Clinical Neuropsychiatry (2024) 21, 1, 99-109

RESEARCH PAPER

NO IMPACT OF TDCS ON STRESS-INDUCED STATE RUMINATION AND NO INFLUENCE OF EXECUTIVE CONTROL AND TRAIT RUMINATION: A DOUBLE-BLIND SHAM-CONTROLLED WITHIN-SUBJECTS STUDY

Yorgo Hoebeke, Marie-Anne Vanderhasselt, Marion Carême, Pierre Maurage, Alexandre Heeren

OPEN ACCESS

Abstract

Objective: Rumination is conceptualized as a critical transdiagnostic vulnerability and maintenance factor for affective dysregulation and related emotional disorders. Recent research has pointed to transcranial direct current stimulation (tDCS) as a novel therapeutic tool for alleviating rumination, especially stress-induced rumination. However, the mechanisms of action underlying this effect remain unclear, particularly regarding the potential moderating role of executive control and trait-like rumination. Therefore, in this study, we investigated the impact of anodal tDCS on stress-induced rumination and the potential moderating influence of executive control and trait-like rumination on this effect.

Method: Forty participants from the general community (i.e., unselected sample) took part in a double-blind within-subjects design study wherein we compared anodal stimulation over the left dorsolateral prefrontal cortex(dlPFC) with a sham-stimulation procedure. Participants completed an N-back task, reflecting executive control, during tDCS stimulation, followed by a stress-induction protocol wherein we assessed stress-induced state rumination.

Results: We found no significant effect of tDCS on stress-induced state rumination and no modulation by executive control or trait rumination. Post-hoc Bayesian analyses corroborated these results and even supported the hypothesis that anodal tDCS does not impact stress-induced rumination.

Conclusions: From a clinical perspective, our results are at odds with the current outlook that tDCS is a viable tool for reducing rumination, particularly stress-induced rumination. However, we firmly believe that the results of null-finding studies, such as those from this study, are particularly valuable for future iterations and meta-research on tDCS as a potential tool for targeting transdiagnostic processes, such as rumination. We also addressed methodological limitations and directions for future research in this area.

Key words: rumination, tDCS, executive control, brain stimulation, dlPFC, stress

Yorgo Hoebeke[1], Marie-Anne Vanderhasselt[2], Marion Carême[1], Pierre Maurage[1,3,4], Alexandre Heeren[1,3,4]
[1] Psychological Science Research Institute, UCLouvain, Louvain-la-Neuve, Belgium
[2] Department of Head and Skin, Psychiatry and Medical Psychology, Ghent University Hospital, Ghent University, Ghent, Belgium
[3] Institute of Neuroscience, UCLouvain, Brussels, Belgium
[4] National Foundation for Scientific Research (FRS-FNRS), Brussels, Belgium

Yorgo Hoebeke https://orcid.org/0000-0003-2565-8311
Marie-Anne Vanderhasselt https://orcid.org/0000-0002-4045-1055
Pierre Maurage https://orcid.org/0000-0003-0197-0810
Alexandre Heeren https://orcid.org/0000-0003-0553-6149

Data availability statement: All data, code, and computerized tasks that support the findings of the study are openly available on the Open Science Framework at the following repository link: https://osf.io/yq8j5/

Author contributions: YH: Conceptualization, Software, Formal Analysis, Investigation, Data Collection, Writing – Original Draft; MAV: Validation, Writing – Review & Editing. PM: Validation, Writing – Review & Editing. MC: Investigation, Data Collection. AH: Conceptualization, Methodology, Supervision, Funding Acquisition, Writing – Original Draft.

Citation: Hoebeke, Y., Vanderhasselt, M.A., Carême, M., Maurage, P., Heeren A. (2024). No impact of tDCS on stress-induced state rumination and no influence of executive control and trait rumination: A double-blind sham-controlled within-subjects study. *Clinical Neuropsychiatry, 21*(1), 99-109.

doi.org/10.36131/cnfioritieditore20240107

Funding: Data collection and equipment acquisition were supported by the FRS-FNRS Belgian National Science Foundation (Research Grant: "1.C.059.18F"; Project: Networks4ExecutiveControl&Rumination) awarded to Alexandre Heeren. Yorgo Hoebeke and Alexandre Heeren were funded by a "Special Research Funds"—FSR Research Grant from the Université catholique de Louvain. Alexandre Heeren (Research Associate) and Pierre Maurage (Research Associate) are also funded by the Belgian Fund for Scientific Research (Fonds de la Recherche Scientifique–FNRS, Belgium) via a tenured fellowship. Marie-Anne Vanderhasselt received funding from the special research funds (BOF) [grant number BOF17/STA/030], as well as from FWO-Flanders for research projects for fundamental research (Grant Numbers: G044222N; G044019N).

Competing interests: Dr. Alexandre Heeren receives honoraria for his editorial work from Elsevier. This financial support had no influence on the study design, data collection, analysis, decision to publish, or writing of the article. The other authors declare that they have no conflict of interest.

Corresponding author
Alexandre Heeren
E-mail: alexandre.heeren@uclouvain.be

Submitted for Fast Track Evaluation
Submitted January 2024, accepted February 2024

Introduction

Rumination is characterized by negative, repetitive thoughts about one's concerns and their causes, meanings, and consequences without taking action to resolve them (Nolen-Hoeksema et al., 2008). It is considered a transdiagnostic feature of various mental disorders (McLaughlin & Nolen-Hoeksema, 2011; Watkins, 2015), and is implicated in their maintenance (e.g., depression, anxiety, binge eating, and substance use disorders). Given its clinical relevance, researchers have sought to gain a deeper understanding of rumination and find ways to reduce it.

Prominent cognitive models postulate that executive control impairments contribute to rumination (e.g., Koster et al., 2011; Watkins & Roberts, 2020). They postulate that deficits in executive control lead to difficulty disengaging from thoughts or shifting attention to other thoughts, resulting in persistent rumination. Cross-sectional studies support this hypothesis, showing associations between rumination and poor executive control at behavioral (Zetsche et al., 2018) and brain levels (Kühn et al., 2014; Vanderhasselt et al., 2011). However, the exact nature and direction of this relationship remain unclear: whereas experimental studies suggest that improving executive control can reduce trait-like rumination (Zwalmen et al., 2023), stress-induced state rumination conversely alters executive control (Philippot & Brutoux, 2008).

Taking stock of this growing literature, researchers applied techniques such as transcranial direct current stimulation (tDCS) to investigate the causal links between rumination and executive control. Indeed, tDCS is a noninvasive brain neuromodulation technique that affects cognitive and motor domains by modulating cortical excitability (Fregni & Pascual-Leone, 2007). Systematic reviews and meta-analyses have demonstrated the safety and therapeutic efficacy of tDCS for various mental disorders (Borrione et al., 2018; Stein et al., 2020; Zortea et al., 2019). Researchers have also successfully modulated executive control (Strobach & Antonenko, 2017) and working memory (Brunoni & Vanderhasselt, 2014) in healthy populations by stimulating the dorsolateral prefrontal cortex (dlPFC), a region involved in executive control (Barbey, Colom, et al., 2013; Barbey, Koenigs, et al., 2013; Brosnan & Wiegand, 2017) and rumination (Cooney et al., 2010).

Given the involvement of the dlPFC in executive control and rumination, researchers have started investigating whether tDCS can modulate rumination by stimulating the dlPFC (e.g., De Raedt et al., 2017; Vanderhasselt et al., 2013). In a recent systematic review (i.e., Hoebeke et al., 2021), five of the nine identified studies showed a significant effect of tDCS on rumination. Four of these studies found a significant effect of a single tDCS session on state rumination, while one reported a significant effect of ten tDCS sessions on trait rumination (Movahed et al., 2018). However, Hoebeke et al. (2021) identified that between-study heterogeneity was high, especially in terms of stimulation parameters and experimental settings, thus precluding any conclusion that one can draw on the impact of tDCS on rumination.

In addition, the mechanisms underlying the effect of tDCS on rumination remain unclear and require further investigation. The prevailing hypothesis suggests that anodal tDCS applied over the dlPFC can increase the cortical excitability of a neural network involved in executive control, thereby assumedly enhancing executive control, which in turn would reduce rumination (e.g., De Raedt et al., 2017; Koster et al., 2011). Moreover, trait rumination might modulate this mediation effect. Participants with a higher tendency to ruminate have, on average, poorer executive control (Zetsche et al., 2018) and might therefore benefit more from the tDCS-induced executive control improvement. However, this hypothesis of moderated mediation—i.e., tDCS impacts state rumination via the improvement of executive control (mediating variable) only among those exhibiting a general tendency to ruminate (moderating variable)—has only been tested and found in one study (Vanderhasselt et al., 2013), leaving open the question of whether changes in executive control serve as a mechanism whereby tDCS influences rumination.

Previous studies also considered rumination as a single, latent entity by using a unique, global scale-score value of rumination (Bernstein et al., 2017, 2020; Hoebeke et al., 2022, 2023). However, as stated elsewhere (e.g., Bernstein et al., 2017; Hoebeke et al., 2022, 2023), such a procedure obscures information about the features of rumination. Indeed, several theoretical approaches have suggested that state rumination encompasses several key features. For instance, according to Nolen-Hoeksema's prominent approach (e.g., Nolem-Hoeksema & Morrow, 1991; Nolen-Hoeksema et al., 2008), state-rumination involves five key features, namely *perseveration* (i.e., the time spent thinking about emotional experiences); *negativity* (i.e., to what extent one's thoughts are negative); *self-criticism* (i.e., having self-critical thoughts); *brooding* (i.e., thinking of the causes and consequences of emotional experiences); and *replaying* (i.e., mentally reviewing parts of emotional experiences). And, empirical research capitalizing on this five-feature approach to state rumination has shown the importance of distinguishing these features (e.g., Bernstein et al., 2017, 2020; Hoebeke et al., 2022, 2023), notably with recent works emphasizing the pivotal role of negativity (Hoebeke et al., 2023) in the emergence of state rumination. A critical next step in tDCS research on state rumination will thus be to examine whether tDCS equally impacts the different features of state rumination.

There are therefore gaps in the literature on the effect of tDCS on rumination at three levels. First, it is unclear how tDCS can influence state rumination. The main hypothesis is that changes in executive control mediate this effect, but only one study has examined this mediating role (i.e., Vanderhasselt et al., 2013). Second, the effect of tDCS on state rumination may depend upon the level of trait rumination, as assessed before the stimulation. In other words, this effect may only occur in individuals already exhibiting a general tendency to ruminate. Third, it is unknown whether these effects equally occur across the five features of state rumination. We addressed all these questions in a double-blind, sham-controlled within-subject study design by examining the impact of anodal tDCS applied over the left dlPFC during an executive control task (i.e., an N-back task), on stress-induced state rumination (as in previous research) and by also assessing trait rumination to examine its potential moderating influence.

We hypothesized that anodal tDCS would reduce state rumination, as comparted to sham stimulation, and that trait rumination would moderate this effect (i.e., higher trait rumination would be associated with a greater tDCS-induced reduction in executive control and state rumination). Furthermore, similar to previous research (Vanderhasselt et al., 2013), we hypothesized that tDCS-induced executive control improvements (here, the N-back task performance) would mediate the effect of tDCS on state rumination and that trait rumination would moderate this mediation effect. Finally, we hypothesized that these effects might vary across the five hallmark features of state rumination discussed above.

Methods

Transparency and Openness

We provide the de-identified data, R code, and supplementary materials sections at https://osf.io/yq8j5/.

Participants

We recruited an unselected sample of 40 participants (77.5% female) via social media as part of a larger data collection. Participants had a mean age of 21.2 years (*SD*=2.03) and an average of 9.18 (*SD*=1.72) years of formal education (after elementary school). All but two participants were students (i.e., one was self-employed and one was employed). To be included in the study, participants had to be between 18 and 60 years old, be exclusively right-handed, speak French, not be pregnant, not have had neurosurgery, not have neurological problems, not have any signs of epilepsy (or family history of epilepsy), and not have chronic migraines, metallic implants in the brain or face, sensitive skin, or ventricular or cerebral drainage (Antal et al., 2017). The project received the approval of the biomedical review board of UCLouvain (REF# 2020/057), and conducted in accordance with the Declaration of Helsinki. All participants provided written informed consent. Participants received 50€ for participating in the entire study.

Materials and measures

Trait rumination. Participants completed the French-validated version of the Ruminative Response Scale questionnaire (Douilliez et al., 2018) before the two tDCS sessions. The short RRS (RRS-10) is a 10-item self-report questionnaire measuring the tendency to ruminate in response to a negative affect or mood (Treynor et al., 2003). The items are scored on a 4-point Likert-scale from 0 (never) to 3 (always). The 10 items of the RRS-10 showed good internal reliability in the present sample (α=.77).

Measures of depression and anxiety. To better describe our community sample, we administered the Beck Depression Inventory (Beck et al., 1996) and the Generalized Anxiety Disorder scale, (Spitzer et al., 2006). The BDI-II is a 21-item scale assessing symptoms depression and the GADD-7 a seven-item scale assessing generalized anxiety disorders symptomatology. We used the validated French versions of the scales (BDI-II; Beck et al., 1996; GAD-7; Micoulaud-Franchi et al., 2016). Both the GAD-7 (α=.76) and the BDI-II (α=.82) showed good internal reliability in the present sample. **table 1** presents the descriptive statistics of these measures.

State rumination. We assessed state rumination as in Bernstein et al. (2017, 2020), who evaluated the five features of rumination via a specific item based on Nolen-Hoeksema's approach to rumination (Nolen-Hoeksema et al., 2008): "perseveration" (i.e., how much they had been thinking about their performance), "negativity" (i.e., how negative their thoughts were), "self-criticism" (i.e., how much they had been criticizing themselves), "brooding" (i.e., how much they thought about their negative emotional experience), and "replaying" (i.e., to what extent they replayed parts of what happened in their mind). Participants were asked to answer these items in relation to their thoughts during the 5-minute rest period and had to indicate their answers on a scale from 0 to 100 (converted into a score from 0 to 1 with two decimals). In line with recent research on state-like psychological constructs (e.g., Blanchard et al., 2023; Contreras et al., 2024), the order of the items was randomized to prevent systematic sequence effects from introducing bias to the data.

Assessment of stress. The participants had to indicate three times on a scale from 0 to 100 how tense and calm they felt in response to the stressor: before the tDCS stimulation, after the tDCS stimulation, and after the rest period.

Executive control. We used an N-back task (Owen et al., 2005) with three difficulty levels. On each trial, participants had to indicate whether the stimulus presented was the same as the one presented n trials earlier. They had to click on the left mouse button if the stimulus had been presented n trials previously and on the right mouse button if it had not been presented n trials previously. On each trial, a fixation cross was presented for 700 ms, then the stimulus (a capital letter) was presented for 2 s, followed by a black dot for 500 ms (i.e., in the practice version of the task, feedback was shown for 500 ms to indicate whether the response was correct or incorrect with a green or red dot). During tDCS stimulation, participants performed four 1-back blocks, seven 2-back blocks, and seven 3-back blocks. Each block comprised 25 trials, five of which were targets (randomized). Before tDCS stimulation, participants performed a practice version of the N-back task with one block for each difficulty level (1-2-3) under close supervision of the experimenter to ensure a correct understanding of the instructions. To analyze performance on the N-back task for each difficulty level, we calculated the average reaction time and the discriminability index *d'*, as recommended by Haatveit et al. (2010). *d'* was calculated using the R package "psycho" (Makowski, 2018). The discriminability index represents how well the participant maximizes their hit rate (i.e., the proportion of target stimuli that are correctly identified) and minimizes their false-alarm rate (i.e., the proportion of non-target stimuli that are incorrectly identified as targets): the higher the *d'*, the better the participant can discriminate target from non-target when performing a task. The discriminability index is a useful measure because it considers both the accuracy and the response bias of the person (Haatveit et al., 2010). We adjusted extreme values following the recommendations of Hautus (1995) and coded the task in OpenSesame V3.3.6 (Mathôt et al., 2012).

Stress induction

Following Bernstein et al. (2017), we used a serial subtraction task to induce stress. In this task, participants had to count backward as fast as possible for three minutes (i.e., start at 572 and then subtract 13 each time). Participants had to start over if they were too slow (i.e., took more than three seconds to answer) or made a mistake, in which cases the experimenter said "Too slow" or "Error." This task was designed to put participants under pressure and elicit rumination in a subsequent five-minute rest period in which they were asked to sit still and do nothing. Supplementary Material (Section 3) gives more details regarding the manipulation check.

tDCS

Direct electrical current was delivered via a NeuroConn DC-Stimulator Plus device with integrated "double-blind study mode" (Neuroconn, GmbH, Ilmenau, Germany) and applied via a pair of sponge rubber electrodes (35cm2) soaked in saline (i.e., 0.9% NaCl concentration). We used a sham-controlled within-

subjects design so that all participants served as their own control. We placed the anode electrode vertically and centered over F3, according to the international 10–20 system for electroencephalogram electrode placement, to stimulate the left dlPFC. As in prior research (e.g., Heeren et al., 2015; Vanderhasselt et al., 2013), we placed the cathode electrode horizontally on the right supraorbital area. A constant direct current of 2 mA, starting with a 30 s ramp-up, was applied for 20 minutes, with a 30 s ramp-down at the end.

During sham stimulation, we placed the electrodes in the same location. However, the current ramped down to 0 mA after the first 30s. This procedure is commonly used in tDCS research and is an optimal method to convey the initial sensations of the effects of the stimulation on cortical excitability (Nitsche et al., 2008). We used predefined codes assigned to either sham or real stimulation to start the stimulator, allowing for a double-blind study design. We randomized and counterbalanced the order of anodal and sham stimulations between participants. The stimulation started 5 minutes before the N-back task and lasted for 20 minutes (see procedure in the next section). Thus, the N-back task was performed simultaneously with the stimulation. Finally, the second stimulation was performed one week later (if possible, at the same time of day) to avoid carry-over effects.

General procedure

Before coming to the laboratory sessions, each participant received a link to an online form, wherein they provided all the information relevant for a first general assessment of the exclusion criteria and the general demographic information. Participants completed the RRS-10, GAD-7, and BDI-II via this online assessment.

When arriving at the laboratory session, the instructor carefully checked once again all the inclusion and exclusion criteria, and participants completed questionnaires on substance use.

After installing the electrodes, a practice version of the N-back task was conducted. After this task, the participants indicated how tense versus calm they were from 0 ("*Calm*") to 100 ("*Tense*"). The anodal stimulation, or sham stimulation, began 5 minutes before the start of the N-back task and was carried out for 15 minutes. After completion of the N-back task and tDCS stimulation, we removed the tDCS, and participants again indicated how tense/calm they felt. Next, participants underwent a stress induction. They then had a five-minute rest period, during which they were asked to sit still and do nothing. After this rest period, participants completed a state measure of rumination and indicated how tense/calm they felt during the serial subtraction task. At the end of the second tDCS session, participants completed a questionnaire adapted and translated by Antal and colleagues (Antal et al., 2017) to assess tDCS side effects, sensations (see Supplementary Materials), and blinding. To assess blinding, participants indicated for each session whether they believed they were receiving real stimulation or sham stimulation, or whether they did not know which stimulation they had received (Antal et al., 2017). Importantly, participants were informed that they received real stimulation twice to obtain more consistent measures, and we did not disclose the true aim of the study until the end of the second session, after the questionnaires. **Figure 1** provides an overview of the procedure.

Data analysis plan

We computed linear mixed models and Bayesian analyses using R, version 4.2.2 (R Core Team, 2022). Each analysis was performed by accounting for time and order effects. We fitted linear mixed models estimated with REML, type 3 sum of squares, and Satterthwaite's degrees of freedom (Luke, 2017). We used the R package "DHARMa" to check the assumptions of the mixed models (Hartig, 2022). For all models, we calculated the conditional R^2 (considering both fixed and random effects) and the marginal R^2 (considering only fixed effects) using the method of Nakagawa et al. (2017) as implemented in the R package "performance" (Lüdecke et al., 2021). Following recent guidelines (Biel & Friedrich, 2018), we also computed Bayesian mixed models using Bayesian statistics with the R package "BayesFactor" (Morey & Rouder, 2022) to further test the effect of tDCS on rumination and N-back performance. To do so, we used Bayesian model averaging and reported the posterior inclusion probability for each predictor for each dependent variable (Hinne et al., 2020). When reporting the results of the post-hoc Bayesian analyses, we used Jeffrey's guidelines to interpret the Bayes factors (Jeffreys, 1998; Wetzels et al., 2011), translating the value of the Bayes factor into a qualitative judgement on the level of evidence (i.e., "Barely worth mentioning"; "Substantial"; "Strong"; "Very Strong"; "Decisive"). Finally, we performed moderated mediation analyses in SPSS using the macro MEMORE (Montoya, 2019).

Results

We removed one participant from the analysis because data from one session was missing due to a technical error. We also removed five participants who correctly guessed the type of stimulation in both sessions, which can bias the results (Supplementary Materials, Section 4). **Table 1** shows the descriptive statistics of all our variables of interest.

Effects of tDCS on rumination

There was no significant effect of tDCS on state rumination, neither at the total scale score nor at the level of its distinctive features (all *ps*>.05), controlling for session and stimulation order. Likewise, the interaction between the "tDCS condition" and "trait rumination" had no significant effect on state rumination, neither at the total scale score nor at the level of its distinctive features (**table 2**). Regarding our third hypothesis about the role of the different features of rumination, there was no significant effect.

Effects of tDCS on executive control

We tested the effect of tDCS on N-back performance before performing the full mediation analysis in SPSS. We only report the results of the 3-back task, as this was the most difficult task, considering that tDCS may have a greater effect on more difficult tasks (Papazova et al., 2020). We verified this assumption: the condition (anodal vs sham tDCS) did not influence 1-back and 2-back reaction times or *d′* prime (Supplementary Materials, Table S2).

After checking for outliers, we removed two participants for the 3-back reaction time analyses and three participants for the *d′* analyses. TDCS significantly

Figure 1. *Study protocol*

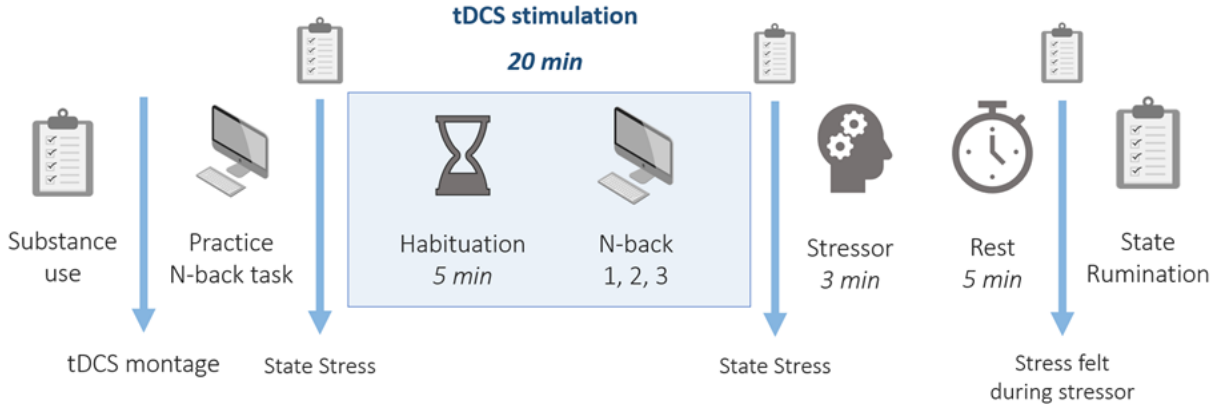

Table 1. *Descriptive statistics*

	Observations	*mean*	*SD*	*median*	*min*	*max*	*range*
RRS-10	40	10.38	5.09	11	1	22	0–30
BDI-II	40	11.8	6.9	11	1	34	0–63
GAD-7	40	6.25	3.81	6.5	0	16	0–21
Age	40	21.2	2.03	21.5	18	26	
Years of studies	40	9.18	1.72	9.5	6	12	
d' 1-back	78	3.9	0.52	3.97	2.77	4.48	
d' 2-back	78	3.6	0.62	3.6	2.21	4.89	
d' 3-back	78	2.78	0.56	2.77	1.29	4.03	
RT 1-back	78	540.32	97.25	541.40	364.52	771.57	
RT 2-back	78	673.99	151.89	665.38	387.36	1231.61	
RT 3-back	78	726.67	163.36	708.34	394.78	1218.22	
Total Rumination	78	2.17	1.03	2.16	0.1	4.31	0–5
Brooding	78	0.41	0.27	0.35	0.00	1	0–1
Negativity	78	0.32	0.25	0.26	0.00	0.8	0–1
Replaying	78	0.48	0.28	0.55	0.01	0.97	0–1
Self-criticism	78	0.42	0.26	0.4	0.00	0.9	0–1
Perseveration	78	0.53	0.27	0.58	0.00	0.98	0–1

Note. Observations = the total number of assessments throughout the entire protocol; GAD-7 = general anxiety disorders symptoms; BDI-II = depression symptoms; RRS-10 = comprises the brooding and the reflection subscales of the Ruminative Response Scale. Years of studies = completed years of formal education after high school. The minimum and maximum correspond to the minimum and maximum score observed in our sample. The range represents the possible scores for each questionnaire.

affected 3-back reaction times (i.e., slower reaction times in the anodal stimulation condition, $t(1,29)=2.25$, $p=0.032$, but not d', $t(1,28)=0.43$, $p=0.674$, controlling for session and stimulation order). The effect of session on RT and d' was significant (RT: $t(1,29)=8.41$, $p<.001$; d': $t(1,28)=2.94$, $p=0.007$), indicating faster reaction times in the second session. The main effect of trait rumination and the interaction effect between the condition and trait rumination were not significant for d' or 3-back RT (**table 3**).

Moderated mediation

Although none of our main effects were significant, we decided to run the moderated mediation model exploratory, using the MEMORE macro for SPSS with trait rumination as the centered moderator variable and the reaction times of the 3-back task as the mediator variable. The moderated mediation was not significant, neither at the total scale score nor at the level of its distinctive key features. Interestingly, 3-back RT positively predicted total state rumination scores and also the scores of the individual features of rumination except for negativity (see Supplementary Materials, Tables S3-S8, for the full results of the mediation analysis for each variable).

Additional Exploratory Analyses

The absence of a direct effect of tDCS on rumination combined with the significant prediction of rumination only by the 3-back RT task in the mediation analysis prompted us to further investigate the relationship between the "N-back task" and "rumination". To this end, we conducted post-hoc exploratory analyses in

Table 2. *Linear Mixed models of total state rumination and features of rumination*

Predictors	Total State rumination				Negativity				Brooding				Replaying				Self-Criticism				Perseveration			
	B	*SE*	*t(31)*	*p*	*B*	*SE*	*t(31)*	*p*	*B*	*SE*	*t(31)*	*p*	*B*	*SE*	*t(31)*	*p*	*B*	*SE*	*t(31)*	*p*	*B*	*SE*	*t(62)*	*p*
(Intercept)	2.08	0.12	17.49	<0.001	0.31	0.03	8.87	<0.001	0.38	0.03	12.78	<0.001	0.46	0.03	13.41	<0.001	0.41	0.03	11.9	<0.001	0.51	0.03	17.7	<0.001
Stimulation order	0.1	0.13	0.78	0.442	0.01	0.04	0.31	0.755	0.02	0.03	0.54	0.596	0	0.04	0.04	0.972	0.01	0.04	0.38	0.707	0.05	0.03	1.76	0.083
Session	0.47	0.11	4.3	<0.001	0.04	0.02	1.72	0.095	0.09	0.03	3.09	0.004	0.12	0.03	4.11	<0.001	0.08	0.03	2.94	0.006	0.14	0.03	4.61	<0.001
Condition	-0.14	0.1	-1.35	0.188	-0.04	0.02	-2.01	0.053	-0.03	0.03	-0.94	0.353	-0.02	0.03	-0.89	0.379	-0.03	0.02	-1.15	0.258	-0.02	0.03	-0.61	0.543
RRS-10	0.04	0.02	1.74	0.091	0.02	0.01	2.26	0.031	0.02	0.01	2.88	0.007	0	0.01	-0.36	0.723	0.01	0.01	1.35	0.187	0	0.01	0.26	0.793
Condition × RRS-10	0	0.02	0.12	0.904	0	0	-0.27	0.788	0	0.01	-0.4	0.694	0	0.01	0.33	0.742	0	0	0.74	0.462	0	0.01	0.08	0.94
Marginal R^2 / Conditional R^2	0.252 / 0.357				0.151 / 0.561				0.239 / 0.277				0.182 / 0.360				0.120 / 0.409				0.289 / NA[a]			

Note. N = 34; Observations = 68; Condition = tDCS condition, sham vs anodal stimulation; Stimulation order = whether participants received sham or anodal stimulation first); RRS-10 = trait rumination (mean-centered).

[a]The model had a singular fit; random effects were estimated as being null.

which we included 3-back task RT as a predictor in mixed models. In addition to this, we wanted to determine whether participants might have been ruminating about their performance on the N-back task and not about their performance on the backward counting task. Although we did not explicitly ask participants what they ruminated about during the resting period, we indirectly tested this hypothesis by including the stress score related to stress induction in the analyses.

For brevity, the full results are presented in the Supplemental Material (section 7). The full model, which includes the stress score and 3-back RT, explained 33.5% of the variance in total state rumination (Table S9). The main effect of 3-back RT was significant (t(1,36.09)=2.58, p=.014), but not the effect of stress (t(1,53.8)=1.74, p=0.096). These results suggest that slower reaction times during the N-back were associated with higher total state rumination (faster reaction time [-1SD=565 ms]=1.76/5 total state rumination; slower reaction time [+1SD=842ms]=2.46/5 total state rumination). For the features of rumination, the results were mixed: brooding was significantly predicted by RT, whereas perseveration and replaying were predicted by stress. In contrast, negativity and self-criticism were predicted by neither stress nor RT. Moreover, we found the same pattern of findings as in our first analyses (see **table 2**): a considerable proportion of the variance of negativity and self-criticism was explained by random effects, whereas only a tiny proportion was explained by fixed effects, as shown by the difference between marginal and conditional R^2 (Supplementary Materials, Section 7, Tables S10–S14).

Bayesian analyses

We used Bayesian analyses to further test the effect of tDCS on state rumination and the 3-back task. **Table 4** shows the results of the Bayesian model averaging procedure of Bayesian mixed models with participants as the random variable, condition, session, trait rumination, 3-back RT, and stress after the stress induction as predictors, always accounting for at least "session" as a predictor, with the denominator being a null model. The inclusion Bayes factors reported hereafter indicate how much more likely the observed data is under a model with a term compared to a model without this term.

First, contrary to our hypotheses, there was substantial evidence indicating that neither the condition (active vs sham tDCS) nor the interaction between condition and trait rumination explained the observed data for total rumination and *d′* prime (all BFs≤.33). The evidence regarding the effect of the condition on 3-back RT was inconclusive. Moreover, there was decisive level of evidence for the inclusion of "participants" as a random factor in predicting 3-back reaction time (RT), with a Bayes factor of 12456.97. This suggests that there are significant individual differences in 3-back RT that are not accounted for by the fixed effects in the model. However, there was considerable evidence against the inclusion of "participants" (i.e., the random effect) as a predictor of total state rumination and 3-back *d′*, with Bayes factors of 0.21 and 0.32, respectively, suggesting individual differences beyond the fixed effects included in the model played a lesser role in these outcomes. Finally, there was strong evidence for 3-back RT as a predictor of total rumination (BF=13.29), but no evidence for or against the effect of stress on rumination (BF=1.12). We also examined this effect on the five key hallmark features of rumination and found substantial evidence supporting the hypothesis that tDCS had no impact on the features (all BFs≤.33), apart from negativity (anecdotal

Table 3. *Linear Mixed models of d' and reaction time on the 3-back task*

	d' 3-back				*RT* 3-back (log-transformed)			
Predictors	*B*	*SE*	*t(28)*	*p*	*B*	*SE*	*t(29)*	*p*
(Intercept)	2.75	0.06	44.26	<0.001	2.84	0.01	228.4	<0.001
Stimulation order	-0.1	0.07	-1.48	0.15	0.02	0.01	1.43	0.163
Session	-0.18	0.06	-2.94	0.007	0.04	0.01	8.41	<0.001
Condition	-0.02	0.06	-0.43	0.674	-0.01	0	-2.25	0.032
RRS-10	-0.02	0.01	-1.36	0.186	0	0	0.28	0.783
Condition × RRS-10	0	0.01	-0.1	0.924	0	0	-0.52	0.609
N	31				32			
Observations	62				64			
Marginal R^2 / Conditional R^2	0.176 / 0.261				0.300 / 0.809			

Note. Condition = tDCS condition, sham vs anodal stimulation; Stimulation order = whether participants received sham or anodal stimulation first; RRS-10 = trait rumination (mean-centered)

Table 4. *Inclusion Bayesian Factors for total state rumination, rumination features, and 3-back performance*

		Total Rumination		d' 3-back		RT 3-back	
Predictor		post. P()	Incl. BF	post. P()	Incl. BF	post. P()	Incl. BF
Condition	0.6	0.25	**0.23**	0.24	**0.21**	0.68	1.42
RRS-10	0.6	0.58	0.91	0.31	**0.3**	0.38	0.41
Session	0.5	0.67	2.02	0.94	**15.95**	1.00	**7E+06**
ID	0.5	0.12	**0.13**	0.20	**0.25**	1.00	**12457**
3-back RT	0.5	0.93	**13.29**				
Stress during stressor	0.5	0.53	1.13				
Condition*RRS-10	0.2	0.04	**0.18**	0.03	**0.11**	0.09	0.37
Stimulation order	0.5	0.23	**0.3**	0.33	0.49	0.46	0.86

Note. Incl. BF = indicates how much more likely the observed data is under a model with this term compared to a model without this term; prior P() = prior probabilities; post. P() = posterior (inclusion) probabilities (i.e., the model-average probability of including a certain predictor in the model, given the observations); Condition = tDCS condition, sham vs anodal stimulation; Stimulation order = whether participants received sham or anodal stimulation first); RRS-10 = trait rumination (mean-centered).

Inclusion Bayes factors higher than 3 (i.e., substantial evidence for including this term in the model) and lower than 1/3 (i.e., substantial evidence against including this term in the model) are in bold.

evidence for H0: BF=.52) More details regarding these analyses are provided in the Supplementary Materials (see Section 7).

Discussion

We investigated the effects of tDCS on rumination. We postulated that anodal tDCS stimulation over the left dlPFC would decrease state rumination, with trait rumination moderating this effect. We predicted that the N-back task performance would mediate the impact of anodal tDCS on state rumination, with trait rumination moderating it. Moreover, we expected that these effects would vary across five features of state rumination (i.e., perseveration, replaying, brooding, negativity, self-criticism). Yet, none of our predictions were confirmed. Instead, post-hoc Bayesian analyses even lent strong credence to the null hypothesis: tDCS has no impact on stress-induced state rumination.

One possible explanation for this lack of effect is that, in contrast to previous studies (Brunoni & Vanderhasselt, 2014; Strobach & Antonenko, 2017, but see Coussement et al., 2019, 2020), we did not observe any improvements in executive control during anodal tDCS. However, relying upon a community sample might have resulted in a ceiling effect in executive control, making it difficult to observe improvements with tDCS (Coussement et al., 2019, 2020). There is even research suggesting that tDCS may disrupt efficient processing in healthy participants by interfering with optimal neural homeostasis (Habich et al., 2020). This disruption could explain why active tDCS tended to slow reaction times in our 3-back block of the N-back task; an observation consistent with previous research in healthy samples (de Boer et al., 2021).

These points raise further questions about the effects of tDCS on rumination and its mechanisms. How can we reconcile our results with studies demonstrating tDCS effects in healthy participants? Sources of variability, such as individual cortical thickness and electric field magnitude, could account for these differences. For instance, thinner cortical thickness (Razza et al., 2022) and higher electric field magnitudes (Razza et al., 2023)

of the dlPFC predicted faster N-back reaction times during tDCS. Furthermore, differences in outcomes could be due to differences in the executive control abilities of the participants in the different "healthy" samples. Future research should examine these sources of variability or directly assess participants' executive control abilities. But, in any case, perhaps the most striking implication of the present study is that, from a clinical perspective, the current results, and particularly those resulting from the post-hoc Bayesian analyses, suggest that tDCS is not yet ready to be considered a viable clinical tool for alleviating rumination. As discussed in detail elsewhere (i.e., Hoebeke et al., 2021), more robust and stable findings across different contexts, cultures, and clinical populations need to be established before the prospect of tDCS as a viable promise for the mitigation of rumination in clinical practice can be considered.

Our findings also have two additional implications, which are critical for future research iterations on the impact of tDCS on state rumination. The first one pertains to measuring rumination in a way that best captures tDCS-induced changes. Based on the results of our mixed regression models, we identified distinct patterns in content-related versus process-related features of rumination — to dovetail with the Ehring and Watkins (2008)'s proposal that features of rumination can either be tapping into content-related or process-related aspects. Specifically, we found that the variance of content-related features, such as negativity and self-criticism, was primarily accounted by random effects, which explained 25-30% of the variance. This indicates that individual differences play a significant role in these features — a view consistent with existing research on negative affectivity (Watson & Clark, 1984) and self-criticism (Schanche, 2013; Zuroff et al., 2016) as persistent traits. Conversely, the variance of process-related features (i.e., replaying, brooding, and perseveration) was mostly accounted by fixed effects, which explained 30-36% of the variance. This implies that the variability in these process-related features is more influenced by the predictors incorporated into our model than by individual differences. Overall, our findings underscore the necessity of differentiating between content and process aspects in rumination research to fully capture this multifaceted construct. Future studies could therefore focus on measuring only process-related features of rumination.

The second implication concerns the potential consequences of the 3-back RT on stress. Indeed, our results suggest that 3-back RT predicted total state rumination, even when controlling for stress induced by the serial subtraction task. There are two possible explanations for the fact that N-back RT significantly predicted total state rumination. One possibility is that slower reaction times in the N-back task are associated with limited cognitive resources. Consequently, they were less able to inhibit their thoughts and ruminated more during the rest period. An alternative explanation could therefore be that the N-back task was stressful (perhaps even more stressful than the serial subtraction task) and that participants reflected on it during the rest period, especially if they performed poorly (i.e., longer reaction times) on the 3-back task. Considering that the experience of failure can lead to rumination (Koole et al., 1996; van der Kaap-Deeder et al., 2016; Watkins, 2004), the stress induced by highly-demanding computerized cognitive tasks, especially when particularly cognitively demanding, could alter tDCS effects.

Our study has several limitations. First, the tDCS montage used here, although common in studies examining the impact of tDCS on rumination (for a review, see Hoebeke et al., 2021), might not optimally influence rumination. Simulation studies suggest that different montage configurations could affect different parts of the prefrontal cortex, not just the dlPFC, and alter cortical electric field distributions (Bikson et al., 2010; Soleimani et al., 2021), with the extracephalic montage showing promising results (Martin et al., 2023; Noetscher et al., 2014). Second, although we used self-reported measures of stress, we did not rely on physiological measures such as heart rate variability (Shaffer & Ginsberg, 2017) or salivary cortisol (Zoccola et al., 2008). Therefore, uncertainty remains as to whether the stressor indeed elicited a stress response in participants. Finally, participants were tested during the COVID-19 pandemic, and, as such, one cannot exclude that wearing masks and the extensive hand-washing and equipment sanitizing protocols implemented at the beginning of the experiment impacted participants' involvement. Likewise, since the COVID-19 pandemic's lockdown and other related social distancing measures have been particularly distressing and sources of respective negative thinking processes, such as rumination and worries (e.g., Heeren et al., 2021; Mertens et al., 2020; Suen et al., 2022), one may wonder about the influence of the pandemic on our participants' reactivity to laboratory-induced stressors.

Conclusion

In this study, tDCS had no effect on rumination, neither at the level of global scale scores nor at the level of its five hallmark features. Although none of our hypotheses were supported, the present null findings will benefit future meta-research in this area. Future research should consider diversifying participant samples, exploring other potential variables, and refining experimental designs to gain a comprehensive understanding of the multilayered interactions at play.

References

Antal, A., Alekseichuk, I., Bikson, M., Brockmöller, J., Brunoni, A. R., Chen, R., Cohen, L. G., Dowthwaite, G., Ellrich, J., Flöel, A., Fregni, F., George, M. S., Hamilton, R., Haueisen, J., Herrmann, C. S., Hummel, F. C., Lefaucheur, J. P., Liebetanz, D., Loo, C. K., … Paulus, W. (2017). Low intensity transcranial electric stimulation: Safety, ethical, legal regulatory and application guidelines. *Clinical Neurophysiology : Official Journal of the International Federation of Clinical Neurophysiology*, *128*(9), 1774–1809. https://doi.org/10/gf9368

Barbey, A. K., Colom, R., & Grafman, J. (2013). Dorsolateral prefrontal contributions to human intelligence. *Neuropsychologia*, *51*(7), 1361–1369. https://doi.org/10.1016/j.neuropsychologia.2012.05.017

Barbey, A. K., Koenigs, M., & Grafman, J. (2013). Dorsolateral prefrontal contributions to human working memory. *Cortex*, *49*(5), 1195–1205. https://doi.org/10.1016/j.cortex.2012.05.022

Beck, A. T., Steer, R. A., & Brown, G. K. (1996). *Beck depression inventory (BDI-II)* (Vol. 10). Pearson London, UK.

Bernstein, E. E., Heeren, A., & McNally, R. J. (2017). Unpacking Rumination and Executive Control: A Network Perspective. *Clinical Psychological Science*, *5*(5), 816–826. https://doi.org/10/gdmwkw

Bernstein, E. E., Heeren, A., & McNally, R. J. (2020). A Network Approach to Understanding the Emotion Regulation Benefits of Aerobic Exercise. *Cognitive Therapy and Research*, *44*(1), 52–60. https://doi.org/10.1007/s10608-019-10039-6

Biel, A. L., & Friedrich, E. V. C. (2018). Why You Should Report Bayes Factors in Your Transcranial Brain Stimulation Studies. *Frontiers in Psychology*, *9*, 1125. https://doi.org/10/gfbxsk

Bikson, M., Datta, A., Rahman, A., & Scaturro, J. (2010). Electrode montages for tDCS and weak transcranial electrical stimulation: Role of "return" electrode's position and size. *Clinical Neurophysiology : Official Journal of the International Federation of Clinical Neurophysiology*, *121*(12), 1976–1978. https://doi.org/10/fhfnpm

Blanchard, M. A., Contreras, A., Kalkan, R. B., & Heeren, A. (2023). Auditing the research practices and statistical analyses of the group-level temporal network approach to psychological constructs: *A systematic scoping review. Behavior Research Methods, 55*, 767–787. https://doi.org/10.3758/s13428-022-01839-y

Borrione, L., Moffa, A. H., Martin, D., Loo, C. K., & Brunoni, A. R. (2018). Transcranial Direct Current Stimulation in the Acute Depressive Episode: A Systematic Review of Current Knowledge. *The Journal of ECT*, *34*(3), 153–163. https://doi.org/10/gf94qj

Brosnan, M. B., & Wiegand, I. (2017). The Dorsolateral Prefrontal Cortex, a Dynamic Cortical Area to Enhance Top-Down Attentional Control. *The Journal of Neuroscience*, *37*(13), 3445–3446. https://doi.org/10.1523/JNEUROSCI.0136-17.2017

Brunoni, A. R., & Vanderhasselt, M.-A. (2014). Working memory improvement with non-invasive brain stimulation of the dorsolateral prefrontal cortex: A systematic review and meta-analysis. *Brain and Cognition*, *86*, 1–9. https://doi.org/10/xmk

Contreras, A., Blanchard, M. A., Mouguiama-Daouda, C., & Heeren, A. (2024). When eco-anger (but not eco-anxiety nor eco-sadness) makes you change! A temporal network approach to the emotional experience of climate change. *Journal of Anxiety Disorders*, 102822. https://doi.org/10.1016/j.janxdis.2023.102822

Cooney, R. E., Joormann, J., Eugène, F., Dennis, E. L., & Gotlib, I. H. (2010). Neural correlates of rumination in depression. *Cognitive, Affective, & Behavioral Neuroscience*, *10*(4), 470–478. https://doi.org/10/fj5tfz

Coussement, C., De Vega, M. R., & Heeren, A. (2020). The impact of anodal tDCS on The attentional networks as a function of trait anxiety and depressive symptoms: A preregistered double-blind sham-controlled experiment. *Clinical Neuropsychiatry*, *17*(4), 225–235. https://doi.org/10.36131/cnfioritieditore20200404

Coussement, C., Maurage, P., Billieux, J., & Heeren, A. (2019). Does Change in Attention Control Mediate the Impact of tDCS on Attentional Bias for Threat? Limited Evidence from a Double-blind Sham-controlled Experiment in an Unselected Sample. *Psychologica Belgica, 59*(1), 16–32. https://doi.org/10.5334/pb.449

de Boer, N. S., Schluter, R. S., Daams, J. G., van der Werf, Y. D., Goudriaan, A. E., & van Holst, R. J. (2021). The effect of non-invasive brain stimulation on executive functioning in healthy controls: A systematic review and meta-analysis. *Neuroscience & Biobehavioral Reviews*. https://doi.org/10.1016/j.neubiorev.2021.01.013

De Raedt, R., Remue, J., Loeys, T., Hooley, J. M., & Baeken, C. (2017). The effect of transcranial direct current stimulation of the prefrontal cortex on implicit self-esteem is mediated by rumination after criticism. *Behaviour Research and Therapy*, *99*, 138–146. https://doi.org/10.1016/j.brat.2017.10.009

Douilliez, C., Baeyens, C., & Philippot, P. (2018). *Measure of the Brooding and Reflection Dimensions of Rumination in the Ruminative Response Scale: A French Validation*. Unpublished manuscript.

Ehring, T., & Watkins, E. R. (2008). Repetitive negative thinking as a transdiagnostic process. *International journal of cognitive therapy*, *1*(3), 192-205. https://doi.org/10.1521/ijct.2008.1.3.192

Fregni, F., & Pascual-Leone, A. (2007). Technology Insight: Noninvasive brain stimulation in neurology—perspectives on the therapeutic potential of rTMS and tDCS. *Nature Clinical Practice Neurology*, *3*(7), 383–393. https://doi.org/10/fhwxmr

Haatveit, B. C., Sundet, K., Hugdahl, K., Ueland, T., Melle, I., & Andreassen, O. A. (2010). The validity of *d* prime as a working memory index: Results from the "Bergen *n* -back task." *Journal of Clinical and Experimental Neuropsychology*, *32*(8), 871–880. https://doi.org/10/d2wq4p

Habich, A., Fehér, K. D., Antonenko, D., Boraxbekk, C.-J., Flöel, A., Nissen, C., Siebner, H. R., Thielscher, A., & Klöppel, S. (2020). Stimulating aged brains with transcranial direct current stimulation: Opportunities and challenges. *Psychiatry Research: Neuroimaging*, *306*, 111179. https://doi.org/10.1016/j.pscychresns.2020.111179

Hartig, F. (2022). *DHARMa: Residual diagnostics for hierarchical (multi-level / mixed) regression models* [Manual]. https://CRAN.R-project.org/package=DHARMa

Hautus, M. J. (1995). Corrections for extreme proportions and their biasing effects on estimated values of d′. *Behavior Research Methods, Instruments, & Computers*, *27*, 46–51. https://doi.org/10.3758/BF03203619

Heeren, A., Baeken, C., Vanderhasselt, M. A., Philippot, P., & de Raedt, R. (2015). Impact of Anodal and Cathodal Transcranial Direct Current Stimulation over the Left Dorsolateral Prefrontal Cortex during Attention Bias Modification: An Eye-Tracking Study. *PloS one, 10*(4), e0124182. https://doi.org/10.1371/journal.pone.0124182

Heeren, A., Hanseeuw, B., Cougnon, L. A., & Lits, G. (2021). Excessive Worrying as a Central Feature of Anxiety during the First COVID-19 Lockdown-Phase in Belgium: Insights from a Network Approach. *Psychologica Belgica, 61*(1), 401–418. https://doi.org/10.5334/pb.1069

Hinne, M., Gronau, Q., van den Bergh, D., & Wagenmakers, E.-J. (2020). A Conceptual Introduction to Bayesian Model Averaging. *Advances in Methods and Practices in Psychological Science*, *3*, 251524591989865. https://doi.org/10.1177/2515245919898657

Hoebeke, Y., Blanchard, A., Contreras, A., & Heeren, A. (2022). An experience sampling measure of the key features of rumination. *Clinical Neuropsychiatry*, *19*, 288–297. https://doi.org/10.36131/cnfioritieditore20220504

Hoebeke, Y., Blanchard, M. A., Bernstein, E. E., McNally, R. J., & Heeren, A. (2023). Negativity is key for understanding the interplay between rumination's features, attention control, and their dynamic nature: A temporal network approach. *Cognitive Therapy and Research*. https://doi.org/10.1007/s10608-023-10432-2

Hoebeke, Y., Desmedt, O., Özçimen, B., & Heeren, A. (2021). The impact of transcranial Direct Current stimulation on rumination: A systematic review of the sham-controlled studies in healthy and clinical samples. *Comprehensive Psychiatry*, *106*, 152226. https://doi.org/10/f83m

Jeffreys, S. H. (1998). *The theory of probability* (Third Edition, Third Edition). Oxford University Press.

Koole, S. L., Smeets, K., van Knippenberg, A., & Dijksterhuis, A. (1999). The cessation of rumination through self-affirmation. *Journal of Personality and Social Psychology, 77*(1), 111–125. https://doi.org/10.1037/0022-3514.77.1.111

Koster, E. H. W., De Lissnyder, E., Derakshan, N., & De Raedt, R. (2011). Understanding depressive rumination from a cognitive science perspective: The impaired disengagement hypothesis. *Clinical Psychology Review*, *31*(1), 138–145. https://doi.org/10/dtbknm

Kühn, S., Vanderhasselt, M.-A., De Raedt, R., & Gallinat, J. (2014). The neural basis of unwanted thoughts during resting state. *Social Cognitive and Affective Neuroscience*,

9(9), 1320–1324. https://doi.org/10.1093/scan/nst117
Lüdecke, D., Ben-Shachar, M. S., Patil, I., Waggoner, P., & Makowski, D. (2021). performance: An R package for assessment, comparison and testing of statistical models. *Journal of Open Source Software*, *6*(60), 3139. https://doi.org/10.21105/joss.03139
Luke, S. G. (2017). Evaluating significance in linear mixed-effects models in R. *Behavior Research Methods*, *49*(4), 1494–1502. https://doi.org/10.3758/s13428-016-0809-y
Makowski, D. (2018). The psycho package: An efficient and publishing-oriented workflow for psychological science. *Journal of Open Source Software*, *3*(22), 470. https://doi.org/10.21105/joss.00470
Martin, D. M., Rushby, J. A., De Blasio, F. M., Wearne, T., Osborne-Crowley, K., Francis, H., Xu, M., Loo, C., & McDonald, S. (2023). The effect of tDCS electrode montage on attention and working memory. *Neuropsychologia*, *179*, 108462. https://doi.org/10.1016/j.neuropsychologia.2022.10846t2
Mathôt, S., Schreij, D., & Theeuwes, J. (2012). OpenSesame: An open-source, graphical experiment builder for the social sciences. *Behavior Research Methods*, *44*(2), 314–324. https://doi.org/10/ft2dgc
McLaughlin, K. A., & Nolen-Hoeksema, S. (2011). Rumination as a transdiagnostic factor in depression and anxiety. *Behaviour Research and Therapy*, *49*(3), 186–193. https://doi.org/10/ff978m
Mertens, G., Gerritsen, L., Duijndam, S., Salemink, E., & Engelhard, I. M. (2020). Fear of the coronavirus (COVID-19): Predictors in an online study conducted in March 2020. *Journal of anxiety disorders, 74*, 102258. https://doi.org/10.1016/j.janxdis.2020.102258
Micoulaud-Franchi, J.-A., Lagarde, S., Barkate, G., Dufournet, B., Besancon, C., Trébuchon-Da Fonseca, A., Gavaret, M., Bartolomei, F., Bonini, F., & McGonigal, A. (2016). Rapid detection of generalized anxiety disorder and major depression in epilepsy: Validation of the GAD-7 as a complementary tool to the NDDI-E in a French sample. *Epilepsy & Behavior*, *57*, 211–216. https://doi.org/10/f8jjpk
Montoya, A. K. (2019). *Conditional Process Analysis in Two-Instance Repeated-Measures Designs* [Preprint, The Ohio State University]. https://doi.org/10.35542/osf.io/a2hxw
Morey, R. D., & Rouder, J. N. (2022). *BayesFactor: Computation of bayes factors for common designs* [Manual]. https://CRAN.R-project.org/package=BayesFactor
Movahed, F. S., Goradel, J. A., Pouresmali, A., & Mowlaie, M. (2018). Effectiveness of Transcranial Direct Current Stimulation on Worry, Anxiety, and Depression in Generalized Anxiety Disorder: A Randomized, Single-Blind Pharmacotherapy and Sham-Controlled Clinical Trial. *Iranian Journal of Psychiatry and Behavioral Sciences*, *12*(2), e11071. https://doi.org/10.5812/ijpbs.11071
Nakagawa, S., Johnson, P. C., & Schielzeth, H. (2017). The coefficient of determination R 2 and intra-class correlation coefficient from generalized linear mixed-effects models revisited and expanded. *Journal of the Royal Society Interface*, *14*(134), 20170213. https://doi.org/10.1098/rsif.2017.0213
Nitsche, M. A., Cohen, L. G., Wassermann, E. M., Priori, A., Lang, N., Antal, A., Paulus, W., Hummel, F., Boggio, P. S., Fregni, F., & Pascual-Leone, A. (2008). Transcranial direct current stimulation: State of the art 2008. *Brain Stimulation*, *1*(3), 206–223. https://doi.org/10/fd6s2h
Noetscher, G. M., Yanamadala, J., Makarov, S. N., & Pascual-Leone, A. (2014). Comparison of Cephalic and Extracephalic Montages for Transcranial Direct Current Stimulation—A Numerical Study. *IEEE Transactions on Biomedical Engineering*, *61*(9), 2488–2498. https://doi.org/10.1109/TBME.2014.2322774
Nolen-Hoeksema, S., Wisco, B. E., & Lyubomirsky, S. (2008). Rethinking Rumination. *Perspectives on Psychological Science*, *3*(5), 400–424. https://doi.org/10/fbnqtj
Nolen-Hoeksema, S., & Morrow, J. (1991). A prospective study of depression and posttraumatic stress symptoms after a natural disaster: The 1989 Loma Prieta Earthquake. *Journal of personality and social psychology, 61*(1), 115-121. https://doi.org/10/dqc65k
Owen, A. M., McMillan, K. M., Laird, A. R., & Bullmore, E. (2005). N-back working memory paradigm: A meta-analysis of normative functional neuroimaging studies. *Human Brain Mapping*, *25*(1), 46–59. https://doi.org/10.1002/hbm.20131
Papazova, I., Strube, W., Wienert, A., Henning, B., Schwippel, T., Fallgatter, A. J., Padberg, F., Falkai, P., Plewnia, C., & Hasan, A. (2020). Effects of 1 mA and 2 mA transcranial direct current stimulation on working memory performance in healthy participants. *Consciousness and Cognition*, *83*, 102959. https://doi.org/10/ggznsd
Philippot, P., & Brutoux, F. (2008). Induced rumination dampens executive processes in dysphoric young adults. *Journal of Behavior Therapy and Experimental Psychiatry*, *39*(3), 219–227. https://doi.org/10/fqhf97
R Core Team. (2022). *R: A language and environment for statistical computing.* [Computer software]. R Foundation for Statistical Computing. https://www.R-project.org/
Razza, L. B., Smet, S. D., Hoornweder, S. V., Witte, S. D., Luethi, M. S., Baeken, C., Brunoni, A. R., & Vanderhasselt, M.-A. (2023). *The effects of prefrontal tDCS on working memory associate with the magnitude of the individual electric field in the brain* (p. 2023.06.13.544810). bioRxiv. https://doi.org/10.1101/2023.06.13.544810
Razza, L. B., Vanderhasselt, M.-A., Luethi, M., Rapple, J., Busatto, G., Buchpiguel, C., Brunoni, A., & Silva, P. H. R. (2022). *Cortical thickness relates to working memory performance after non-invasive brain stimulation*. https://doi.org/10.21203/rs.3.rs-2235830/v1
Schanche, E. (2013). The transdiagnostic phenomenon of self-criticism. *Psychotherapy*, *50*(3), 316–321. https://doi.org/10.1037/a0032163
Shaffer, F., & Ginsberg, J. P. (2017). An Overview of Heart Rate Variability Metrics and Norms. *Frontiers in Public Health*, *5*. https://doi.org/10.3389/fpubh.2017.00258
Soleimani, G., Saviz, M., Bikson, M., Towhidkhah, F., Kuplicki, R., Paulus, M. P., & Ekhtiari, H. (2021). Group and individual level variations between symmetric and asymmetric DLPFC montages for tDCS over large scale brain network nodes. *Scientific Reports*, *11*(1), 1271. https://doi.org/10.1038/s41598-020-80279-0
Spitzer, R. L., Kroenke, K., Williams, J. B. W., & Löwe, B. (2006). A Brief Measure for Assessing Generalized Anxiety Disorder: The GAD-7. *Archives of Internal Medicine*, *166*(10), 1092–1097. https://doi.org/10/d7z8rz
Stein, D. J., Fernandes Medeiros, L., Caumo, W., & Torres, I. L. (2020). Transcranial Direct Current Stimulation in Patients with Anxiety: Current Perspectives. *Neuropsychiatric Disease and Treatment*, *16*, 161–169. https://doi.org/10/ggkkwd
Suen, P. J. C., Bacchi, P. S., Razza, L., Dos Santos, L. A., Fatori, D., Klein, I., Passos, I. C., Smoller, J. W., Bauermeister, S., Goulart, A. C., de Souza Santos, I., Bensenor, I. M., Lotufo, P. A., Heeren, A., & Brunoni, A. R. (2022). Examining the impact of the COVID-19 pandemic through the lens of the network approach to psychopathology: Analysis of the Brazilian Longitudinal Study of Health (ELSA-Brasil) cohort over a 12-year timespan. *Journal of anxiety disorders, 85*, 102512. https://doi.org/10.1016/j.janxdis.2021.102512
Strobach, T., & Antonenko, D. (2017). tDCS-Induced Effects on Executive Functioning and Their Cognitive Mechanisms: A Review. *Journal of Cognitive Enhancement*, *1*(1), 49–64. https://doi.org/10.1007/s41465-016-0004-1
Treynor, W., Gonzalez, R., & Nolen-Hoeksema, S. (2003). Rumination reconsidered: A psychometric analysis. *Cognitive Therapy and Research*, *27*(3), 247–259. https://

doi.org/10/dvn9n3

Vanderhasselt, M.-A., Brunoni, A. R., Loeys, T., Boggio, P. S., & De Raedt, R. (2013). Nosce te ipsum—Socrates revisited? Controlling momentary ruminative self-referent thoughts by neuromodulation of emotional working memory. *Neuropsychologia*, *51*(13), 2581–2589. https://doi.org/10/f5mk7b

Vanderhasselt, M.-A., Kühn, S., & De Raedt, R. (2011). Healthy brooders employ more attentional resources when disengaging from the negative: An event-related fMRI study. *Cognitive, Affective, & Behavioral Neuroscience*, *11*(2), 207–216. https://doi.org/10.3758/s13415-011-0022-5

van der Kaap-Deeder, J., Soenens, B., Boone, L., Vandenkerckhove, B., Stemgée, E., & Vansteenkiste, M. (2016). Evaluative concerns perfectionism and coping with failure: Effects on rumination, avoidance, and acceptance. *Personality and Individual Differences*, *101*, 114–119. https://doi.org/10.1016/j.paid.2016.05.063

Watkins, E. R. (2004). Adaptive and maladaptive ruminative self-focus during emotional processing. *Behaviour Research and Therapy*, *42*(9), 1037–1052. https://doi.org/10.1016/j.brat.2004.01.009

Watkins, E. R. (2015). An Alternative Transdiagnostic Mechanistic Approach to Affective Disorders Illustrated With Research From Clinical Psychology. *Emotion Review*, *7*(3), 250–255. https://doi.org/10/f7jpsw

Watkins, E. R., & Roberts, H. (2020). Reflecting on rumination: Consequences, causes, mechanisms and treatment of rumination. *Behaviour Research and Therapy*, *127*, 103573. https://doi.org/10/ggj84p

Watson, D., & Clark, L. A. (1984). *Negative Affectivity: The Disposition to Experience Aversive Emotional States*. https://doi.org/10.1037/0033-2909.96.3.465

Wetzels, R., Matzke, D., Lee, M. D., Rouder, J. N., Iverson, G. J., & Wagenmakers, E.-J. (2011). Statistical evidence in experimental psychology: An empirical comparison using 855 t tests. *Perspectives On Psychological Science*, *6*(3), 291–298. https://doi.org/10.1177/1745691611406923

Zetsche, U., Bürkner, P.-C., & Schulze, L. (2018). Shedding light on the association between repetitive negative thinking and deficits in cognitive control – A meta-analysis. *Clinical Psychology Review*, *63*, 56–65. https://doi.org/10.1016/j.cpr.2018.06.001

Zoccola, P. M., Dickerson, S. S., & Zaldivar, F. P. (2008). Rumination and Cortisol Responses to Laboratory Stressors. *Psychosomatic Medicine*, *70*(6), 661–667. https://doi.org/10/cgwtjj

Zortea, M., Ramalho, L., da Silveira Alves, C. F., Braulio, G., Lopes, R., Torres, I. L., Fregni, F., & Caumo, W. (2019). Transcranial Direct Current Stimulation to improve the dysfunction of descending pain-modulating system related to opioids in chronic noncancer pain: An integrative review of neurobiology and meta-analysis. *Frontiers in Neuroscience*, *13*, 1218. https://doi.org/10/ggrbhc

Zuroff, D. C., Sadikaj, G., Kelly, A. C., & Leybman, M. J. (2016). Conceptualizing and Measuring Self-Criticism as Both a Personality Trait and a Personality State. *Journal of Personality Assessment*, *98*(1), 14–21. https://doi.org/10.1080/00223891.2015.1044604

Zwalmen, Y. V., Liebaert, E., Hoorelbeke, K., de Mévergnies, C. N., Baeken, C., Verhaeghe, N., & Koster, E. H. W. (2023). Treatment Response Following Adaptive PASAT Training for Depression Vulnerability: A Systematic Review and Meta-Analysis. *Neuropsychology Review*. https://doi.org/10.1007/s11065-023-09581-8