocols (Supplementary Table 2). This way, tDCS protocols from different studies that were identical in terms of these parameters were assigned with the same protocol number. The table with studies included, along with their protocols (electrode parameters and other details used for running simulations), effect sizes and corresponding standard errors are detailed in our repository (https://osf.io/e9x4a).

2.4. Risk of bias assessment

We assessed RoB of included studies using the Cochrane risk of bias tool (Higgins et al., 2011) at study level. A score of 0 was given when the study had low risk of bias, a score of 1 was given when study had unclear risk of bias and a score of 2 was given when study has high risk of bias. To estimate methodological quality in the best way possible, we also assessed whether the study protocol was pre-registered (0 score if pre-registered, score of 2 if not pre-registered), and whether the study was published as a registered report (0 score if published, score of 2 if not published) and added these scores to the RoB score. A total of 11 criteria were evaluated: 1) whether the study was pre-registered, 2) whether it was published as a registered report, 3) randomization – selection bias, 4) allocation concealment – selection bias, 5) blinding of participants before experimental session, 6) post-session verification of blinding, 7) blinding of personnel before experimental session, 8) blinding of personnel during outcome assessment, 9) incomplete outcome data – attrition bias, 10) selective reporting – reporting bias, and 11) other bias. This approach yielded a maximum score of 22. In comparison, the maximum score according to original RoB

assessment could be 18 or less. We present the RoB profile of each study in Supplementary Figure 3. Out of the 15 studies included in this meta-analysis, we identified only four with low (score ≤ 4) RoB, while nine have been associated with high RoB (score ≥ 8). The majority of studies (10 in total) were not pre-registered, 13 were not published as registered reports, 3 lacked proper randomization, 9 used only single blinding, and for 11, the outcome assesment for blinding was not stated clearly.

2.5. Search results

Figure 1 presents the screening and selection procedures based on the PRISMA guidelines. The search resulted in 254 studies, 92 of which were duplicates and therefore removed. The remaining 162 papers went through initial and full-text screening, of which 147 were excluded. Therefore, a final set of 15 published articles fulfilled the selection criteria and were included in the meta-analysis. These articles are summarized in Table 1. The studies possess considerable heterogeneity in terms of methodological quality and effect sizes as shown in Figure 2, but also in target and reference brain regions as well as the task used (Supplementary Figures 1 and 2).

Out of 15 studies, 12 used bipolar, 2 used HD-tDCS 4x1 montages and 1 study used double HD-tDCS 3x1montage. Out of 15 studies, 9 targeted the lDLPFC, 5 targeted the IPL and 1 study targeted the mPFC (Supplementary Figure 1). There was considerable heterogeneity in whether anodal or cathodal stimulation was applied above these target regions. Cognitive tasks also contributed to heterogeneity: the majority of studies (7) used the SART task, while 6 other tasks were used more sporadically (Supplementary Figure 2). Four studies assessed both online and offline effects, 3 studies assessed only online, and 8 studies assessed only offline effects (Supplementary Figure 2).

As shown in Figure 2 by contrasting reported effect size with its precision (the inverse of the corresponding standard error), we observed a striking negative

relationship (larger effects associated with weaker precision), we also highlight that studies reporting large effects were those characterized by high RoB, while low RoB was linked to predominantly weak/null-effects, but high precision. Only 5 studies had a sample size of minimum 50 participants, only 5 studies were double-blinded and 1 study was triple blinded.

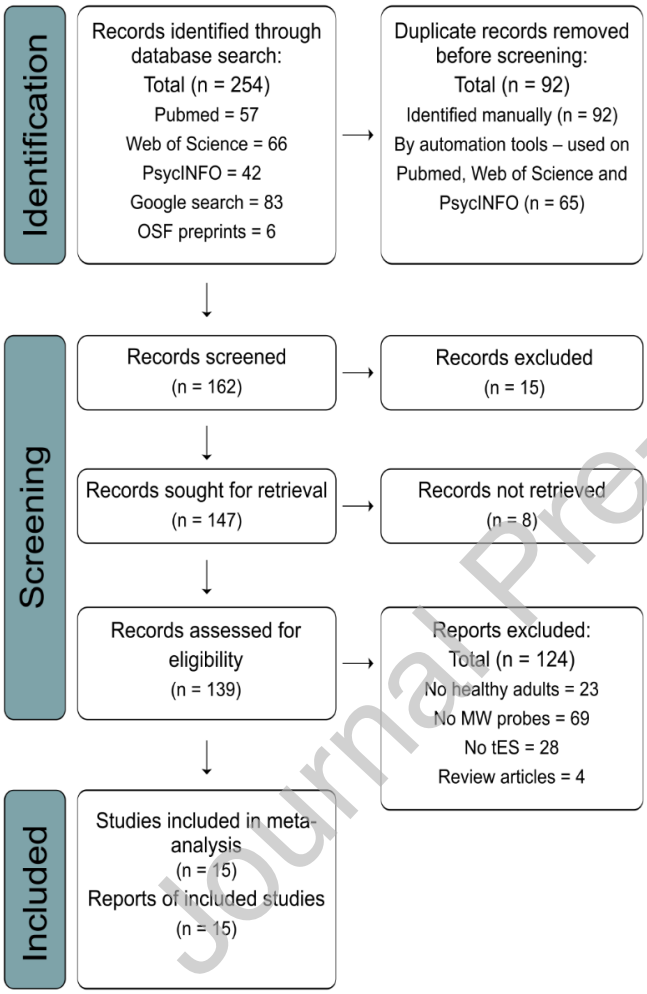

Figure 1. (single column width) The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram, summarizing search results and the inclusion/exclusion process. Abbreviations: MW – mind wandering; OSF – open science framework; tES – trans electrical stimulation.

Table 1. Summary of tDCS based mind wandering studies included in this meta-analysis, presented by type of protocol.

Study and abbreviation	Sample size for real tDCS	Target region	Target region polarity	Montage type	Stimulation duration (min)	Current Intensity (mA)	Contrast	Task	Protocol number
Alexandersen et al, 2021, Al21	50	lDLPFC	anodal	HD-tDCS, 4x1	20	2	online, offline	FT-RSGT	1
Axelrod et al, 2015, Ax15	24	lDLPFC	anodal	bipolar	20	1	online, offline	SART	2, 15
Axelrod et al,2018, Ax18	30	lDLPFC	anodal	bipolar	30	1	online, offline	SART	2, 15
Bertossi et al, 2017, Be17	24	mPFC	cathodal	bipolar	15	2	offline	Choice reaction time	13, 14
Boayue et al, 2018, Bo18	96	lDLPFC	anodal	bipolar	20	1	online, offline	SART	2
Boayue et al, 2020, Bo20	30	lDLPFC	anodal	HD-tDCS, 4x1	20	2	online	FT-RSGT	1
Chou et al, 2020, Ch20	60	bilateral IPL	anodal, cathodal	HD-tDCS, double3x1	30	2	offline	MSIT	9, 10
Clarke et al, 2020, Cl20	25	lDLPFC	anodal	bipolar	20	2	online	Intrusive thoughts task	20
Coulborn et al, 2020, Co20	23	rIPL	anodal, cathodal	bipolar	20	1.5	offline	SART	3, 4
Filmer et al, 2019, Fi19	120	lDLPFC	anodal, cathodal	bipolar	20	1, 1.5, 2	offline	SART	2, 17, 18, 19
Filmer et al, 2021, Fi21	120	lDLPFC	anodal, cathodal	bipolar	20	1, 2	offline	SART	5, 6, 7, 8
Kajimura et al, 2015, Ka15	49	rIPL	anodal, cathodal	bipolar	20	1.5	offline	Perceptual load task	11, 12
Kajimura et al, 2016, Ka16	34	rIPL	anodal, cathodal	bipolar	20	1.5	offline	Perceptual load task	11, 12
Kajimura et al, 2019, Ka19	12	rIPL	anodal	bipolar	20	1.5	offline	SART	3, 16
Nord et al, 2017, No17	31	lDLPFC	anodal	bipolar	20	1	online	Attentional distractibility task	21

Abbreviations: FT-RSGT: finger tapping random sequence generation task; HD-tDCS: high-definition tDCS; lDLPFC – left dorsolateral prefrontal cortex; mPFC – medial prefrontal cortex; MSIT: multi-source interference task; rIPL – right inferior parietal lobule; SART: sustained attention to response task.

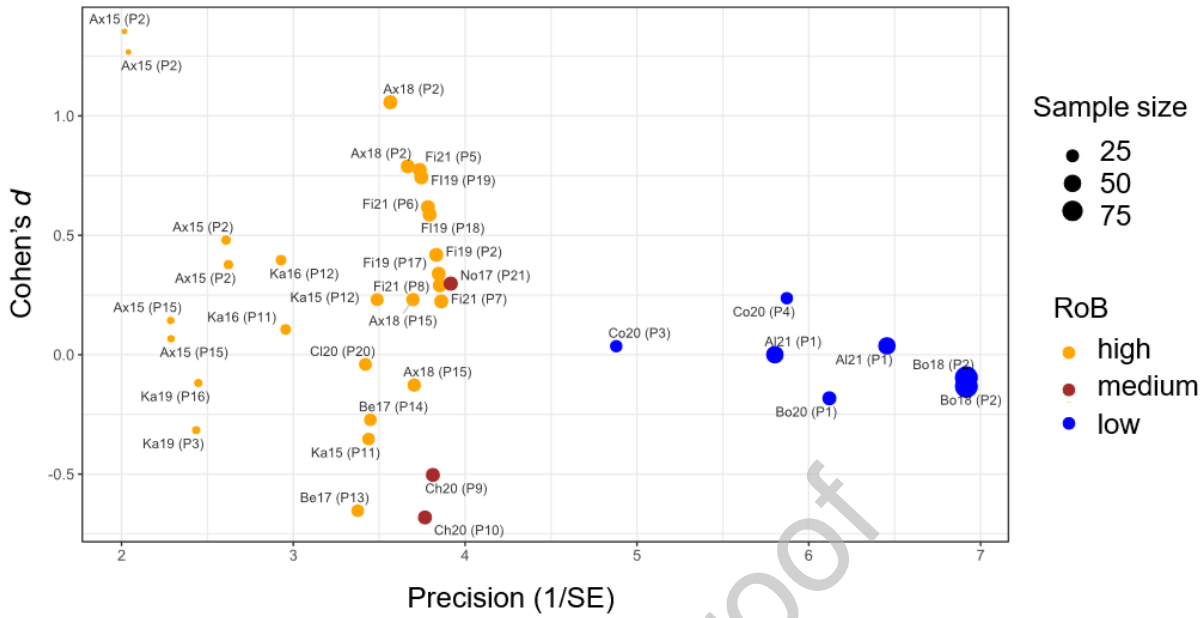

Figure 2. (double column width) Heterogeneity in effect sizes and methodological quality. Precision calculated as inverse of standard error (SE) for Cohen's *d*. The titles of studies (e.g., "Bo20 (P1)") can be read as the first two letters of first authors name (Bo for Boayue), followed by year of publication (20 for 2020), followed by protocol number (P1). Details of the studies are presented in Table 1, while the protocols are described in Supplementary Table 2.

2.6. Meta-analytic steps

Our MA pipeline is shown in Figure 3. During pre-processing, different tDCS protocols were identified, and data was extracted (Cohen's *d*, corresponding standard error and RoB for each study, study design, tDCS protocol and/or contrast). This yielded a total of 37 effect size estimates from the 15 studies.

Finite element method (FEM; (Thielscher et al., 2015) simulations were run on 21 protocols using SimNIBS version 3.2.5 (Saturnino et al., 2019). We simulated the cortical distribution of the tDCS-induced EF for each protocol on the Montreal Neurological Institute (MNI) head model provided by SimNIBS. Specific tDCS

parameters (electrode location, size, shape, orientation), polarity and intensity, as described in each study, were used for simulations, with a constant electrode thickness of 1mm. For montages with an extracephalic electrode placed on the shoulder, we placed the electrode on the neck, since the shoulder was not available for the MNI head. Tissue conductivities were as follows: electrode rubber = 29.4 S/m, eyeballs = 0.5 S/m, cerebrospinal fluid = 1.65 S/m, gray matter = 0.27 S/m and white matter = 0.12 S/m. The resultant spatial maps of tDCS-induced EF distributions per protocol were saved as two-dimensional maps, registered to the average surface ('fsaverage') of FreeSurfer (Fischl et al., 1999). Simulation plots for four protocols are shown in Figure 4. The simulation plots for the remaining 17 protocols are available in Supplementary Figure 4.

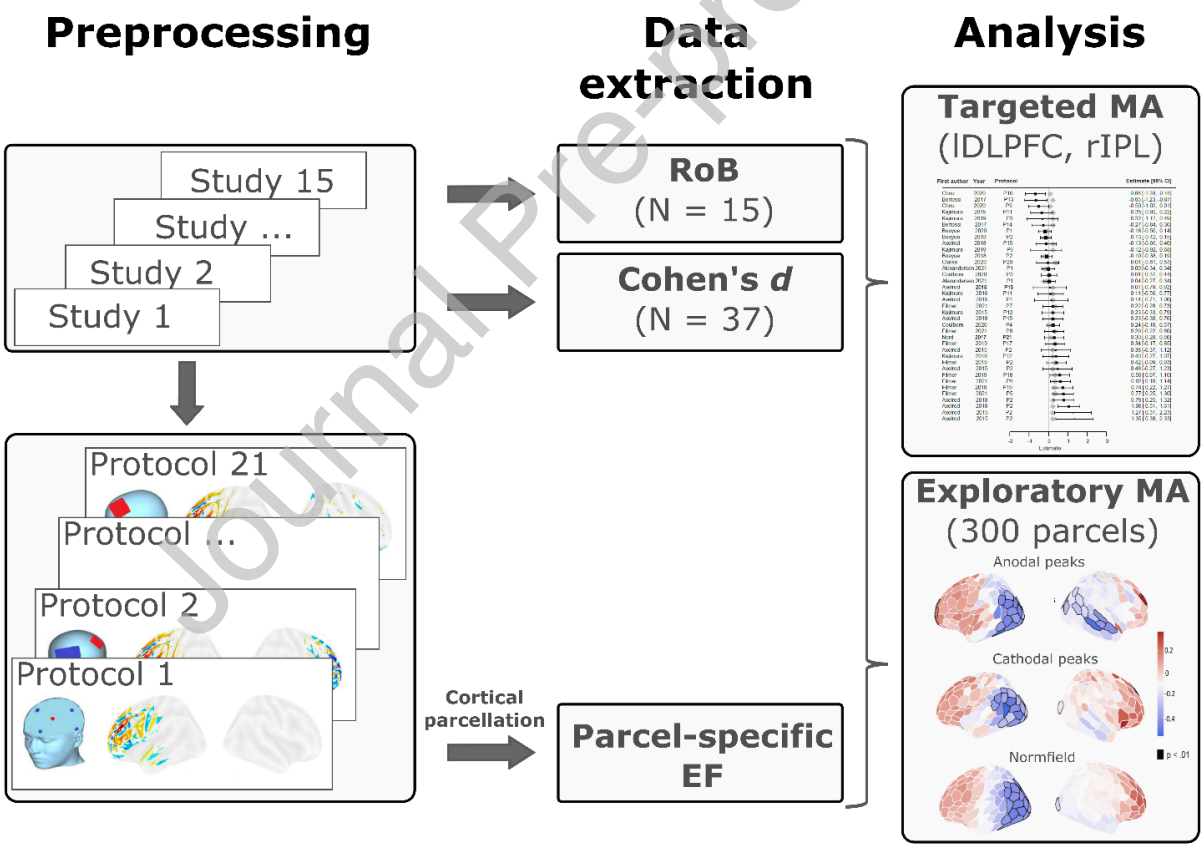

Figure 3. (double column width) Diagrammatic representation of the steps of the meta-analysis. Abbreviations: lDLPFC: left dorsolateral prefrontal cortex; MA: meta-analysis; rIPL: right inferior parietal lobule; RoB: risk of bias.

To extract region-specific EF values, we first parcellated the entire cerebral cortex into 300 regions using the Schaefer 300 parcel atlas (Schaefer et al., 2018). For our targeted MA that included EFs from *a priori* defined cortical regions, we extracted the peak positive (anodal) and peak negative (cathodal) values for the normal component of the EF for both the lDLPFC and the rIPL. Our two regions of interest were defined by merging parcels from the Schaefer atlas that corresponded to the FPCN ("Control A" subnetwork for the lDLPFC) and to the DMN ("Default A" and "Default C" subnetwork for the rIPL) based on the 17-network resting state functional connectivity atlas (Yeo et al., 2011), as detailed in Supplementary Table 3. Next, we performed random-effects MA using the *metafor* package (Viechtbauer., 2010) in R version 4.2.1, with Cohen's *d* as outcome variable. This enabled us to estimate the efficacy of tDCS irrespective of stimulation montage, current intensity, and other parameters of stimulation. First, we tested if, in comparison to the null-model, adding RoB as moderator resulted in a better model fit. This was followed by evaluating the contribution of region-specific EF peaks of any polarity (anodal, cathodal) to the MA model, resulting in 11 meta-analytic models in total. Model comparison was done by comparing the Akaike Information Criterion (AIC), the Bayesian Information Criterion (BIC) and the log-likelihood (LL) values estimated for each MA model.

In models with region-specific EF as moderator(s), raw EF values were multiplied by 10, so that the corresponding regression coefficients would reflect the change in effect size by increasing EF magnitude in units of 0.1 mV/mm. For cathodal peak values, the absolute value was calculated, to make the interpretation of the regression coefficient more straightforward (i.e., a positive coefficient for both the anodal and cathodal peak EF indicates that the stronger the anodal/cathodal peak EF in the region, the more MW propensity is increased for real vs. sham tDCS).

In the exploratory analysis, three MAs were run for all 300 cortical parcels, with Cohen *d* as outcome and RoB as moderator. These three models differed in whether the positive or negative peak EF value of the normal component, or the mean normfield EF value was added as second moderator. In this analysis, we estimated the regression coefficient for the region-specific EF, and assessed if its contribution to the MA model was significant at a more conservative alpha level ($p < .01$, uncorrected).

The R and Python scripts used for running all MA models and for generating plots for exploratory analysis with Schaefer 300 parcellations atlas, are provided online (https://osf.io/ukfjx/).

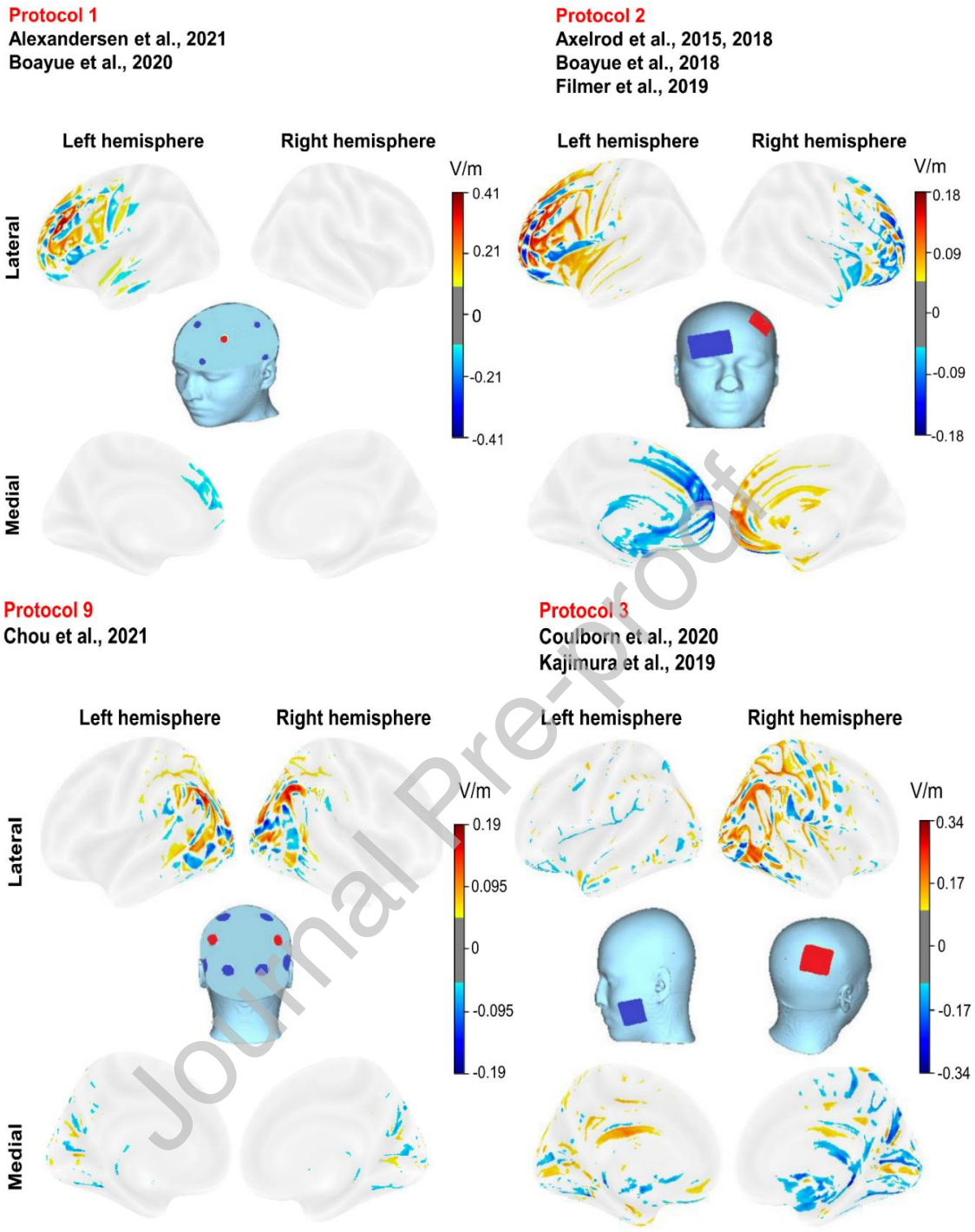

Figure 4. (double column width) Normal EF components from four different protocols, the different target - reference region, stimulation intensity and polarity create heterogeneity across different studies. We present here two protocols targeting the lDLPFC (upper row) and two targeting the rIPL (lower row), with one HD-tDCS (left column) and one bipolar montage (right column).

3. Results

3.1. Targeted meta-analysis

We observed a significant increase in MW with real tDCS compared to sham stimulation in the null-model, without any additional moderators (Table 2), as indicated by a significant intercept (b_0 = 0.16, p = .01). Heterogeneity was also significant (Q = 91.13, τ = 0.31, I^2= 61.96, p < .0001). In model 2, RoB was added as moderator, resulting in a non-significant overall effect of tDCS on MW (b_0 = -0.15, p = .21). However, the coefficient for RoB was significant (b = 0.04, p = .0035), as well as total heterogeneity (Q = 71.71, τ = 0.24, I^2 = 48.72, p = .0002). Importantly, all model selection criteria favored model 2 (AIC = 44.17, BIC = 49.00, LL = -19.08) over model 1 (AIC = 49.44, BIC = 52.66, LL = -22.72), indicating that RoB substantially accounted for variability in effect size across studies. Due to this, RoB was always included as a moderator in the subsequent analysis (models 3-11). Effect size estimates for model 2 with RoB as moderator are presented in a forest plot (Figure 5).

Next, we systematically added region-specific EFs (anodal or cathodal peak values derived from the normal component) from the lDLPFC and/or rIPL as moderator(s) to assess 1) whether stimulation of these regions would contribute to the effect of tDCS on MW, and 2) if such effects were polarity specific. Results from these models are presented in Table 2 (models 3-11). While the coefficient for RoB remained significant in all models, the peak anodal EF value in the rIPL also contributed significantly to models 6 (rIPL anodal peak: b = -0.14, p = .01; RoB: b = 0.06, p = .0002) , model 8 (rIPL anodal peak: b = -0.14, p = .02; lDLPFC anodal peak: b = 0.06, p = .25; RoB: b = 0.06, p <.0001), model 10 (rIPL anodal peak: b = -0.15, p = .01; lDLPFC cathodal peak: b = 0.07, p = .29; RoB: b = 0.06, p = .0001) and model 11 (rIPL anodal peak: b = -0.36, p = .02; rIPL cathodal peak: b = 0.23, p =

.13; lDLPFC anodal peak: b = 0.01, p = .88; lDLPFC cathodal peak: b = 0.05, p = .65).

However, heterogeneity remained significant in all models, even after controlling for different stimulation protocols and RoB. Out of all 11 models, model selection favored model 6 with RoB and peak anodal EF in the rIPL as moderators (Table 2).

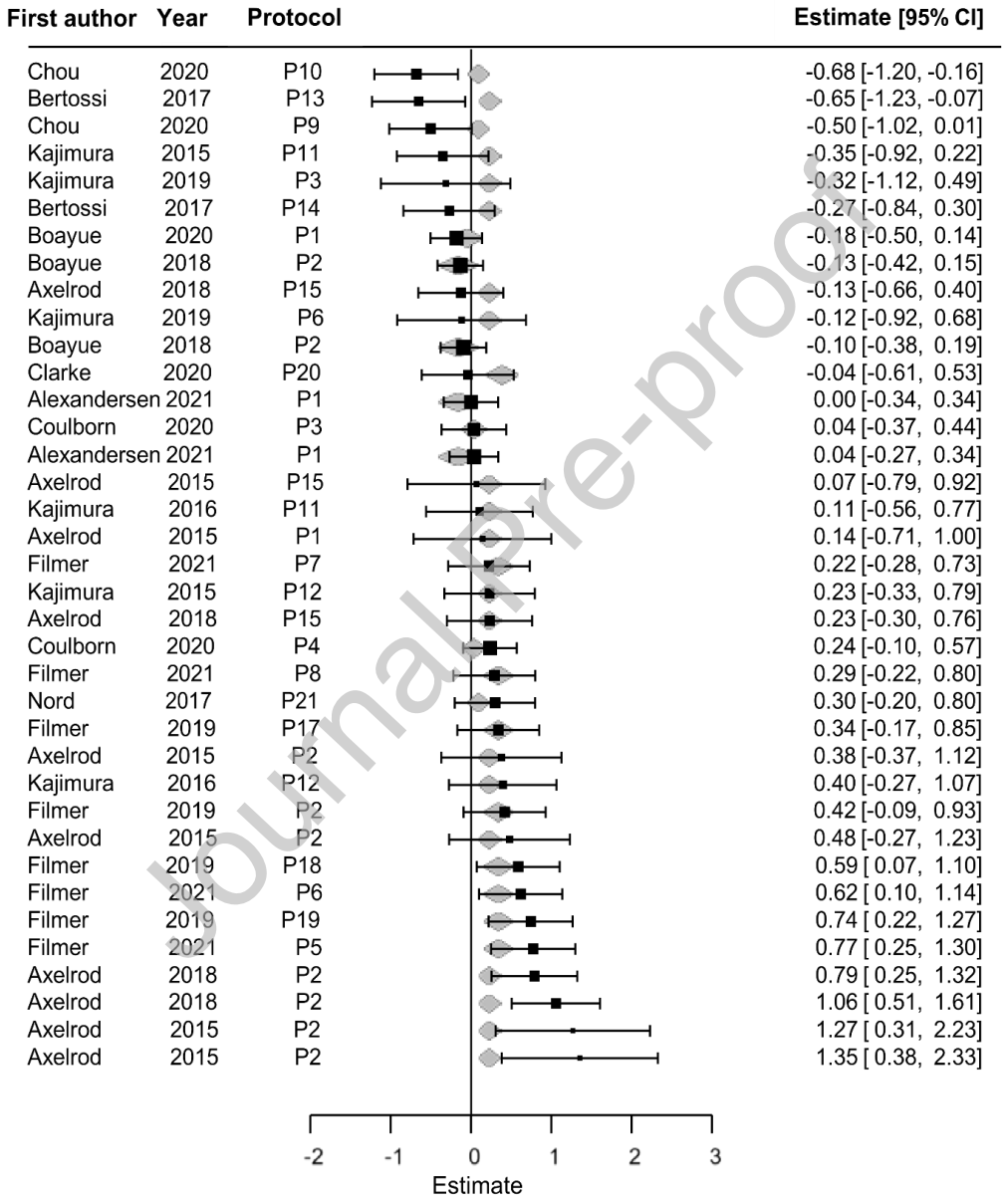

Figure 5. (double column width) Forest plot of effect size estimates for studies included in meta-analysis with RoB as moderator. Black squares represent the effect size reported in the original publications, black bars represent the corresponding 95%

confidence interval (95% CI), whereas grey diamonds indicate the effect size estimate from the model, after accounting for RoB.

Table 2. The results of random effects model on 11 MA models.

Model No	Moderators	Intercept	RoB	$EF_{+lDLPFC}$	EF_{-rIPL}	$EF_{-lDLPFC}$	EF_{+rIPL}	Q	τ	I^2(%)	AIC	BIC	LL
1	none	0.16*						91.13***	0.31	61.96	49.44	52.66	-22.72
2	RoB	-0.15	0.04**					71.71***	0.24	48.72	44.17	49.00	-19.08
3	RoB + $EF_{+lDLPFC}$	-0.34	0.05**	0.08				69.00***	0.23	45.05	44.33	50.77	-18.16
4	RoB + EF_{-rIPL}	-0.08	0.05***		-0.10			68.91***	0.23	46.42	43.41	49.86	-17.70
5	RoB + $EF_{-lDLPFC}$	-0.25	0.04**			0.06		70.12***	0.23	46.30	45.42	51.86	-18.71
6	RoB + EF_{+rIPL}	-0.06	0.06***				-0.14*	64.98**	0.21	42.72	40.52	46.97	-16.26
7	RoB + $EF_{+lDLPFC}$ + EF_{-rIPL}	-0.27	0.06***	0.07	-0.10			66.97***	0.22	43.98	43.86	51.91	-16.93
8	RoB + $EF_{+lDLPFC}$ + EF_{+rIPL}	-0.23	0.06***	0.06			-0.14*	63.52**	0.21	40.79	41.22	49.27	-15.61
9	RoB + $EF_{-lDLPFC}$ + EF_{-rIPL}	-0.19	0.05***		-0.10	0.06		67.56***	0.22	44.48	44.55	52.61	-17.27
10	RoB + $EF_{-lDLPFC}$ + EF_{+rIPL}	-0.18	0.06***			0.07	-0.15*	63.56**	0.21	40.67	41.45	49.50	-15.72
11	RoB + $EF_{+lDLPFC}$ + EF_{-rIPL} + $EF_{-lDLPFC}$ + EF_{+rIPL}	-0.23	0.06***	0.01	0.23	0.05	-0.36*	59.14**	0.18	34.39	43.10	54.37	-14.55

*p < .05, **p < .01, ***p < .001

Abbreviations: EF: electric field; lDLPFC: left dorsolateral prefrontal cortex; MA: meta-analysis; rIPL: right inferior parietal lobule; RoB: risk of bias.

3.2. Exploratory analysis

Next, in an exploratory approach, we assessed the association between EF (separately for anodal peak EF, cathodal peak EF and parcel-specific mean normfield) and the change in MW propensity for real vs. sham tDCS at each of the 300 cortical parcels, while controlling for RoB, corresponding to running independent MAs for every parcel. This relationship is represented by the regression coefficient for the estimated EF, as shown in Figure 6. We highlight parcels with a significant association between EF and effect size at a more conservative alpha level ($p < .01$, not corrected for multiple comparisons). Labels of cortical parcels, the corresponding regression coefficient estimates and *p*-values for all three EF measures are presented at OSF (https://osf.io/ukfjx/)

In the left hemisphere, several posterior (primarily occipital and temporoparietal) parcels in the lateral and medial aspects showed significant ($p < .01$) coefficients. Altogether, we identified 32 posterior parcels for the anodal peak of the normal EF (Figure 6A), 26 posterior parcels for the cathodal peak of the normal EF (Figure 6B) and 32 posterior parcels for the normfield EF (Figure 6C) in this hemisphere. In contrast, only 3 parcels in the left frontal lobe showed a significant association between the anodal peak of the normal EF and reported effect size (Figure 6A), whereas for cathodal peaks, only one parcel was identified (Figure 6B), and none for the normfield EF (Figure 6C). Importantly, neither of these anterior parcels were located in the lDLPFC, but rather, in dorsomedial and frontopolar regions.

With respect to posterior regions in the right hemisphere, the effect of the EF on MW propensity was strongest in superior temporal and temporoparietal regions (anodal peak of the normal EF: 11 parcels (Figure 6A); cathodal peak of the normal EF: 5 parcels (Figure 6B); normfield EF: 6 parcels (Figure 6C)). Moreover, only five

frontal parcels (anodal peak of the normal EF: 4 parcels (Figure 6A); cathodal peak of the normal EF: 1 parcel (Figure 6B); normfield EF: none (Figure 6C)) were associated with modulatory effects of tDCS on MW propensity, but again, all were located outside the right DLPFC.

A key finding from the exploratory analysis was that the direction by which EFs in significant parcels were related to MW was strongly constrained by cortical anatomy, with EFs in anterior and posterior parcels being exclusively associated with increasing and reducing MW propensity (negative and positive coefficients), respectively. Crucially, and in line with coefficients extracted from the targeted MA, region-specific effects were polarity-independent, i.e., coefficients obtained for anodal vs. cathodal peaks indicated effects in the same direction (with identical signs). The direction of the effect (i.e., positive coefficients in frontal areas and negative coefficients in posterior regions) corresponded to the sign of the regression coefficients from the analysis including normfield EF values (Figure 6), despite this latter measure reflected only the strength of the EF in any parcel, without taking the orientation of current flow into account.

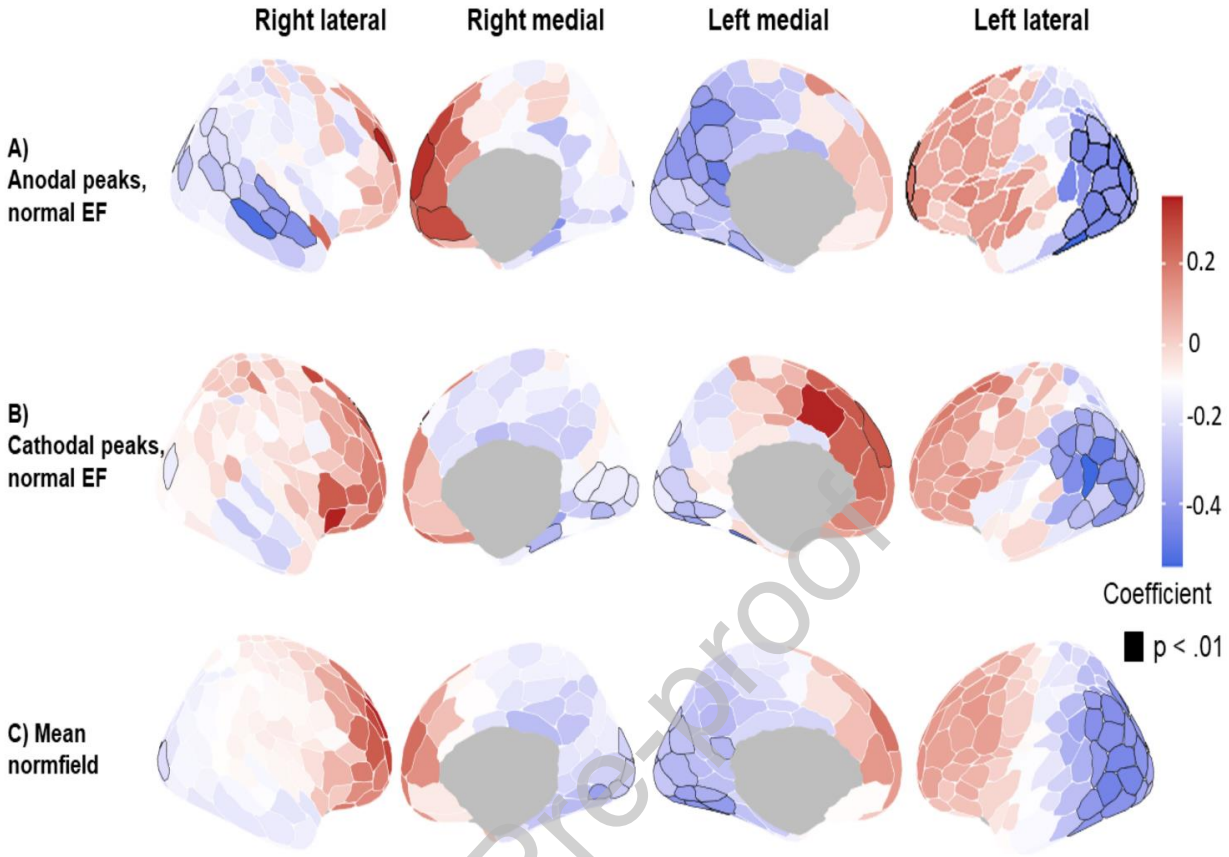

Figure 6. (two column width) Exploratory analysis in which RoB and anodal (A) or cathodal (B) peaks of the normal EF component, or the mean normfield EF (C) were used as moderators in the meta-analytic model for all 300 cortical parcels from the Schaefer Atlas.

4. Discussion

The literature on the impact of tDCS on MW is inconsistent as both increases, decreases and no effects have been observed in studies featuring different brain stimulation protocols. In this MA using a novel approch incorporating EF simulations, we assessed whether there was any evidence that 1) tDCS can modulate MW in any direction (either increasing or reducing it), and if so, 2) which cortical regions contribute to the effect, and 3) which polarity of the stimulation is associated with the effect. We included 37 effect sizes and 21 tDCS protocols from 15 studies,

and observed a small but significant increase in MW with tDCS, unless RoB was included in the model. The small overall effect of tDCS is consistent with small-to-medium reported effect sizes in previous meta-analyses on the efficacy of tDCS on various cognitive domains (Begemann et al., 2020; Schroeder et al., 2020; Wischnewski et al., 2021). However, this effect diminished once we accounted for RoB in the analysis, supporting the conclusion that across the 15 included studies, we found no reliable evidence for the modulation of MW propensity via real tDCS. Despite this, we could still identify cortical areas (in particular, the rIPL), in which the peak EF magnitude might be associated with MW. While this latter finding seems to be at odds with our primary conclusion about no overall reliable effects of tDCS on MW, we will argue below that they are not necessarily contradictory and provide novel insights for future empirical studies.

Risk of bias contributes significantly to the reported effect of tDCS on MW

According to our knowledge, none of the previous MAs conducted on tDCS studies focusing on various cognitive processes formally accounted for potential risk of bias. RoB assessment encorporates the identification of methodological problems such as issues with randomization and blinding, as well as a possibility for flexible data analysis due to the lack of pre-registeration or manuscript submission as registered reports. After adding RoB as moderator in our analysis, the change in MW propensity with tDCS was not significant, while the contribution of RoB was substantial. Crucially, the association between RoB and effect size estimates was significant in all models, even after controlling for EF in the lDLPFC and/or rIPL. The positive regression coefficient for RoB indicates that studies with less methodological rigor (high RoB scores) likely overestimated the potential to which tDCS affected MW propensity (Boayue et al., 2020). Overall, this indicates that, when considering all tDCS protocols and designs in these studies, and accounting for potential methodological shortcomings, there is no reliable evidence that real tDCS significantly influences MW propensity relative to a sham condition. We recommend

following the Cochrane guidelines as well as pre-registeration and/or considering registered reports in future studies so that effects of tDCS on MW can be tested more transparently and precisely.

Anodal rIPL stimulation might lead to reduced MW propensity

In our targted MA, only the anodal peak of the normal component EF in rIPL was found to be a significant predictor of the reported effect sizes (models 6, 8, 10 and 11), even after controlling for RoB. While the overall effect of tDCS on MW propensity (as reflected by the intercept) was not significant in these models, the variance in the primary outcomes across studies was still negatively associated with the peak anodal EF in the rIPL, including the model which was favored by our model selection criteria. In this model, both predictors were significant, indicating that, after controlling for RoB and anodal tDCS currents in the rIPL, no evidence for an effect of real stimulation on MW remains. However, since the EF in any cortical area is related to effects of real stimulation, this result still points at the rIPL as a promising target region for future studies attempting to reduce MW via tDCS, while keeping in mind that currently we lack firm empirical evidence for such effect to occur at all.

Earlier neuroimaging studies found positive associations between self-referential mental processes, MW propensity and DMN activation (Christoff et al., 2016; Fox et al., 2015; Mason et al., 2007). Based on this assumption, one can expect an increase in MW propensity with anodal stimulation of DMN nodes such as the rIPL. However other studies also pointed out that the association between MW and activity in the DMN may not always be positive (Groot et al., 2022; Kucyi et al., 2017). These latter reports are also in accordance with other lines of research showing that the DMN cannot be regarded as a task-negative network, since it is also involved in encoding task-relevant information during cognitive tasks (Crittenden et al., 2015). Therefore, our finding that anodal EF peaks in the rIPL is associated with lower MW propensity are in contrast with the task-negative characteristics of the DMN, since all included

studies measured MW during cognitive tasks, and might in turn indicate that DMN stimulation could improve task-focus.

Another possible explanation for the possible involvement of the rIPL in MW relates to how this area is involved in regulating the dynamic interactions between nodes of the DMN. Our result is in line with the findings by Kajimura and colleagues (Kajimura et al., 2019; Kajimura et al., 2016; Kajimura & Nomura, 2015), reporting that anodal tDCS above the rIPL decreases MW propensity. Considering that functional connectivity between the rIPL to the posterior cingulate cortex (PCC) is negatively related to daydreaming frequency (Kucyi & Davis, 2014), the authors proposed that anodal tDCS above the rIPL increases effective connectivity from rIPL to PCC, and hence reduces MW propensity (Kajimura et al., 2016). Thus, this view posits that the right IPL inhibits MW by regulating PCC activity within the DMN. Indeed, in their subsequent study, the same group found that anodal tDCS of the right angular gyrus (rAG) changed effective connectivity within the DMN and led to reduced MW, while the left AG was linked to increase in MW (Kajimura et al., 2019). Finally, Kajimura et al. (2019) raised the possibility that anodal tDCS above the rIPL might modulate task-related sustained attention via interactions with the ventral attention network (VAN). In this view, norepinephrinergic (NE) inputs from the locus coeruleus (LC) to the rIPL are of key importance (Singh-Curry & Husain, 2009), as they regulate the shift from task-focus to MW via an intermediate exploratory state (Mittner et al., 2016).

We provide meta-analytic evidence for the potential contribution of anodal tDCS above the rIPL to reducing MW propensity, which is in line with a series of studies (Chou et al., 2020; Kajimura et al., 2019; Kajimura et al., 2016; Kajimura & Nomura, 2015). In order to elucidate the neural mechanism behind this phenomenon, we recommend future studies to trace functional and effective connectivity in DMN regions pre- vs. post-tDCS sessions, possibly combining with pupillometry to assess the involvement of the LC-NE system (Groot et al., 2021; Groot et al., 2022). In

addition, the putative role of rIPL in reducing MW could be probed with other excitatory non-invasive brain stimulation techniques, such as high-frequency repetitive TMS or intermittent theta-burst stimulation (Ridding & Rothwell, 2007).

Stimulation of the lDLPFC does not contribute to changes in MW propensity

In the literature there is an agreement that executive functions (ExFu) are related to MW, though the exact nature of this association is not clear (Christoff et al., 2009; McVay & Kane, 2009, 2010; Smallwood et al., 2012). According to the "executive function use" (ExFu-use) view, MW shares the same executive resources with ongoing tasks, so the resources must be allocated to either MW or ongoing task (Smallwood & Schooler, 2015). According to the "executive function failure" (ExFu-fail) hypothesis of MW, during cognitive tasks executive resources are recruited to maintain task-related focus and to suppress MW thoughts (McVay & Kane, 2010). Both views can explain why performance on cognitive tasks decreases with the onset of MW, either because a proportion of ExFu resources are dedicated to MW (ExFu-use), or because MW occurs as a consequence of declined ExFu and task performance (ExFu-fail). However, they have opposing predictions about how excitatory stimulation of ExFu-associated brain areas (such as the lDLPFC) influences MW propensity. According to ExFu-fail, anodal tDCS above the lDLPFC decreases MW due to more efficient allocation of attentional resources to the task at hand. However, if MW and executive performance share resources (ExFu-use account), tDCS-associated enhancement in FPCN activity could lead to more MW without hindering task performance (Boayue et al., 2021). Based on these considerations, an increasing number of studies targeted the lDLFPC (Axelrod et al., 2018; Boayue et al., 2021; Clarke et al., 2020; Filmer et al., 2021; Nord et al., 2017) to interfere with MW. While most of these studies reported an effect for real tDCS when compared to a sham condition, two were failed replications and provided support for a null-effect (Boayue et al., 2020; Alexandersen et al., 2022). In line with these latter studies, we also did not observe any effect of either anodal or cathodal

peaks of the normal component EF from lDLPFC after controlling for RoB. The robustness of our result concerning the lDLPFC is further strengthened by a very recent study that we became aware of at the time of manuscript submission, in which the authors targeted the lDLPFC with anodal tDCS to interfere with MW propensity, but found no effects for real vs. sham stimulation (Coulborn & Fernández-Espejo, 2022) A possible explanation for these findings is that the lDLPFC may not be crucial for MW, as was also pointed out by recent neuroimaging studies (Fox et al., 2015; Groot et al., 2022). On the other hand, the nature and degree to which the lDLPFC regulates MW during cognitive tasks might be context-specific, and thus, heterogeneity in the cognitive paradigms used in these studies might have confounded our results.

Regions outside the rIPL may also be potential targets to interfere with MW

In an exploratory analysis, we included EFs from 300 cortical parcels as moderators while controlling for RoB. We have identified numerous parcels with significant contributions to MW, with surprising general patterns. A key finding was that the direction to which EFs were related to MW was strongly constrained by cortical anatomy. Namely, EFs in some anterior regions were associated with increasing MW propensity, while posterior areas predominantly showed an effect to the opposite direction. Crucially, the distinct anterior vs. posterior gradient was independent of stimulation polarity, since the pattern was present for both anodal and cathodal peaks of the normal component, as well as for the analysis that used parcel-specific EF magnitude (normfield) as moderator. Filmer et al (Filmer et al., 2021) reported that cathodal stimulation to the lDLPFC and anodal stimulation to the right IPL did not modulate MW, possibly because the two areas were targeted simultaneously and their respective contributions to MW simply cancelled out. Such an interpretation is in line with the results reported here.

With respect to posterior areas, we found that both anodal and cathodal tDCS to predominantly left posterior (and to a limited extent, also right posterior) cortical regions reduces MW. Moreover, in the left hemisphere, significant effects were identified in both the lateral and medial aspects of occipital and temporoparietal areas. Even though this result stems from an exploratory analysis and is not corrected for multiple comparisons (albeit relying on a more stringent alpha-level), it warrants extending our discussion on the role of rIPL in MW.

Since posterior parcels showing an association with MW propensity are very heterogeneous in their putative functions (belonging to either the visual, dorsal/ventral attention, default mode, limbic or frontoparietal control networks), and their potential contribution to reduced MW is polarity-independent, we propose a more general framework to account for our results, namely, that tDCS interfered with internally-oriented mentation in these studies. In particular, we speculate that, rather than increasing or reducing neural excitability, EFs in these regions might disrupt ongoing computations associated with the neural correlates of consciousness (Koch et al., 2016). According to the integrated information theory (IIT), the "posterior hot zone", which was identified in task-negative states, largely overlaps with cortical areas associated with content-specific correlates of consciousness during waking (Koch et al., 2016). The posterior hot zone encompasses parietal, temporal and occipital areas (Seth & Bayne, 2022), and has been proposed to exhibit neuroanatomical properties that can generate integrated information, or consciousness (Tononi et al., 2016). This region has been also found to be active while dreaming, with high-frequency oscillatory activity within posterior regions correlating with specific dream content, suggesting that it may constitute a core correlate of conscious experiences in sleep (Siclari et al., 2017). MW bears resemblance to dreaming as both are internally-generated and less influenced by external stimuli (Fox et al., 2013). Based on the above, since both anodal and cathodal tDCS on these regions decreased MW, the effect of tDCS can be related to polarity-independent perturbation in neural

activity that are linked to consciousness. While, on the same grounds, it could be argued that conscious processing of task-related stimuli might have also been disrupted by tDCS, we posit that real stimulation was influencing internal mentation more robustly, since cognitive tasks typically used in MW-research are purposefully designed to be very simple to facilitate engagement in task-unrelated thoughts. On the other hand, MW can be very vivid and content-rich (Smallwood et al., 2021; Wang et al., 2018), and therefore, any interference with activity in these posterior regions could have led to less intensive MW episodes, manifesting in reduced MW self-reports.

In contrast to posterior regions, several anterior regions showed a positive association between EFs and MW propensity, an effect that was also polarity independent. Despite our unsuccessful attempt to show a contribution of EFs in the lDLPFC to MW, in an exploratory approach we have identified cortical parcels in the frontal lobe that contribute to the effect of real tDCS on MW. These parcels were outside the left and right DLPFC, which is in line with the results of our targeted MA. Despite this, we have identified two parcels that are functionally associated with task-related cognition, one in the left frontopolar region (part of the FPCN), and one in the right superior frontal gyrus (part of the ventral attention network). Given that EFs in these parcels might contribute to increased MW propensity regardless of the direction of current flow, it may be tempting to view this result as some support for the ExFu-fail account of MW. In particular, polarity-independent disruption in task-relevant neural activity in these regions could theoretically weaken executive control, reducing task-focus and leading to more MW episodes. However, this assumption warrants more systematic testing in future studies, since other frontal parcels that belong to the DMN or the limbic network have also showed a significant positive association with MW. With respect to the mPFC, some neuroimaging findings indicate that the effective connectivity from the mPFC to the PCC is involved in generating MW (Kajimura et al., 2016), or that mPFC activation is increased during MW (Di &

Biswal, 2014; Jiao et al., 2011; Mason et al., 2007). While these observations can provide explanation for our result, it warrants caution until tested more systematically, possibly with other non-invasive brain stimulation methods such as TMS.

Heterogeneity contributes significantly to effect of tDCS on MW

Despite relying on a random-effects MA model and controlling for the large variety of tDCS parameters in the 15 protocols, as well as accounting for methodological quality via RoB assessment, all models in our targeted meta-analysis showed significant heterogeneity. Model 2 with RoB as moderator had less heterogeneity than our null-model, but even the winning model (model 6 with anodal EF peaks in rIPL and RoB as moderators) showed substantial heterogeneity. A possible source for the residual heterogeneity might be due to the different cognitive tasks used in the studies, as well as to how MW was assessed via thought-probes. Other contributing factors could be due to study design (within- vs. between-subject), whether online vs. offline effects of tDCS were evaluated, or other factors which can influence the effect of brain stimulation , such as age, gender, hormonal fluctuations, initial brain-state and caffeine consumption (Krause & Cohen Kadosh, 2014). We acknowledge that conclusive evidence from this MA is constrained by heterogeneity and therefore, we emphasize that the results must be interpreted with caution.

5. Limitations

This MA has several limitations. First, it is based on fifteen studies only and therefore, the results should be interpreted with caution and tested systematically in the future. Second, we have not accounted for the variability in cognitive tasks used in these studies. Although the SART was the most frequently used task (in 7 studies, corresponding to 46.6%), others relied on a variety of tasks, focusing on different components of sustained attention and/or executive control. This could have

influenced the outcomes as task complexity and/or difficulty alter individual responsiveness to tDCS (Hsu et al., 2016) and TMS (Silvanto et al., 2008). The third limitation is that, even though we have controlled for tDCS dose to a greater extent via EF modelling, we have not accounted for variability in stimulation duration (although 12 out of 15 studies applied tDCS for 20 minutes). The length of tDCS can influence neuroplasticity and hence both the strength and duration of behavioral after-effects following stimulation (Agboada et al., 2019; Hurley & Machado, 2017). However, at present there is no agreed general framework as to how to determine the optimum dose of tDCS (Giordano et al., 2017; Kuo et al., 2013) for a given cognitive task or at individual level (Li et al., 2015; Nikolin et al., 2018), and there is evidence that healthy adults exhibit non-linear dose-response relationships regarding tDCS (Hoy et al., 2013; Nikolin et al., 2018). The fourth limitation is that we have not corrected for differences in study designs, namely, whether authors analyzed online or offline effects of tDCS, or both. Again, variability in cognitive tasks and the duration of tDCS across studies can influence behavioral (after-)effects, and therefore, the timing of stimulation with respect to task implementation and outcome assessment is crucial (Martin et al., 2014). All these factors mentioned above create heterogeneity and limit the generalizability of our findings.

Finally, the analysis plan for the current MA was not pre-registered. Given that the authors of this study are intimately familiar with many of the studies selected for this meta-analysis (in fact, MM and GC are authors on 3 of the studies), it was impossible to pre-register the analysis before knowing the data. Therefore, we do not believe that pre-registration of our study would have contributed meaningfully to reduce the analyst's bias. We are aware that pre-registration for MAs has been recommended by some authors to reduce overly flexible data analysis (Moreau & Gamble, 2022; Quintana, 2015), and therefore, we note its absence as a possible limitation.

6. Conclusion

In our study we identified methodological problems that may have contributed to overestimated effect sizes in several studies, an issue that should be remedied in the future. Our primary conclusion is that the 15 studies included in this meta-analysis did not provide reliable evidence for the potential of tDCS to influence MW in healthy adults. However, we also found that, based on the current literature, the rIPL might be the most promising cortical area for influencing MW, provided that this assumption is tested with sufficient methodological rigor. Given that EF in this region was negatively associated with MW propensity, the rIPL can serve as a candidate target for future brain stimulation studies (including TMS) aiming at reducing MW in psychiatric disorders such as ADHD or MDD. The lDLPFC did not seem to be of key importance in modulating MW, and instead, other PFC regions (mPFC, frontopolar cortex) could be targeted instead. The influence of cognitive task choice should be also more systematically explored to understand the nature of task-related effects. We recommend future studies to incorporate more than one tDCS session within a day to check for accumulating effects or to have multiple sessions within-subject on multiple days to assess test-retest reliability. Further, the behavioral effects of tDCS (or other brain stimulation techniques) on MW could be supplemented by assessing functional and effective connectivity within and between resting-state networks to elucidate the neural mechanisms of the putative effects. Due to issues with RoB and heterogeneity, the above recommendations could help us to understand not only how tDCS modulates MW, but to clarify, if tDCS is influencing MW at all.

Data and Code Availability Statement

Data availability: All relevant data and code are reported in the manuscript, supplementary materials and OSF.

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Data and Code Availability Statement

Data availability: all relevant data and code are reported in the manuscript, supplementary materials and OSF.