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Research article

Single session and repeated anodal transcranial direct current stimulation over the right dorsolateral prefrontal cortex increases reflective thinking but not working memory updating performance

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A R T I C L E I N F O

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A B S T R A C T

Background: Anodal transcranial direct current stimulation (tDCS) over the right dorsolateral prefrontal cortex (DLPFC) has shown to have effects on different domains of cognition yet there is a gap in the literature regarding effects on reflective thinking performance.
Objective: The current study investigated if single session and repeated anodal tDCS over the right DLPFC induces effects on judgment and decision-making performance and whether these are linked to working memory (updating) performance or cognitive inhibition.
Methods: Participants received anodal tDCS over the right DLPFC once (plus sham tDCS in a second session) or twice (24 h apart). In the third group participants received a single session of sham stimulation only. Cognitive characteristic measures were administered pre-stimulation (thinking disposition, impulsivity, cognitive ability). Experimental tasks included two versions of the Cognitive Reflection Test (numeric vs verbal-CRT), a set of incongruent base-rate vignettes, and two working memory tests (Sternberg task and n-back task). Forty-eight participants (mean age = 26.08 ± 0.54 years; 27 females) were recruited.
Results: Single sessions of tDCS were associated with an increase in reflective thinking performance compared to the sham conditions, with stimulation improving scores on incongruent base rate tasks as well as marginally improving numeric CRT scores (compared to sham), but not thinking tasks without a numeric component (verbal-CRT). Repeated anodal stimulation only improved numeric CRT scores. tDCS did not increase working memory (updating) performance. These findings could not be explained by a practice effect or a priori differences in cognitive characteristics or impulsivity across the experimental groups.
Conclusion: The current results demonstrate the involvement of the right DLPFC in reflective thinking performance which cannot be explained by working memory (updating) performance or general cognitive characteristics of participants.

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1. Introduction

Can non-invasive brain stimulation improve cognitive performance? In general, the answer seems to be yes: the effects of a single session of transcranial direct current stimulation (tDCS) on cognition has been examined across many cognitive domains, including working memory (WM) [1–3], risk-taking [4,5], face recognition [6–9] and even decision-making [10], which is the focus of the current study. Non-invasive brain stimulation such as tDCS has been shown to alter neuronal membrane excitability, affecting spontaneous neural firing, and inducing neuroplasticity. Thus this technique can help to address important questions about neural and cognitive mechanisms involved in higher level cognitive tasks such as the interplay between working memory and judgment and decision-making performance [11,12].

The nature of cognitive processes involved in reflective thinking (as part of judgment and decision-making) is a matter of vigorous debate. Judgment and decision-making processes are often characterised within a framework of dual-process accounts which assume two different basic types of thinking: intuitive (Type 1) and reflective/analytical (Type 2) processes [13,14]. Intuitive thinking is associated with fast, automatic processing with little effort being expanded on a problem. This type of thinking leads to the use of mental short-cuts (heuristics; [15]) that are associated with suboptimal decision outcomes (e.g., Ref. [16]). Intuitive thinking is therefore characterised as underlying fast but often normatively inadequate judgments and decisions (termed 'cognitive miserliness' [17,18]; but see Ref. [19]). Reflective thinking, however, requires slow, effortful, and rule-based processes and is advantageous when working on abstract and complex content [13,20]. Reflective thinking is often found to produce normatively more correct results [18, 20] and seems to correlate positively with working memory capacity [21–24]. Thus, processes underlying reflective thinking are assumed to typically represent the "smart deliberator" in us [19]. Many theorists propose a serial account, arguing that reflective processes detect and inhibit ("override") faulty automatic (intuitive) responses [13,25] and then find the correct answer through processes involving working memory [26]. Yet more recent work suggests that intuitive processes can also successfully produce correct answers, and that people with higher cognitive capacity simply have more accurate intuitions [27–29], sometimes called "smart intuitors" [19]. One explanation for smart intuitions is that they are based on highly trained mindware (procedures, rules and knowledge structure) that generates normative responses fast and automatically [30] and in this case reflective processing may consist of selecting between potentially competing intuitive solutions coming to mind [19,31].

Beyond respective debates between scholars of dual-process theories, the basic assumptions of qualitatively different dual-processes in general has been put into question (e.g., Refs. [32–37]. It is not easy to differentiate experimentally between these views, as many contributions have shown (see Refs. [19,26,38]). Dual-process theorists have employed tasks that concurrently often elicit automatic but also reflective answers in thinking problems [39], for example the incongruent base-rate vignettes which are based on the classic findings of representativeness heuristics [15]. In these tasks a person described in a short vignette could belong to one of two categories (e.g., a fan of Star Trek/a fan of Eastenders) based on a combination of a description of their 'personality' traits (e.g., likes to play video games) and a base rate probability (e.g., 4 out of 1000 persons whose favourite television show is Star Trek and 996 ones whose favourite show is Eastenders). In incongruent cases the personality description conflicts with the base-rate (e.g., the description of a personality typical of a Star Trek fan, but with a given base-rate that is indicative for a higher probability of being an Eastenders fan). These responses indicate either following intuitive processing which would result in responses in line with the personality description (e.g., Star Trek fan) or reflective processing which would reflect answers following the base-rate information (e.g., fan of Eastenders) [40]. A relatively recent but now often used test of reflective (non-heuristic) processing is the Cognitive Reflection Test (CRT) [16,39] which was introduced as a measure of dual-processing. It contains brain teaser-like problems with lures that are designed to elicit an incorrect intuitive response (i.e., plausible solution to a short maths problem) before a correct reflective response comes to mind [39,41]. For example, participants are asked: "A bat and a ball cost $1.10 in total. The bat costs a dollar more than the ball. How much does the ball cost? ___ cents". The implied (intuitive) but wrong answer is 10 cents, although the correct answer is 5 cents. According to Refs. [16,39] these two different responses are based on qualitatively different processes. Recently, however this assumption is critically discussed, with some studies suggesting that performance can be mainly explained by numerical ability [42]. However, there are now versions of the CRT that explicitly aim to reduce any demands on numerical ability. The verbal-Cognitive Reflection Test (verbal-CRT) [43], does not contain any questions with numerical components but elicits - like the CRT – intuitive responses that can be corrected by reflective thinking.

The brain region of interest of this study was the right DLPFC, which has previously been associated with executive functions that underlie judgment and decision-making. The left DLPFC has a role in attention [44,45] and emotion regulation [46], whilst the right DLPFC is more strongly involved in inhibitory control [47,48] and updating [2]. These latter two functions are both crucial processes for the use of reflective thinking over intuitive thinking as utilised in the dual-process framework [13,49]. Using the 3-item CRT as the dependent variable Oldrati and colleagues [41] have shown that cathodal tDCS to the DLPFC reduces performance, potentially due to reduced inhibitory control (which, however, still leaves the possibility that reduced working memory performance produced this effect).

In a recent study Edgcumbe and colleagues [10] followed up this finding and showed improved CRT scores and higher performance when solving incongruent base-rate vignettes after a single session of 'offline' (i.e., stimulation before the task) anodal tDCS over the right DLPFC, as compared to sham or left DLPFC stimulation. Potential individual differences, measured by a proxy of the Intelligence Quotient (IQ), thinking dispositions (e.g., inclination to habitually engage in reflective thinking), and other demographic variables did not explain these results, and the study therefore demonstrated that the right DLPFC causally increases reflective thinking in line with the dual-process framework. However, the exact mechanism of how tDCS over the right DLPFC increases reflective thinking scores is not clear. For example, the results of Edgcumbe et al. [10] could also be explained by right DLPFC stimulation simply reducing a person's general impulsivity [50] and consequently increasing performance on thinking tasks like the CRT and base-rate vignettes. Furthermore, according to Stanovich [30] the amelioration in reflective thinking (increased CRT score and increased incongruent base-rate performance) could in principle be explained as a consequence of improved monitoring and detection of automatic heuristic responses, increased inhibition (or "override") performance, or increased working memory performance to sustain the override [1,51] and create an alternative solution.

Studies employing multiple sessions of brain stimulation are largely restricted to the clinical neuroscience literature, such as schizophrenia [52,53], and depression [54,55], and are mainly focused on therapeutic effects. Of the few papers describing the use of multiple session anodal tDCS for non-clinical purposes, we found four studies that have administered tDCS for the investigation of the neural substrates of working memory [56–59] and four for the examination of cumulative effects of anodal stimulation over the motor cortex [60–63]. With respect to working memory the results in the literature have been mixed with single session performance enhancement in several studies [56,57,59], with no overall further improvement to working memory across multiple stimulation sessions. However, there is some evidence of an overall enhancement across multiple sessions which was larger than that of a single session [58]. The other multiple session studies found that direct current stimulation of the motor cortex results in prolonged effects of stimulation at the neurophysiological level [60,61]. When Ho and colleagues [62] applied anodal tDCS over the motor cortex in multiple tDCS sessions they found that with repeated sessions of 1 mA and 2 mA current intensity further increased motor cortex excitability beyond that of single session stimulation. The authors suggested that there is a cumulative effect of the stimulation on cortical excitability. Based on the clinical literature it also seems that the cumulative effect of stimulation is thought to increase in a stepwise manner from the first session of stimulation to the second stimulation session in a clinical setting [62,63]. It is therefore reasonable that the same cumulative increase in stimulation effects would be present when stimulation sessions with the same 24-h intra-session interval are introduced in our present study. This current design, then, allows testing new hypotheses about the role of these Type 2 components in Stanovich's [49] 'tripartite' model of thinking and JDM, by controlling reflective thinking dispositions (aka 'reflective mind", e.g., AOT, REI) while measuring WM ('algorithmic mind') performance. Type 1 processes (impulsivity) and mindware (NART) are also assessed.

In the current study, we extended on the Edgcumbe et al. [10], study in at least four points: 1. We measure working memory performance (updating) in addition to reflective thinking performance after stimulation to gauge the influence of algorithmic thinking on judgment and decision-making (JDM) performance; 2. We measure additionally impulsivity using the Barratt Impulsiveness Scale (BIS) [64] to control for potential individual differences across stimulation groups; 3. We investigate the pattern of intuitive answers (also including the verbal-CRT items) to check for differences in cognitive inhibition, and, finally, 4. We introduce a second tDCS session, to investigate whether there are cumulative effects of stimulation on working memory and reflective thinking performance and whether these effects differ across sessions. Previous reviews suggest that working memory performance is susceptible to single session tDCS with currently used protocols only to a low degree [65,66] but that repeated sessions of stimulation result in more profound effects [1,67].

In order to operationalise and quantify working memory, judgment and decision-making, reflective thinking dispositions, Type 1 processes (e.g., impulsivity) and mindware (e.g., NART) established tasks from the literature were employed. Our main dependent variables operationalised judgment and decision-making performance, using the Cognitive Reflection Test [16,39], the verbal-Cognitive Reflection Test [43] and incongruent base-rate vignettes [40,68]. To clarify whether tDCS affected JDM-specific processes or more broader cognitive ability, we also measured working memory, using the [69] and n-back [70,71]. To control for the influence of individual cognitive characteristics we measured reflective thinking dispositions with the Actively Open-minded Thinking Scale (AOT [72], and the Rational-Experiential Inventory (REI, [73]. Impulsivity was measured using the Barratt Impulsiveness Scale [64]. The National Adult Reading Test [74,75] assessed mindware ([30]).

To re-iterate, the rationale for repeated stimulation was therefore two-fold: a) to further investigate whether cognitive reflection was driven by repeated stimulation and thereby strengthen the evidence; and b) to investigate whether such an effect is associated with working memory (e.g., Ref. [24]) or inhibition performance (the effects of which may only show after repeated sessions).

1.1. *The present study*

To investigate the effects of single and multiple sessions of anodal stimulation on reflective thinking performance as defined by the dual-process framework, a mixed between and within-subjects design was used in this study. Anodal or sham stimulation was applied to the right DLPFC depending on the experimental condition and group. It was hypothesised that anodal tDCS over the right DLPFC would increase reflective processing by activity enhancement of this area, compared to sham, as shown by Edgcumbe et al. [10], for the CRT and incongruent base-rate vignettes. While [41] had shown a decrease in performance (cathodal stimulation), we aimed to replicate and enhance the Edgcumbe et al. study [10] using an enhanced CRT set and anodal stimulation to show an improvement in CRT scores. In addition, we included thinking disposition scales, WM tasks and a second session, to disentangle Type 2 processes (WM, inhibition)."If performance in the numerical CRT and verbal-CRT relied on similar processes [43], such as monitoring and cognitive inhibition of intuitive processes, then the latter scores should also improve after stimulation. We furthermore hypothesised that a second session of stimulation would result in cumulative effects on performance scores [1,62]. As for executive functioning tasks, based on a recent meta-analysis [65] it was hypothesised that working memory (updating; [76]) performance as measured by the n-back and Sternberg tasks [1,69] would improve after right DLPFC stimulation compared to sham, and again cumulatively after a second session, potentially linked to similar physiological mechanisms that have already been associated with an improvement of reflective thinking in the right DLPFC [10].

To summarise, to investigate whether brain stimulation effects on reflective thinking are due to the inhibition of intuitive responses or rather increased algorithmic processing power [30], we administered the CRT [39], verbal-CRT [43] and incongruent base-rate vignettes [40] and measured working memory updating performance as a potential moderating variable. Experimental conditions were either single or repeated (24 h apart) stimulation of the right DLPFC compared to sham conditions. We hypothesised that there would be an effect of anodal stimulation over the right DLPFC on judgment and decision-making (JDM) performance after single as well as repeated intervention and if these effects are linked to working memory processes, then we should find similar improvements in the updating tasks.

2. Methods

2.1. Participants

Forty-eight participants (mean age = 26.08 ± 0.54 years; 27 females; Supplementary Table 1) were recruited through advertising and word-of-mouth at the University of East London (UEL). A power analysis calculation using G Power 3.1 revealed that in order to detect an a MANOVA global effect with 3 dependent variables (Cognitive Reflection Test, Verbal-Cognitive Reflection Test, and Incongruent Base-rate Vignettes) in a between-subjects design experiment with 2 groups (sham vs stimulation) based on an effect size of $f^2 = 0.30$ (as obtained in the study by Edgcumbe et al. [10], with a power level of 0.80, and an alpha (α) of $p = 0.05$, a total of 42 participants (21 per group) are needed. To accommodate our design with 3 groups (2 stimulation groups collapsed for the main group comparison analysis in first session, and then repeated measures for first 2 groups) we opted for a total of 48 participants.

The inclusion criteria were (i) aged 18 years or older; (ii) fluent English speakers; (iii) right-handed; (iv) naïve to tDCS and (v) naïve to the behavioural tasks used. To ensure that the participants were naïve to these tasks participants were asked both when they signed up to participate and in the Participant Information Form whether they had taken part in any studies with each of these tasks before. The exclusion criteria were (i) history of seizures; (ii) family history of seizures; (iii) past or present neurological history; (iv) past or present psychiatric history; (v) past head injury or surgery; (vi) metal implants; (vii) current medication usage; (viii) drug or alcohol dependence (including smoking); (ix) pregnancy and (x) past training in logic reasoning (e.g., during an university course). Each of the exclusion criteria are established safety precautions taken in laboratories that use transcranial electrical stimulation methods, including tDCS. All participants provided informed written consent. This experiment was approved by the University of East London (UEL) Research Ethics Committee. All ethical considerations met the standards set out in the Declaration of Helsinki. After giving informed consent, participants first completed the questionnaires about demographic information and cognitive characteristics/traits (NART, AOT, REI and BIS). The demographics form asked about sex (male, female or do not wish to say), age, religiosity (1 = not at all religious to 5 = very religious, and yes or no), paranormal beliefs (yes or no) and education level – self reported highest current education level ranging from a first educational certificate (1) to doctorate (8) in accordance with The United Kingdom qualification

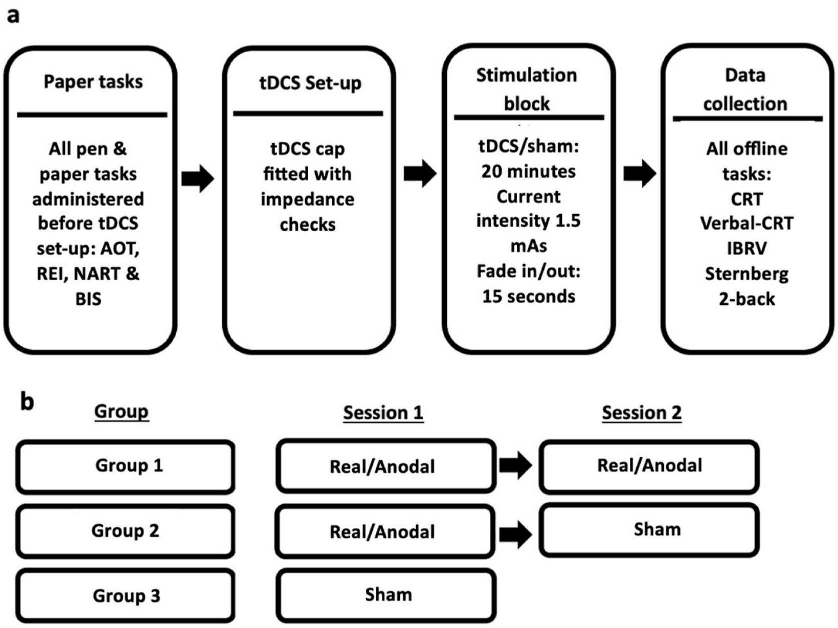

Fig. 1. Schematic presentation of the procedure (panel a) and experimental design (panel b). Arrows denote time course. Abbreviations: Transcranial direct current stimulation (tDCS), Actively Open-minded Thinking scale (AOT), Rational-Experiential Inventory (REI), National Adult Reading Test (NART), Barratt Impulsiveness Scale (BIS), Cognitive Reflection Test (CRT), incongruent base-rate (representativeness) vignettes (IBRV) Verbal-Cognitive Reflection Test (verbal-CRT), Sternberg task and 2-back (n-back). After stimulation, judgment and decision making (JDM) tasks were administered in random order, followed by working memory (WM) tasks followed, also in random order. Repeated sessions were conducted on consecutive days.

levels [77] (Supplementary Table 1). Participants were asked about religiosity both on a scale and as a "yes" or "no" response based on the dual-process framework literature, which suggests that high levels of religiosity positively correlate with high levels of intuitive thinking in the CRT [78,79].

2.2. Materials

All experimental tasks were randomized for task order with JDM tasks and WM tasks in separate blocks with the WM block following the JDM block in every condition. Items within each task were further randomized (Fig. 1). For each of these tasks the material (i.e., items within tasks) was presented on a 55-cm computer monitor using E-Prime 2.0. The text was presented in Times New Roman font size 12. Responses were recorded with the participants either selecting a response or typing an answer on the screen.

2.2.1. Judgment, decision-making and working memory tasks

Cognitive Reflection Test: The Cognitive Reflection Test (CRT) measures intuitive (Type 1) and reflective (Type 2) thinking [16,39]. One block of ten CRT items was administered to participants in each session. No participant was exposed to the same CRT twice as the two blocks differed in terms of the items presented. Within each block of the CRT, the presentation of the items was randomized. Each participant had a maximum of 3 min to respond to each item by typing the response on the computer. As such, there was a maximum duration of 30 min for this task – no participant took the full 30 min to complete the task. The task ended after this duration so that participants could not overrun the time constraints in this task. The CRT items consisted of short brain teaser-like questions (e.g., Jerry received both the 15th highest and the 15th lowest mark in the class. How many students are in the class?) with lures that are designed to initially prompt an incorrect intuitive answer (e.g., 30). With some consideration of their answer participants could then arrive at the correct reflective answer (e.g., 29) or an entirely incorrect answer (e.g., 31). Reflective (i.e., correct) scores were summed for an overall reflective score on this test and intuitive (i.e., incorrect lure-based) scores were summed for the intuitive score (for published sources of CRT items used, [16,39,80–84]).

Verbal-Cognitive Reflection Test: The Verbal-Cognitive Reflection Test (verbal-CRT) measures intuitive and reflective/analytic thinking [43]. Unlike the original version of the CRT, it is considered not to rely on processes linked to numerical ability but rather measures the monitoring and inhibition of intuitive responses [43]. Like in the original CRT, participants viewed short brain teaser-like questions (e.g., Would it be ethical for a man to marry the sister of his widow?) with lures that are designed to prompt intuitive incorrect answer (e.g., Yes or No) before arriving at the correct reflective answer (e.g., He cannot as he is dead). The verbal-CRT was administered in two blocks of six randomized items with one block per session. Participants had a maximum of 3 min to respond to an item, did not see the same item twice and responded by typing their answer into the computer keyboard. For this task participants had a maximum of 18 min to complete it – no participant took the full duration to complete this task. The task was programmed to end after the maximum time allocation so that no participant could overrun the time constraints of this task. Like the CRT, reflective (i.e., correct) scores were summed for an overall reflective score on this test, albeit there was no intuitive score for this test as this would be the inverse of the correct scores. In this paper the verbal-CRT items included those published by Refs. [43,80].

Incongruent base-rate vignettes: The incongruent base-rate task was administered with vignettes (e.g., stereotype of an occupation or age) and base-rates (e.g., the probability of independent events occurring) that conflict at the level of the description and base-rate [40,68]. Participants were administered with one block of ten randomized description items per session. No participant was exposed to the same item twice. They responded by selecting one of two answers presented on the screen. One answer was consistent with intuitive thinking (e.g., the description) and the second possible answer denoted the use of reflective thinking (e.g., the base-rate). Participants had a maximum of 3 min to respond to each item. The task was programmed to end after the maximum time allocation so that no participant could overrun the time constraints of this task. No participant took the maximum time allocation of 30 min to the complete this task. The correct reflective scores were summed up for an overall reflective score in this test, intuitive scores were not used as they were the inverse of the correct scores.

Sternberg task: The Sternberg task measures working memory performance (specifically, updating) [69]. In this task participants were presented with a short-list of eight letters (e.g., E G H I N **K** O W). After the initial presentation of the stimuli the participant was shown one letter (e.g., **K**) and asked if the letter had appeared in the previously presented short-list of letters. A total of one hundred and eighty trials were presented to participants with a maximum score of sixty correct ("target present") responses. Participants had a maximum of 10 min to complete the Sternberg task with 3 s per trial. The task was programmed to end after the maximum time allocation so that no participant could overrun the time constraints of this task. No participant took the maximum time allocation to the complete this task. A brief practice session was provided with ten trials before the main task began.

n-back: In the n-back measures working memory task [70,71], participants were presented with a continuous sequence of letter stimuli. The stimuli consisted of a single letter (e.g., A or B) presented in the centre of the computer monitor. Participants were instructed to watch the sequence of letters (3 s on screen per letter without a button press) and report any repetitions of a stimulus with a load factor of 'n' ("2-back"; e.g., T L H C **O** K **O** M) by pressing the space bar at the time of the repeated letter. The presented letter immediately moved onto the next letter following a button press response. There was a total of eighty trials with a maximum of thirty correct responses (target present) possible. Participants had a maximum of 5 min to complete the n-back task with each trial lasting for a maximum of 3 s. The task ended after this duration so that participants could not overrun the time constraints of this task. A brief practice session was provided with ten trials before the main task began.

The following tasks were administered before stimulation and presented in paper and pen format. Participants had a total of 20 min to complete all of the following Cognitive Characteristics tasks. No participants took longer than the allocated time to complete these tasks.

2.2.2. Cognitive characteristics materials

Actively Open-minded Thinking (AOT) scale: The Actively Open-minded Thinking (AOT) scale measures the thinking disposition of 'open-mindedness' which refers to the willingness to consider new information that conflicts with own beliefs [72]. Participants rated short statements (e.g., changing your mind is a sign of weakness) on a scale from 1 (completely disagree) to 7 (completely agree). This version of the scale contains a total of seven items.

Rational-Experiential Inventory: The Rational-Experiential Inventory (REI) contained 10 items that measured two thinking dispositions, rational thinking and experiential thinking [73]. Participants responded to short statements (e.g., I don't like to have to do a lot of thinking) using a scale from 1 (strongly disagree) to 5 (strongly agree).

National Adult Reading Test: The National Adult Reading Test (NART) contains a list of 50 short words with irregular pronunciations (e.g., Bouquet, Placebo) [74,75]. Participants read the words aloud and the experimenter marked whether the words were pronounced correctly or not. Results were scored by summing up the number of correctly pronounced words.

Barratt Impulsiveness Scale: The Barratt Impulsiveness Scale (BIS) is a questionnaire that measures impulsivity [64]. Participants responded to thirty items (e.g., *I don't pay attention*) on a four-point Likert scale ranging from 1 (never/rarely) to 4 (almost always/always).

2.3. Design

Participants were informed about the general content and basic order of the tasks before having the tDCS cap fitted. They firstly completed the pen and paper cognitive characteristic measures (see Fig. 1a). This was then followed by setting-up the tDCS cap and a stimulation period of 20 min without any tasks whilst the participants relaxed in a comfortable chair. Following the stimulation, the tDCS equipment was removed from the participant's head and they started to perform the judgment and decision-making (JDM) cognitive tasks and the working memory (WM) tasks. While the order of these task groups was always identical, with WM tasks last, the order of specific tasks within these task groups was randomized (Fig. 1).

This experiment had a partially crossed design with mixed between-subjects and within-subjects properties. Participants in the first two groups completed two sessions each (Group 1: both sessions anodal stimulation; Group 2: only the first anodal stimulation, the second sham) with sessions spaced 24 h apart, whilst participants in the sham-only group (Group 3) completed only one session (Fig. 1b). This design was used as the main aim was to replicate [10], i.e. comparing 2 groups (collapsed stimulation groups 1 and 2) with group 3 (sham). For the second aim, to compare repeated stimulation effects, a second sham session for Group 3 was not needed, as any group or within comparison with this condition would have not added to the results to answer our questions. The independent between-subjects variable was Stimulation Group (anodal right DLPFC or sham stimulation). We expected this design to detect any cumulative effect of neuromodulation on task performance across the stimulation sessions.

2.4. Procedure

All participants were tested individually in a sound-attenuated room. They received instructions about each task on the screen and verbally before performance of each task to ensure that they understood how to complete each task. Short practice trials were included immediately before each WM task, i.e. after the stimulation intervention, to ensure that each participant knew how to respond to each task (see supplementary materials section). Before each practice trial participants read the instructions carefully and indicated whether they understood the instructions or not before completing the practice trials, and completed each task after they indicated that they understood the instructions.

2.5. tDCS montage and parameters

TDCS was delivered using a battery-driven stimulator (Neuroelectrics, Barcelona) using two sponge electrodes (anodal target and cathodal return), each circular with a surface area of 25 cm^2. The tDCS montage was bilateral with an anodal target and a cathodal return electrode, either: (i) anode right DLPFC and cathodal return electrode left DLPFC, (ii) or sham right DLPFC sham left DLPFC. The electrodes were placed over the right DLPFC (F4, anodal target electrode), and left DLPFC (F3, cathodal return electrode) according to the EEG 10–20 international system [85]. The fade-in and fade-out duration was 15 s each at the onset and offset of 20 min stimulation with 1.5 mA current intensity to decrease the likelihood of discomfort. The sham group received 15 s of stimulation with 1.5 mA at the beginning and end of the 20 min, framed by fade-in and -out as described above. Participants were blinded to which group they were assigned to using the sham function of the tDCS device. The experimenter (DE) was not blinded because of the experimental design using the 3rd group as sham only (control group) for one (first) session and therefore not requiring a second session of them. This rationale was based on the previous work by the authors as published in Edgcumbe et al., [10] using originally 3 groups (left, right and sham stimulation) in a one session design had already shown an effect for right but not left stimulation compared to sham.

2.6. Analysis plan

The raw data was screened for outliers (greater than two interquartile ranges from the median) and missing values. The individual values for each JDM and WM task were calculated as summed correct scores. In general, the plan for these statistical analyses were similar to those in several other papers [10,41,86,87]: we used MANOVAs to assess the effect of (stimulation) group on sets of dependent variables (e.g., set of JDM variables), and then follow up significant results with ANOVAs. Group differences between demographic variables were tested with Chi Square and t-tests.

A total of three multivariate analyses of variance (MANOVA) tests were performed. The first MANOVA (see supplementary material) investigated whether there were any a priori differences between the stimulation groups (Group 1, Group 2 and Group 3) regarding cognitive characteristics measured on a metric level (NART, AOT, REI 10R and REI 10E). The between-subjects factor (independent variable – IV) was experimental group. Dependent variables were scores for each cognitive characteristic. This was followed by ANOVAs to exclude any differences in the individual cognitive characteristics across stimulation groups. Multiple pairwise comparisons then examined any statistically significant differences in scores of the cognitive characteristics across the stimulation groups.

The second MANOVA (see supplementary material) examined whether there were any a priori differences between stimulation groups (Group 1, Group 2 and Group 3) regarding impulsiveness using the BIS second order factors (attentional impulsivity, motor impulsivity and non-planning impulsivity). The between-groups factor was experimental group. Dependent variables were the BIS scores.

A set of Chi square tests then examined whether there were any differences between the stimulation groups (Group 1, Group 2 and Group 3) for demographic variables (nominal scale). Demographic variables here were sex (male, female or do not wish to say), education (first educational certificate, second educational certificate, third certificate, fourth certificate, first higher education certificate, undergraduate, master's degree or doctorate) and the categorical component of religiosity (yes or no). Two separate one-way ANOVAs then examined any potential difference in Age and Religiosity scale results across stimulation groups.

The remainder of the analyses assessed the effect of stimulation on judgement and decision-making (JDM) and working memory (WM) performance. The third MANOVA examined the effect of stimulation on reflective thinking in the JDM tasks using the CRT, verbal-CRT and incongruent base-rate vignettes during the first experimental sessions only, to examine if a single session of tDCS altered JDM task performance. Between-factor was experimental group with two factors (first sessions of Group 1 and 2 (active stimulation) and Group 3 (sham stimulation). Dependent variables were the JDM tasks. Follow-up ANOVAs investigated differences in individual JDM task scores across stimulation groups.

Next, a series of mixed ANOVAs examined any differences in JDM (CRT, verbal-CRT or incongruent base-rate vignettes) and WM (Sternberg or n-back) task performance across stimulation groups (Group 1, Group 2 or Group 3) and stimulation sessions (session 1, session 2). For the CRT, correct and intuitive scores were analysed in different ANOVAs. For these mixed ANOVAs, Stimulation Group (Group 1 or Group 2) was the between subject factor and Session (session 1, session 2) was the within subject factor. Dependent variables were CRT correct scores, CRT intuitive scores, incongruent base rate vignette scores, verbal-CRT correct scores, Sternberg correct scores and n-back correct scores. Post hoc Student's t-tests followed up any statistically significant ANOVAs. Single session effects of stimulation on performance were tested by comparing results after the first sessions of cumulative Groups 1 and 2 (real stimulation) with Group 3 (sham stimulation). The single session effects of stimulation in the first sessions only between Groups 1 and 2 were also compared (but otherwise these first sessions were identical in terms of group and procedure). A cumulative effect of stimulation was explored separately for each task. Sessions 1 and 2 were compared in Group 1. Sessions 1 and 2 were then explored in Group 2. Session 2 was then compared between Groups 1 and 2 to detect a cumulative effect of the second intervention (the main analyses plans are presented in Table 1 and Supplementary Fig. 1).

3. Results

3.1. Cognitive and personality characteristics

The first set of analysis investigated whether there were any a priori differences between the stimulation groups (Group 1, Group 2 and Group 3) regarding cognitive or demographic characteristics to rule them out as confounding results on JDM and WM tasks. The means and standard deviation of the cognitive characteristics scores of the NART, AOT, REI 10 R and REI 10 E are presented in Supplementary Table 2. For BIS scores see Supplementary Table 3. MANOVAs and follow-up ANOVAs for cognitive characteristics (see Analysis plan) revealed no significant differences in a direction that would preclude further analysis of the JDM and WM scores (see Supplementary Materials and Supplementary Table 4).

A set of Chi square tests of independence were then performed on demographic variables to examine if there were any significant differences between groups in terms of sex and religiosity ($\chi^2 = 1.20$, $p = 0.27$), stimulation and religiosity ($\chi^2 = 2.00$, $p = 0.36$), sex and education ($\chi^2 = 2.10$, $p = 0.15$), and stimulation and education ($\chi^2 = 0.76$, $p = 0.68$). A one-way ANOVA with age as dependent variable and Stimulation Group as factor found no statistically significant difference between the experimental groups for age, F (2, 29.5) = 0.34, $p = 0.71$. A second one-way ANOVA with the Religiosity scale as the dependent variable and Stimulation Group as factor found no significant difference between the experimental groups for Religiosity, F (2, 29.7) = 3.30 p = 0.051. Table 2 shows that the trend for a difference was mainly due to Group 1 scoring higher than Group 2. As higher religiosity scores have been found to correlate with higher CRT scores [88] the direction of this difference was not problematic for our main hypothesis testing in the next section. In summary, there were no statistical differences between experimental groups with respect to demographics that have been associated with CRT scores in the past (see Ref. [87]).

3.2. Judgment, decision-making and working memory task results

There were no missing values or outliers (greater than 2 interquartile ranges from the median) in the scores (i.e., correct response) for the thinking tasks (i.e., CRT, verbal-CRT and incongruent base-rate vignettes/representativeness).

Table 1
Analysis plan table.

Order	Variable sets (inferential test)	Between-subject factors	Within factors	Outcome measures	(Follow-up) Analysis
1	Matching demo-graphic variables	Stimulation groups[a]	N/A	Sex, education, religiosity, age	Chi square & t-tests
2	Matching cogn. Variables[b] (MANOVA)	Stimulation groups[a]	N/A	AOT; REI; BIS; NART	ANOVAs
3	JDM tasks (MANOVA)	Stimulation groups[a]	Stimulation sessions	CRT; verbal CRT; ICBV	Mixed-ANOVA
4	Working memory (MANOVA)	Stimulation groups[a]	Stimulation sessions	Sternberg & n-back task	Mixed-ANOVA
5	JDM & WM (Day 1 and Day 2 Correlations)	N/A	N/A	CRT, verbal-CRT, ICBV, n-back, Sternberg	Pearson's r correlation

Note: JDM = Judgment and decision-making; WM = working memory; CRT = Cognitive Reflection Test; (CRT), verbal-CRT = Verbal-Cognitive Reflection Test; IBRV = Incongruent Base-Rate Vignettes; ANOVA = Analysis of Variance (ANOVA); AOT = Actively Open Minded Thinking test; REI = Rational-Experiential Inventory; BIS = Barratt Impulsivity scale; NART = Sternberg = Sternberg working memory score; n-back = n-back task working memory score.

[a] Stimulation groups: Group 1,2 and 3 for session 1; Groups 1 and 2 for session 2 comparisons.

[b] For details see Supplementary materials.

Table 2
Means (Standard deviations) and follow-up ANOVAs for the MANOVA on the between groups effect of stimulation on a) reflective thinking and b) working memory tasks (first experimental sessions in stimulation groups 1 and 2 = right DLPFC; and 3 = sham; Session 1 only).

Dependent Variable	Group				Follow-up ANOVAs
	Right DLPFC		Sham		
	M	SD	M	SD	
CRT correct	4.60	1.64	3.20	1.33	$F_{(1,46)} = 3.04$, $p = .09$; $\eta_p^2 = .06$
Verbal-CRT correc	2.94	0.62	3.13	1.10	$F_{(1,46)} = 0.58$, $p = .45$; $\eta_p^2 = .01$
IBRV correct	6.72	2.52	4.50	3.16	$F_{(1,46)} = 6.42$, $\mathbf{p = .015^*}$; $\eta_p^2 = .12$
Sternberg	52.06	4.09	53.75	3.13	$F_{(1,46)} = 2.10$, $p = 0.15$; $\eta_p^2 = .04$
n-Back	18.37	4.90	17.00	3.61	$F_{(1,46)} = 0.99$, $p = 0.33$; $\eta_p^2 = .02$

Notes: DLPFC = Dorsolateral prefrontal cortex; CRT = Cognitive Reflection Test, verbal CRT = Verbal-Cognitive Reflection Test; IBRV = Incongruent Base-Rate Vignettes; Sternberg = Sternberg working memory score; n-back = n-back task working memory score. Asterisks denote a statistically significant effect ($p < 0.05$).

A MANOVA was conducted to examine the effect of stimulation over the right DLPFC on reflective thinking during the first experimental sessions only. Between subject-factor was Stimulation Group (right DLPFC or sham). Dependent variables were correct scores for the CRT, verbal-CRT, and incongruent base-rate vignettes. The Box's test results showed no equality of covariance ($p = 0.03$) so Pillai's Trace was used. There was a main effect of stimulation on reflective thinking, Pillai's Trace = 0.21, F (3,44) = 3.83, p = 0.016. The overall performance on thinking tasks improved in the real (right DLPFC) compared to the sham stimulation group. The results of the follow-up ANOVAs and all means and standard deviations are presented in Table 2 and Fig. 2. Only the incongruent base rate task showed a difference, with higher performance in the real stimulation group (p = 0.015), but there was a similar trend for the CRT scores (p = 0.09). Thus these results narrowly confirm the results by Edgcumbe et al., [10] of a right-DLPFC stimulation effect on cognitive reflection scores. There were no effects of stimulation on WM performance (Sternberg and n-back correct scores), all $ps >$ 0.15.

Next, a series of mixed ANOVAs with Stimulation Group (Group 1 or Group 2) as between factor and Session (session 1 or session 2) as within factor were run to examine differences in JDM and WM scores across sessions and stimulation groups. For this analysis, we computed an additional score called CRT-Intuitive, which reflects the number of times a participant responded with the 'intuitive' (or 'lure') response (e.g., "10 cents" in the Bat and Ball question) rather than a random incorrect response [89].[1] As a reminder, Group 1 represents the group with repeated real stimulation, and Group 2 represents the group with real followed by sham stimulation. The results of the ANOVAs are presented in Table 3.

As Table 3 shows, there were significant main effects of group and interactions between the factors stimulation group and session for CRT correct scores and intuitive scores. The follow-up t-tests for the mixed ANOVA with CRT correct scores as dependent variable revealed a significant difference for Stimulation Group 1 with lower scores for Session 1 (M = 4.50; SD = 1.862) than Session 2, (M = 6.375; SD = 1.784), t (30) = 3.382, $p = 0.004$ (see Fig. 3a b), but there was no such difference for Group 2, t (30) < 1, p > .05. A similar pattern was found for the CRT intuitive scores, with a significant difference (now lower intuitive scores) in the second session compared to the first in Group 1, t (30) = 2.951, $p = 0.010$, but no such difference in Group 2, t (30) <1, p > .05.

The follow-up t-tests (see Table 3) for the mixed ANOVA with CRT correct scores between Stimulation Groups revealed furthermore

[1] Intuitive scores for the verbal-CRT and incongruent base-rates were not used as they are the inverse of the reflective correct scores.

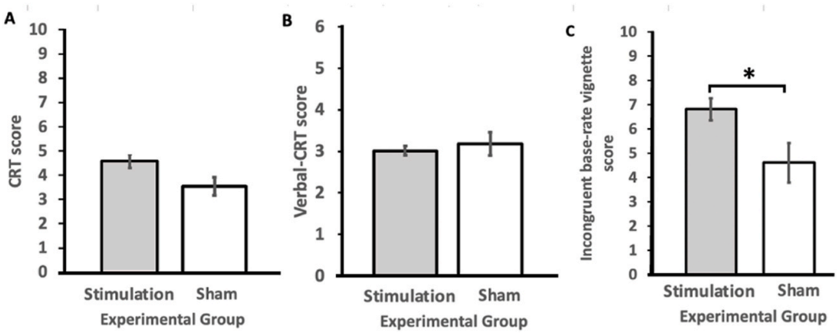

Fig. 2. Means of correct responses in different thinking tasks as a function of stimulation condition after one session. Panel A – Cognitive Reflection Test (CRT). Panel B – verbal-Cognitive Reflection Test (verbal-CRT). Panel C – Incongruent Base-Rate Vignette. Asterisks denote a statistically significant difference ($p < 0.05$) between real stimulation and sham groups. Error bars denote standard error of the mean.

Table 3
Mixed ANOVAs for JDM and WM tasks (first and second sessions in Group 1 and 2).

Group Sess. Task	Group 1				Group 2				Results from the omnibus statistical analysis; those with p < 0.05 in bold
	Session 1		Session 2		Session 1		Session 2		
	M	SD	M	SD	M	SD	M	SD	
CRT Correct	4.50	1.86	6.38	1.78	4.70	1.25	4.50	1.51	Group $F_{(1,30)} = 3.30$, $p = .08$, $\eta_p^2 = .09$ Session $F_{(1,30)} = 6.44$, $\boldsymbol{p = .017}$*, $\eta_p^2 = .06$ Group x Session $F_{(1,30)} = 9.61$, $\boldsymbol{p = .004}$*, $\eta_p^2 = .10$
CRT Intuitive	3.50	1.60	2.00	1.21	3.81	1.33	3.75	1.65	Group $F_{(1,30)} = 6.55$, $\boldsymbol{p = .01}$*, $\eta_p^2 = .18$ Session $F_{(1,30)} = 5.92$, $\boldsymbol{p = .021}$*, $\eta_p^2 = .06$ Group x Session $F_{(1,30)} = 5.01$, $\boldsymbol{p = .033}$*, $\eta_p^2 = .05$
IBRV	6.88	2.20	7.06	2.24	6.44	3.00	4.88	3.22	Group $F_{(1,30)} = 3.30$, $p = .08$, $\eta_p^2 = .10$ Session $F_{(1,30)} = 1.24$, $p = .27$, $\eta_p^2 = .01$ Group x Session $F_{(1,30)} = 2.01$, $p = .16$, $\eta_p^2 = .02$
Verbal CRT Correct	3.00	0.51	2.56	0.90	2.88	0.72	3.06	1.06	Group $F_{(1,30)} = 0.97$, $p = .33$, $\eta_p^2 = .03$ Session $F_{(1,30)} = 0.32$, $p = .57$, $\eta_p^{22} = .01$ Group x Session $F_{(1,30)} = 2.02$, $p = .16$, $\eta_p^2 = .03$
Sternberg	52.60	3.93	53.60	3.85	51.60	4.30	50.60	6.07	Group $F_{(1,30)} = 2.47$, $p = .12$, $\eta_p^2 = .07$ Session $F_{(1,30)} = 0.01$, $p = .99$, $\eta_p^2 = .01$ Group x Session $F_{(1,30)} = 0.94$, $p = .34$, $\eta_p^2 = .01$
n-back	19.40	4.80	19.30	5.78	17.40	4.95	17.30	4.71	Group $F_{(1,30)} = 1.40$, $p = .24$, $\eta_p^2 = .04$ Session $F_{(1,30)} = 0.04$, $p = .83$, $\eta_p^2 = .01$ Group x Session $F_{(1,30)} = 0.01$, $p = .99$, $\eta_p^2 = .01$

Notes: DLPFC = Dorsolateral prefrontal cortex; CRT = Cognitive Reflection Test, verbal CRT = Verbal-Cognitive Reflection Test; IBRV = Incongruent Base-Rate Vignettes; Sternberg = Sternberg working memory score; n-back = n-back task working memory score. Asterisks denote a statistically significant effect ($p < 0.05$).

lower scores for (sham S2) Group 2 (M = 4.50; SD = 1.51) than Group 1 (M = 6.38; SD = 1.78) in Session 2, t (30) = 3.77, $p = 0.001$, but no such between group differences in the first session, t (30) <1, $p > .05$. The t-tests for CRT intuitive scores between Stimulation Groups in Session 1 showed lower scores for Group 1 (M = 3.50; SD = 1.60) than Group 2 (M = 3.81; SD = 1.33), t (30) = 2.07, $p = 0.047$, however, this difference would not survive a Bonferroni correction (alpha >0.0167). Also in Session 2 there were lower CRT intuitive scores for Group 1 (M = 2.00; SD = 1.21) than Group 2 (M = 3.75; SD = 1.65), t (30) = 3.27, $p = 0.003$. As Table 3 shows, no other main effects or interactions were significant or showed a trend towards significance, except a trend (not Bonferroni-corrected) of overall higher scores for the incongruent base rate vignettes scores in Group 1 compared to Group 2, $p = .08$.

There were no main effects or interaction effects for the n-back or Sternberg working memory scores (calculated as correct responses, see Table 3), all *ps* > 0.12.

3.3. Correlations

Pearson's *r* correlational analysis for the CRT, verbal-CRT, incongruent base-rate vignettes, n-back and Sternberg tasks were run. For Day 1 scores there were no significant correlations (all *rs* (30) < .02, *ps* > .88 or rs > - .20, ps > 0.17) except for a positive correlation between verbal CRT and n-back error scores, r (30) = .354, p = .013. For Day 2 scores there were no significant correlations (all *rs* (30) < .24, *ps* > .18, or rs > - 26, ps > 0.14).

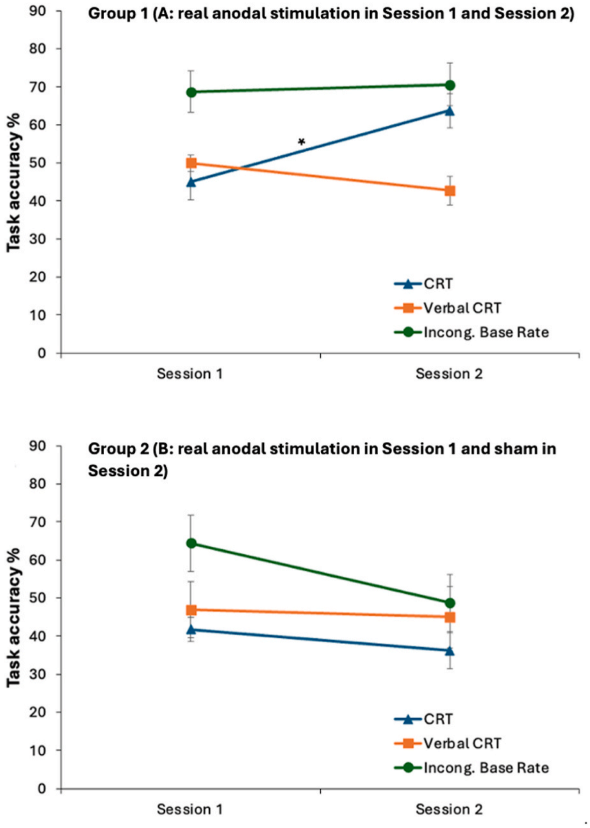

Fig. 3. Percentage of mean correct responses for different reflection tasks across stimulation sessions for Group 1 (Top - Panel A: real anodal stimulation in Session 1 and 2) and Group 2 (Bottom - Panel B: real anodal stimulation in Session 1 and sham in Session 2). The asterisk (*) denotes a significance statistically difference (*$p < .05$*). Abbreviations: CRT = Cognitive Reflection Test; verbal CRT = Verbal- Cognitive Reflection Test; Incong. Base Rate = incongruent base-rate vignettes.

4. Discussion

4.1. Summary of results

The present study examined the influence of anodal tDCS on reflective thinking when applied to the right DLPFC in a bilateral montage. A MANOVA on reflective thinking scores showed an effect of stimulation group after a single session of tDCS, with improved scores compared to the sham group. This was mainly driven by the higher relative performance in the incongruent base-rate tasks, and to a lesser degree by the CRT scores. These results largely concur with the findings in the Edgcumbe et al. [10] study which had used the same tasks and a similar electrode montage. In addition, we found that reflective thinking as measured with the CRT increased from the first session of stimulation to the second session of stimulation. The current study controlled for potential confounds including cognitive characteristics (i.e., impulsiveness, in addition to thinking styles and an IQ proxy measure) that have been previously linked with reflective thinking performance [10,24,90]. Thus, the obtained stimulation effects on reflective thinking could not be explained by individual differences (such as thinking dispositions; [30]) usually associated with cognitive reflection.[2] The results of this study provide thus further evidence that stimulation of the right DLPFC is involved in improving reflective thinking (see Ref. [10]). Furthermore, the improvements seen after a single session intervention or after repeated stimulation seem not to be directly linked to working memory performance (here: updating [76]): Stimulation itself did not improve working memory scores.

4.2. tDCS effects on judgment and decision-making tasks and the dual-process framework

The current results indicate a causal effect of stimulation on reflective-type thinking, thus generally supporting the dual-process framework [13,18,91]. Furthermore, our results narrow down the boundary conditions for explaining improved reflective thinking

[2] Only the rational sub-scale of the REI-R differed between our experimental groups in that it was highest in the sham group, which if anything should have worked against the direction of predicted differences: REI-R usually correlates with CRT correct scores [64,72,73,75].

performance after non-invasive brain stimulation. Interestingly, we found no increase for the structurally very similar but arguably much easier-to-solve verbal-CRT [43] items. This finding does not fit neatly with the tri-partite [30] model because the process of detection of conflict (e.g., that it was Noah and not Moses that brought animals onto the ark) should be easy as long as respondents have sufficient 'mindware' (or knowledge structures, practised rules etc.). It is unlikely for the diverse items used here (which were sourced from the internet, see [43]) that our participants lacked this knowledge structure but still improved on the classic CRT items, as well as the incongruent base rate vignettes. This would leave two other candidate processes as source for success: the ability for inhibiting and overriding the prepotent response, and the ability to sustain this override and keeping external and internal representations separate ("cognitive decoupling") to allow mental simulation in solving the problem [30,92].

These explanations for the increase in reflective thinking after boosting cortical excitability of the right DLPFC would fit with the notion that this brain region is involved in executive functioning that underpins judgment and decision-making, which generally encompasses inhibitory control [93] and updating [2]. For the dual-processes framework these executive functions are crucial: For instance, when an incorrect intuitive response (i.e., the 'lure-based response') comes to mind in the CRT [16,39], the responder must monitor and detect this 'error', inhibit the automatic response, and then engage in reflective thinking to eventually find the correct solution. In doing so, inhibitory control has a role in the suppression of automatic (intuitive) thinking and updating of the initial answer to the new and correct answer, which may only be obtained after "mental simulation" operations that rely on sustained cognitive decoupling of separate representations [18]. However, no effect of stimulation on working memory tasks that would link them with the dual-processes framework [13,49] was found. Our results seem to therefore rule out working memory updating as relevant to the effects of stimulation on reflective thinking. That updating-related processes are not sufficient to explain stimulation effects is also indicated by the lack of improvement in the easier verbal-CRT [43], despite performance being far from ceiling. This does not mean that working memory processes such as updating have no role in general in these tasks such as the CRT [39] (see Ref. [24]), but rather that working memory capability cannot explain the current stimulation effects. A third indication that updating is a less likely candidate process for stimulation effects comes from the analysis of Type 1 responses which shows that CRT score changes were driven by participants following the lures less (presumably because of successful inhibition) rather than simply making fewer other errors (more likely due to computation).

As already mentioned, besides an influence on inhibition processes, neuromodulation could have affected monitoring and detection processes which could have in turn improved scores for both types of the CRT [39,43]. The former seems arguably more relevant for the classic original CRT [39] as opposed to the easier verbal-CRT [43] – once you detect that Moses is an incorrect lure in the 'ark' question, it should be easy to inhibit this response. Thus, if there is not much inhibition needed to boost an easy item, stimulation cannot improve verbal-CRT [43] scores. Of course, it is still possible that CRT [39], verbal-CRT [43] and incongruent base-rate vignettes are measuring reflective thought based on different knowledge structures [24,30]. Nevertheless, the present result is intriguing and points to qualitatively different processes between the CRT [16,39], verbal-CRT [43], and the representativeness vignettes (which did not improve after repeated tDCS sessions). Thus, we propose that within the [30] model our results point to inhibition as the most likely process to be affected by stimulation. It is of course possible that separate processes benefit differently from single versus repeated sessions. Future work therefore should apply designs that are able to further disentangle these processes under single and repeated transcranial electrical stimulation.

4.3. No tDCS effects on working memory and executive functions

Importantly, there were also no ceiling effects for the working memory tasks for either the Sternberg [69] or n-back [70,71] task which would otherwise indicate that both are too easy for the participants. In general, there have been inconsistent findings in the literature regarding stimulation effects– meta-analyses and systematic reviews report small improvements on working memory accuracy [1] and reaction time [94], large improvements in accuracy and reaction time [95] as well as no effects on accuracy and reaction time [96]. However, other executive functions, not explored in the present study, such as set-shifting, which provides the capacity to move from one set of instructions or process to another [76], and inhibitory control [47] may be further candidates for future studies [1,97].

4.4. tDCS effects of repeated stimulation

A further novel finding was that two sessions of neuromodulation spaced 24-h apart resulted in a cumulative increase in reflective thinking as measured by the CRT [39] compared to a single session of the same stimulation over the same target [10]. This provides the first evidence of a cumulative effect of anodal tDCS over the right DLPFC for improving and boosting reflective thinking. Crucially, practice effects could not explain the increase in reflective thinking based on the comparison between the real stimulation and sham session groups. Although cumulative effects of stimulation have been suggested by the results of patient studies for several years [59,98] and motor learning studies in healthy participants [99] this is the first evidence of such an effect on reflective thinking. Furthermore, some studies have found an effect of a single session of stimulation over the right DLPFC on risky decision-making (e.g., [100]) but this result is not consistent across the literature [98]. This suggests that a null effect of a single session of stimulation on cognition might not mean that the intervention is generally ineffective, but efficacy might depend on protocol characteristics. A repeated stimulation study design might be advantageous, which has shown more reliable effects of stimulation for some similar protocols [59].

At the neurophysiological level our results can be explained by long term potentiation-like plasticity effects of anodal stimulation over the right DLPFC after anodal stimulation [63,101]. This includes the involvement of glutamatergic synapses and calcium influx

[102,103]. In our study the strengthening of the DLPFC network that underpins performance on reflective thinking could have at first been strengthened by the first session of stimulation and then boosted further in the second session of neuromodulation. Thus, the task performance and multiple sessions of stimulation when taken together could account for a cumulative effect of stimulation.

4.5. Limitations and future directions

There are some limitations regarding our study. First, we used a bilateral electrode montage over the DLPFC, which poses the question if anodal right, or cathodal left DLPFC stimulation caused the effects. This possibility was considered in our previous study which administered an identical tDCS montage but with a single session of stimulation [10] – this study found no effect of stimulation on the JDM tasks with anodal stimulation over the left DLPFC and the cathodal return electrode over the right DLPFC. Importantly, although efforts were made in that study to control for the effect of stimulation with the reverse montage in the second group the possibility remained that the cathodal (return) electrode reduced any potential improvements in WM. Future studies could disentangle this issue by a stimulation protocol which does not require a contralateral return electrode, for example with the use of either (i) an HD-tDCS unilateral protocol, (ii) an extracephalic return electrode, or an (iii) an active control montage. A further limitation is that although we controlled for cognitive characteristics and cognitive ability with the AOT [72], REI [104], NART [74] and BIS [64] at the beginning of the session, stimulation could have indirectly changed these dispositions and increased CRT performance [16,39]. This is unlikely though as previous work shows that each of these measures have good stability [105–108]. It is also possible that other variables than those controlled by our matching procedures could have influenced some of our results despite our attempt to control these. Third, to better examine practice effects, an experimental group could have been added with a sham condition in both sessions. Further limitations were that due to time constraints, cumulative effects of stimulation were observed over only two experimental sessions and that in our procedure the WM block always followed the JDM block of tasks. Finally, a potential limitation to interpret the current results lies in the relatively small sample size, which we partially addressed by running a Power analysis (see above), as well as by having 32 participants (2 times 16 in each Group 1 and 2 for session 1). This reflects the typical number of participants in a tDCS study at the point of study inception (e.g., see Refs. [41,100]. Nevertheless, a greater sample size should ensure in future studies to better disentangle different effects from Type 2 processes.

4.6. Conclusion

Here we provide the first evidence for a cumulative effect of multiple sessions of anodal stimulation over the right DLPFC on stimulation-induced improvement of reflective thinking. This concurs with previous findings [10] which reported similar effects for a single session of anodal stimulation, but extends these findings by also controlling for impulsivity (BIS – [64]). Our results furthermore suggest that these effects might depend on inhibitory control mechanisms in the right DLPFC, although future studies may employ additional tests specifically probing cognitive inhibition. Although the exact relationship between the neural substrates of reflective thinking and neuromodulation remains complex, the cumulative effects observed here promise exciting opportunities for basic and applied (e.g., clinical) research (see [109]). Overall, these results demonstrate the involvement of the right DLPFC in reflective thinking performance.

Data availability statement

The data that support this findings of this study will be openly available on the Open Science Framework repository website at https://osf.io/jdszr/once this paper is published

CRediT authorship contribution statement

Daniel R. Edgcumbe: Formal analysis, Data curation, Conceptualization. **Davide Rivolta:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Michael A. Nitsche:** Writing – review & editing, Methodology, Conceptualization. **Volker Thoma:** Writing – original draft, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e36078.

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