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Anodal transcranial direct current stimulation over the right dorsolateral prefrontal cortex enhances reflective judgment and decision-making

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ABSTRACT

Background: Accounts of cognitive processes in judgment and decision-making are frequently based on a dual-process framework, which reflects two qualitatively different types of processing: intuitive (Type 1) and analytical (Type 2) processes.
Objective: The present study investigated the effects of bilateral transcranial direct current stimulation (tDCS) to the dorsolateral prefrontal cortex (DLPFC) on judgment and decision-making performance.
Methods: Participants received anodal tDCS stimulation to the right DLPFC, left DLPFC or sham. There were 3 tasks: vignettes measuring heuristic thinking, belief bias syllogisms, and the cognitive reflection test (CRT), a measure of the ability to inhibit automatic responses to reach a correct solution. Fifty-four participants (mean age = 24.63 ± 4.46 years; 29 females) were recruited.
Results: Results showed that anodal tDCS to the right DLPFC was associated with an increase in cognitive reflection performance (Type 2 processing) as compared to left DLPFC and to sham. Logic thinking was reduced following anodal tDCS to the left DLPFC.
Conclusion: These findings are broadly consistent with a dual process framework, and cannot be explained by differences in cognitive ability and thinking style. The results demonstrate the involvement of the right DLPFC in cognitive reflection, and suggest the possibility of improving cognitive performance through tDCS.

Introduction

Dual process accounts explain the complex tasks in judgment and decision-making with the involvement of two qualitatively different types of processing [1,2]: intuitive (Type 1) and analytical (Type 2) processes. Type 1 processes are associated with automatic responses [3] and high impulsivity [4], leading to the use of mental short-cuts (heuristics; [4]) and biased outcome [5]. Type 2 processes require inhibition of pre-potent responses [6,7], high working memory capacity [8] and are considered to be controlled processes [9], which lead to normative correct judgments. In the dual-process framework, error-prone decision-making is thus thought to occur when Type 1 processes are not overcome by more controlled Type 2 processing [1,10].

Brain regions of interest are the dorsolateral prefrontal cortices which have been reliably associated with executive functions and decision-making processes, with evidence for some lateralization of roles [11,12]. The left dorsolateral prefrontal cortex (DLPFC) has been associated with self-regulation [13], affective modulation [14] and attentional processing [15], whilst the right DLPFC has a role in impulsivity control [16], cognitive control [17] and set-shifting (i.e.,

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manipulation of mental models) [16]. In particular, cognitive control and set-shifting are forms of executive functions implicated in judgment and decision-making performance [18,19]. However, evidence for causal links between DLPFC activity and reflective decision-making performance is scarce.

Transcranial direct current stimulation (tDCS) is an important technique which allows experimental investigation of the neural basis of behaviour and executive function [20,21]. TDCS is a non-invasive brain stimulation tool which modulates cortical excitability [20]. TDCS generates a weak electrical current (usually 0.5–2 mA) which modulates resting membrane potentials toward hyperpolarisation or depolarisation [22–24]. Anodal tDCS increases cortical excitability by depolarising the neuronal membrane, and cathodal tDCS decreases excitability by hyperpolarising the membrane [22,24]. Stimulation for a few minutes has been associated with neuroplastic after-effects, which share some characteristics with long term potentiation and depression, including the involvement of glutamatergic synapses and calcium influx [25,26].

TDCS has been used to examine the neural substrates of executive functions, including planning [11], set-shifting [12], attention [27] and working memory [28]. Dedoncker, Brunoni, Baeken, and Vanderhasselt's (2016) [29] meta-analysis of the application of anodal tDCS to the DLPFC reported an improvement in reaction time during cognitive tasks via single session tDCS. This effect was evident whether the stimulation was applied to either the right or left DLPFC.

In order to specifically investigate judgment and decision-making performance, Oldrati, Patricelli, Colombo, and Antonietti [30] applied cathodal tDCS to the right DLPFC (with a contralateral return electrode), which was associated with an increase in the likelihood of- normatively incorrect - Type 1 responses as reflected in the scores of the cognitive reflection test (CRT). The CRT measures the ability to override intuitive Type 1 responses and to respond with the correct analytical Type 2 responses [31,32]. In the form of brief maths puzzles, CRT items are designed such that the propensity is to generate an incorrect Type 1 answer, but when applying reflective thinking, participants are more likely to produce the correct Type 2 answer [19,33]. The increase in likelihood of a Type 1 response in Oldrati et al.'s [30] experiment was understood as a reduction in inhibitory control following cathodal stimulation to the right DLPFC. However, performance in the CRT task has been previously correlated with other measures of cognitive ability as well as thinking dispositions. The CRT has been used as a short test of cognitive ability [34,35], such that high cognitive ability (i.e. intelligence) is associated with working memory capacity [36,37] and greater cognitive reflection [38].

Other forms of individual differences in Type 2 processing have been proposed. Variance in CRT performance has been also related to thinking dispositions [39,40] and cognitive style [41]. Thinking dispositions are the tendency toward patterns of thinking that are based on individual differences [42]. For example, actively open-minded thinking (AOT) represents the willingness to change one's mind after assimilating new information which conflicts with a previously held view. Individuals who score highly on the AOT scale [43] are thus open-minded to new information, and high AOT scores have been positively correlated with performance in the CRT and belief bias syllogistic reasoning [39]. For example, Stanovich's [44] tripartite model of decision-making contains not only Type 1 and Type 2 processes, but also the reflective mind (i.e. the proclivity to like and engage in reflective thinking will determine the use of one's algorithmic mind, which is the ability to inhibit Type 1 responses) which corresponds to thinking dispositions.

In the present study, we sought to investigate the effects of tDCS on judgment and decision-making. We used 3 tasks: CRT, logic (belief bias) syllogisms and the representativeness heuristic task. The CRT, as described, is a measure of cognitive reflection ability [31]. The representativeness heuristic task examines the biases associated with given base-rate information [45] and is also associated with a lack of cognitive reflection [19,46]. The belief bias syllogisms task provides a measure of logic reasoning in the context when syllogistic conclusions are incongruent with beliefs about the world [18].

We sought to account for potential influences of thinking disposition on performance, using the AOT scale [43] and Rational Experiential Inventory questionnaire [41], and also controlled for cognitive ability using the National Adult Reading Test [47,48]. In a between-subjects design, we measured decision-making following bilateral tDCS with the anode applied to either the left DLPFC, right DLPFC or a sham stimulation, with a contralateral return electrode. We hypothesised that anodal tDCS to the right DLPFC would inhibit Type 1 processing [49], thus increasing cognitive reflection scores and reducing heuristic thinking. In contrast, we predicted no such enhancing effect on syllogistic reasoning performance (as measured by the logic index) which had previously been associated with left frontal activation [50,51] or inferior frontal areas [52]. Crucially, our prediction was that if Type 1 processing is dissociable from Type 2 processing, then only anodal stimulation to the right DLPFC would improve Type 2 performance. In short, whereas Oldrati et al. [30], had sought to reduce reflective thinking by modulating Type 1 processing, our study sought to investigate whether anodal stimulation to the right DLPFC would improve Type 2 processing.

Materials and methods

Participants

Fifty-four participants were recruited through advertising and word-of-mouth at the University of East London (UEL) (mean age = 24.63 ± 4.46 years; 29 females). The inclusion criteria were: (i) aged 18 years or above; (ii) fluent English speakers; (iii) right-handed; (iv) naïve to tDCS and (v) naïve to the behavioural tasks used. 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; (ix) pregnancy and (x) past training in logic reasoning (e.g., during a lecture) (Table 1). All participants provided informed written consent. The study was approved by the University of East London Research Ethics Committee.

tDCS montage and parameters

TDCS was delivered using a battery-driven stimulator device (Neuroelectrics®, Barcelona) using two circular sponge electrodes

Table 1
Demographics, and cognitive characteristics.

Demographic variable	Stimulation group (anode location) mean (SD)		
	Left-DLPFC	Sham	Right-DLPFC
Sex (F/M)	9/9	9/9	11/7
Age	23.78 (4.63)	24.83 (4.60)	25.28 (4.26)
Religious (Yes/No)	10/8	10/8	9/9
Education	5.80 (1.06)	6.30 (1.07)	6.67 (0.70)
Cognitive characteristics			
NART score	117.83 (4.80)	117.90 (5.91)	118.61 (4.60)
AOT score	38.67 (7.17)	40.83 (3.11)	39.06 (3.45)
REI 10 R subscale	16.83 (3.10)	19.44 (2.72)	18.22 (3.37)
REI 10 E subscale	15.22 (1.86)	15.67 (1.57)	16.17 (1.46)

The means and standard deviations are presented in parentheses. Education represents qualification levels in United Kingdom. Abbreviations: Dorsolateral prefrontal cortex (DLPFC), females (F), males (M), National Adult Reading Test (NART), Actively open-minded thinking (AOT), Rational Experiential Inventory Rational subscale (REI 10 R), Rational Experiential Inventory Experiential subscale (REI 10 E).

(i.e., anodal and return) soaked in a saline solution. Electrodes had a surface area of 25 cm^2. Participants were randomly allocated to one of three bilateral tDCS montages (anode electrode – cathode return electrode): (i) anode right DLPFC - return left DLPFC, (ii) anode left DLPFC –return right DLPFC or (iii) sham right DLPFC – sham left DLPFC condition. The electrodes were placed over the right DLPFC (F4) or left DLPFC (F3) with a return electrode over the contralateral location according to the EEG 10–20 international system [53].

In the stimulation groups, a constant current of 1.5 mA, resulting in a current density of 0.06 mA/cm^2, was administered for 20 minutes before testing ('offline') (Fig. 1). There was a gradual increase and decrease of 15 s each at the onset and offset of stimulation. In the sham group, electrodes were placed over the right DLPFC and left DLPFC, but stimulation was only active for the 30 second duration of onset and offset.

Materials

Materials used in this study were tasks or related questionnaires from the judgment and decision-making literature. The cognitive reflection test [31,33] has been used in a previous neuromodulation study [30], as have belief-bias syllogisms [52].

Belief bias syllogisms

Belief bias syllogisms show the susceptibility of syllogistic reasoning to interference from the believability of conclusions [18]. Participants view two premises (e.g., ALL ROSES NEED WATER and PLANTS NEED WATER) with a conclusion (e.g., THEREFORE, ROSES ARE PLANTS). Participants respond by deciding if the syllogism is valid or invalid [54]. Logical syllogisms are either consistent with beliefs about the world (valid-believable and invalid-unbelievable), or incongruent, in which the logical conclusion is inconsistent with beliefs (valid-unbelievable and invalid-believable). Belief–bias is the degree to which responses in congruent trials vs incongruent trials.

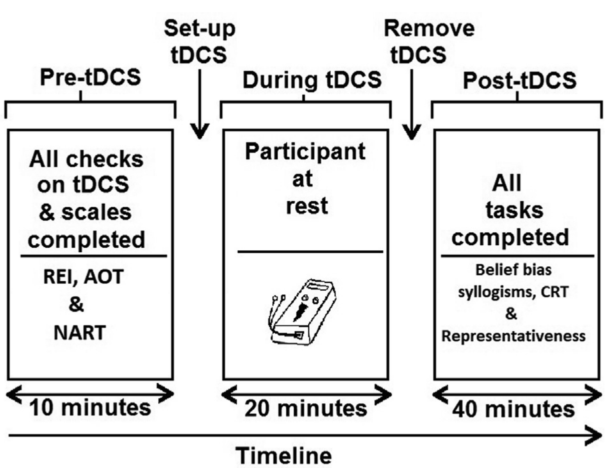

Fig. 1. Procedure of experiment. The duration of the entire experiment was 1 hour and 10 minutes per participant. The first 10 minutes ('Pre-tDCS' box) involved the completion of the consent form, demographics form and the Actively Open-minded thinking (AOT) scale, Rational Experiential Inventory (REI) scale and National Adult Reading Test (NART). Following the completion of these scales, the tDCS equipment was set-up and all equipment checks were conducted (i.e., impedance checks). Next, the participant rested (completing no tasks) during the 20 minutes stimulation duration ('During tDCS' box). Afterwards, the equipment was removed from the participant's heads and they began the experimental tasks. The tasks completed by the participants ('Post-tDCS' box) were counterbalanced in order and included the belief bias syllogisms, Cognitive Reflection Test and representativeness heuristic (incongruent base-rate neglect). *Abbreviations: transcranial Direct Current Stimulation (tDCS).*

For the analysis, responses were transformed into data to indicate if participants accepted or did not accept the conclusion. For scoring and subsequent parametric analyses, a logic index, a belief index, and an interaction index were calculated [55,56]. The logic index is the difference between the acceptance of valid and invalid conclusions, with larger indices being indicative of logical responding. The belief index is the difference between the acceptance of believable and unbelievable conclusions, with larger indices indicating a greater belief bias. The interaction index shows the degree to which belief bias is greater for invalid than valid syllogisms. A total of sixteen syllogisms were given to each participant with a maximum score of 16 correct answers. This included 4 valid-unbelievable, 4 valid-believable, 4 invalid-unbelievable and 4 invalid-believable.

Cognitive reflection test

The cognitive reflection test (CRT) measures intuitive and analytic thinking [31]. Participants view short questions (e.g., *A bat and ball together cost £1.10. The bat costs £1 more than the ball. How* much *does the ball cost?*) with lures that are designed to initially illicit an intuitive answer. With some reflection and consideration, participants generally arrive at the correct, analytic answer. In this study, the number of CRT items included those of Frederick [31] (3 items), Toplak, West and Stanovich [19] (4 items), Thomson and Oppenheimer [33] (4 items).

In addition, we also employed a "verbal" version CRT [57] with 8 items. A single booster item (*A clerk in the butcher shop is 5′ 10″ tall. What does he weigh?*) was added to the 8 items by [57]. This collection of CRT-like puzzles was designed to reduce a potential reliance on numerical skills [57].

A total of twenty CRT and CRT-like items were given to participants in two blocks of the experiment, with ten items per part to avoid fatigue.

Representativeness heuristic (incongruent base-rate neglect)

The representativeness heuristic, also called incongruent base-rate neglect [45,58] shows that when presented with base-rate information (e.g., the probability of independent events or attributes occurring: *Among a sample of 900 people there were 810 farmers and 90 illustrators*) and specific information (i.e., a stereotype of an occupation: *James is a randomly chosen participant. James is meticulous, has a strong eye for detail, enjoys listening to music whilst working and has a creative trait*) participants ignore the former in favour of the latter when asked the question of which is most likely? (e.g., *a. James is an illustrator, or b. James is a farmer)* [58,59]. The representativeness heuristic was used here because of its use in the previous literature that revealed a correlation with the CRT and AOT [46,60] and is therefore associated with a lack of reflective thinking. A total of ten representativeness items were given to participants with a maximum score of ten.

Actively open-minded thinking

The actively open-minded thinking (AOT) scale measures the willingness to consider new information and remain 'open-minded' [43]. Participants respond to items on a scale (e.g., *Changing your mind is a sign of weakness*) from 1 (completely disagree) to 7 (completely agree).

Rational experiential inventory

The Rational Experiential Inventory (REI) measures cognitive style (the use of intuitive or analytic thinking) [41]. Participants respond to items on a scale (e.g., I don't like to have to do a lot of thinking) from 1 (strongly disagree) to 5 (strongly agree).

National adult reading test

The National Adult Reading Test (NART) is a list of 50 short words with irregular pronunciation (e.g., BOUQUET, PLACEBO) [47,48]. Performance on the NART predicts cognitive ability (i.e., intelligence) in the Wechsler Adult Intelligence Scale (WAIS) [47]. Participants are scored on their pronunciation of words in the test.

Participants also worked on brief tasks measuring executive functions: a short-term memory task (*n*-back) and a Stroop task, both of which were not analysed for this study. The order of these tasks was counterbalanced with the judgment and decision-making tasks in each stimulation group.

Analysis

The raw data were screened for outliers and missing values. Two multivariate analyses of variance (MANOVA) were performed. The first analysis investigated whether there were any *a priori* differences between groups regarding cognitive characteristics, such as thinking styles and NART as potential confounding factors. The type of stimulation (right - location always refers to placement of the anode- DLPFC, left DLPFC or sham) was the between-subject factor. Dependent variables were the REI subscales (rational or REI 10 R) (experiential or REI 10 E), the actively open-minded thinking scale (AOT) and National Adult Reading Test (NART).

To test the effects of stimulation on Type 2 responses, a further multivariate analysis of variance (MANOVA) was performed with type of stimulation (right DLPFC, left DLPFC or sham) as the between-subject factor. Dependent variables were CRT scores, verbal-CRT scores, number of correct answers from the representativeness questions, the Logic Index and the Belief Index from the belief bias syllogisms. Significant effects were analysed with ANOVAs to determine the specific contributing contrast.

Results

There were no missing values or outliers in the accuracy scores (i.e., correct responses) for the thinking tasks (i.e., CRT, representativeness and syllogism task) nor for the cognitive characteristics scores.

A MANOVA with cognitive characteristics as dependent variables showed no effect of stimulation group (Pillai's trace = 0.18, $p = .28$). The Box's test results showed that equality of covariance had been violated so Pillai's trace was used. Thus, the three experimental groups did not differ in the cognitive characteristics scores (see Table 1), which have previously been associated with judgment and decision-making performance (e.g., [19]).

The second MANOVA tested the effect of stimulation on the judgment and decision-making tasks. The Box's test results showed equality of covariance matrices ($p = .98$). There was a significant main effect of stimulation (Wilks' $\lambda = 0.67$, $F(10,94) = 2.04$, $p = .03$, partial $\eta^2 = 0.18$) on thinking task performance.

Follow-up ANOVAs were performed for each of the tasks. There was a significant effect of stimulation on CRT scores ($F(2,51) = 4.45$, $p = .01$, partial $\eta^2 = 0.15$). Planned contrasts revealed that CRT performance improved following right DLPFC anodal stimulation (M = 5.33, SD = 2.50) in comparison to both left DLPFC anodal stimulation ($p = .01$, 95% CI [-3.42, −0.57] (M = 3.33, SD = 2.14)) and sham ($p = .03$, 95% CI [-3.03, −0.20] (M = 3.72, SD = 1.67)).

For representativeness correct answers, the follow-up ANOVA showed a significant effect of stimulation ($F(2,51) = 3.20$, $p = .04$, partial $\eta^2 = 0.11$). The planned contrasts revealed that representativeness performance was higher following right DLPFC anodal stimulation (M = 6.83, SD = 4.06) in comparison to both left DLPFC anodal stimulation ($p = .03$, 95% CI [-4.84, −0.15] (M = 4.33, SD = 3.51)) and sham ($p = .03$, 95% CI [-4.95, −0.26] (M = 4.22, SD = 2.82)).

The follow-up ANOVA for the Logic index revealed also a significant effect of stimulation group ($F(2,51) = 3.54$, $p = .03$, partial $\eta^2 = 0.12$). The contrasts revealed that logical responding was higher following right DLPFC anodal stimulation (M = 1.88, SD = 2.24) in comparison to left DLPFC anodal stimulation ($p = .03$, 95% CI [-2.93, −0.17] (M = 0.33, SD = 1.80)), but not to sham ($p = .93$, 95% CI [-1.32, 1.43] (M = 1.94, SD = 2.12)). A post-hoc *t*-test examined the effect of stimulation of the left DLPFC versus sham for the Logic index. The *t*-test revealed a difference between logic index scores after left DLPFC stimulation compared to sham ($t(34) = 2.46$, $p = .02$, 95% CI [0.28, 2.94] − scores were worse after left DLPFC stimulation (M = 0.33, SD = 1.78) compared to sham (M = 1.94, SD = 2.12).

There was no effect of stimulation group on verbal-CRT ($F(2,51) = 1.01$, $p = .37$, partial $\eta^2 = 0.04$) scores or the Belief index ($F(2,51) = 0.74$, $p = .47$, partial $\eta^2 = 0.03$). The relevant summary for means and standard deviations for both stimulation groups are presented in Fig. 2 and in the Supplementary Table 1.

Discussion

The present study demonstrates that anodal tDCS to the right DLPFC improved analytical judgment and decision-making. The effect was evident in comparison to anodal stimulation to the left DLPFC in all tasks with improved Type 2 cognitive reflection in the CRT and representativeness heuristics performance, while the logic index score was diminished after left anodal stimulation.

Our main predictions were that increasing cortical excitability in the right DLPFC would increase performance on judgment and decision-making tasks that require inhibition of automatic processes in order to result in normatively correct (unbiased) answers. This was based on the concept of an algorithmic mind [61] monitoring and inhibiting (Type 1) processes. TDCS applied to the right DLPFC is known to affect executive functions [62,63] that include impulsivity control and set-shifting (see Ref. [49] for a review). Greater resistance to intuitive thinking and pre-potent responses (such as in the CRT and other tasks invoking heuristic thinking) rely on the engagement of impulsivity control and set-shifting during decision-making [63,64]. Our findings that anodal stimulation of the right DLPFC did improve cognitive reflection performance for typical CRT items and representativeness - but not logic thinking - support the notion that there is some distinction in the neural correlates that contribute to Type 1 versus Type 2 processes.

Stimulation with the anode over the right DLPFC did not affect CRT items with non-numerical content (a novel battery, 'verbal' CRT, [57]), but did boost performance for the typical, math-based CRT items. This is potentially because of the CRT's presumed reliance on mathematical ability [33,65]. However, at the same time, tasks invoking representativeness heuristics showed similar patterns as the typical (numerical) CRT, despite there being no need for any number-based operations. This pattern of findings suggests that it is not mere numerical processing that is improved after anodal stimulation of the right DLPFC. One explanation for this result could be that typical CRT items prompt cognitive reflection whilst verbal information primes more intuitive level processes [66]. A more straightforward explanation could be that success in the verbal CRT was simply less reliant on inhibitory processes but rather relied on linguistic ability. In contrast, the typical CRT is reliant on executive functions that may include impulse control [16] and set-shifting [12] − both of which have neural substrates in the right DLPFC [12,17].

The findings extend previous work by Oldrati et al. [30], who showed a decrease in CRT performance following unilateral cathodal stimulation to the right DLPFC as compared to anodal

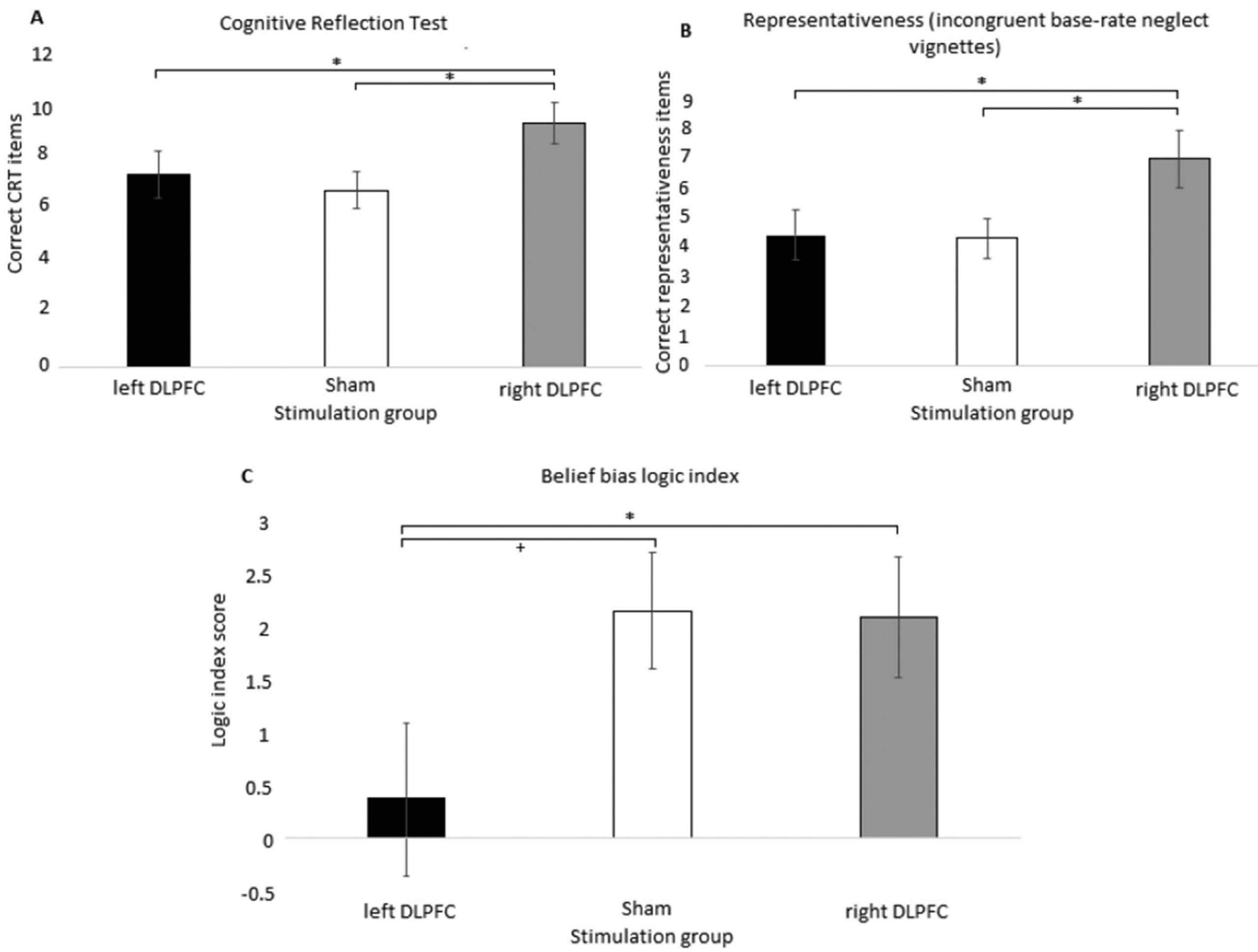

Fig. 2. Effects of tDCS neuromodulation on thinking tasks. The panels show the effects of tDCS (anodal left DLPFC, sham, or anodal right DLPFC) on correct answers for the Cognitive Reflection Test (panel A), correct answers for representativeness (incongruent base-rate neglect vignettes) (panel B), and the effects of tDCS on the Logic index for the belief bias syllogisms (panel C). Here the significance level denoted with a cross (+) based on post-hoc t-test for Logic index with a level of $p < .05$. All other significance levels are based on the respective contrasts of follow-up analyses of variance (ANOVAs): an asterisk denotes $p < .05$. Error bars represent standard error of the mean. Abbreviations: Dorsolateral prefrontal cortex (DLPFC), Cognitive Reflection Test (CRT).

stimulation. In addition, the results show that thinking tasks which do not rely on inhibition (logic syllogisms) did not improve following right DLPFC anodal stimulation relative to sham, but did show an impairment following left DLPFC anodal stimulation. The present data demonstrate a causal relationship between neuromodulation of the right DLPFC and Type 2 (reflective thinking) processes. Importantly, we controlled for individual differences with the NART, AOT, and REI — differences that presumably can influence decision-making [39,40].

As predicted, for belief bias syllogisms we did not find an effect of direct current stimulation on the right DLPFC. An increase of cortical excitability of the right DLPFC might not influence syllogistic reasoning (logic index score) because there is no need for inhibition for all task variants, e.g., when logic and beliefs do not conflict [67,68]. Furthermore, rather than the DLPFC, the inferior frontal cortex has been increasingly associated with correctly solving syllogisms [52,69]. In fact, left DLPFC stimulation in comparison to right DLPFC stimulation reduced overall deductive thinking (indicated by the logic index score). This result does fit in general with previous observations that deductive performance with categorical syllogisms seems associated with left frontal brain areas [50].

There is a possible alternative explanation as to why frontal stimulation caused improved judgment and decision-making performance. Rather than increasing inhibitory performance, transcranial stimulation may increase effective switching between the default mode network (DMN) [70,71] and the dorsal attention network (DAN) [72] and thus improve cognitive performance (for a review, see Greenwood et al., 2018). The internally driven DMN is active during memory retrieval and planning and includes the medial prefrontal cortex, posterior cingulate cortex and posterior inferior prefrontal cortex [70,71]. The externally driven DAN is associated with activation in the intraparietal sulcus and superior parietal cortex during the processing of external events (i.e., attention) [49,72]. Both the DMN and DAN have the capacity to suppress each other when one of the networks is recruited for a cognitive function. However, according to a recent meta-analysis [49] one would expect improved switching behaviour also after stimulation of the left, not only the right DLPFC. Therefore, the more plausible explanation is that it is rather the increased inhibition of pre-potent CRT responses after stimulation [62,63] that explains our findings here.

There are a number of limitations regarding our study. First, we used a bilateral montage, in accordance with the majority of research in risk-based decision-making [73,74]. However, the effect on decision-making was only evident (i.e., cognitive reflection test and representativeness) after anodal stimulation of the right DLPFC (with the return electrode over left DLPFC) compared to the contralateral montage and sham. If an increase in decision-making were the result of the return electrode over the left DLPFC, we would expect to the see a significant decrease in decision-making in the left DLPFC group – which we did not. Furthermore, all participants received real or sham tDCS prior to the tasks, which is considered to be 'offline' stimulation. We limited our study to the 'offline' stimulation because Hill et al.'s [28] meta-analysis reported a significant effect on working memory performance only following 'offline' anodal tDCS in comparison to 'online' stimulation, which was applied during the task. Although we had randomly allocated participants to the three groups and we had assessed factors which could affect task performance, namely cognitive ability (NART), open-mindedness (AOT) and decision-making style (REI), we had not assessed their baseline performance on the bias syllogisms, Cognitive Reflection Test and representativeness heuristic, in order to avoid potential ceiling effects in task performance following intervention. As participants were randomly allocated to the groups, there were no significant differences in their demographic features or cognitive and attitudinal characteristics that have a demonstrated impact on heuristics performance, potential *a priori* differences in performance could be assessed in a pre- and post-test design to test the reliability of our findings.

A suggested future direction of research is to further investigate the exact nature of processes involved when engaging in cognitive reflection. We propose that further neuromodulation research is needed to distinguish between the neural correlates of inhibitory control and cognitive simulations [44] in judgment and decision-making. The impact of tDCS on decision-making and other cognitive functions [75] in addition to beneficial effects on mood in major depression [76], and in other mental health disorders requires further investigation. Multimodal neuroimaging techniques that combine electroencephalography (EEG) and tDCS would also be beneficial in furthering our understanding of the neural correlates of judgment and decision-making.

Conflict of interest declaration

Daniel R. Edgcumbe, Volker Thoma, Cynthia Fu and Davide Rivolta declare that they have no conflicts of interest. There are no affiliations with or involvement in any organization or entity with any financial interest, or non-financial interest in the subject matter or materials discussed in this manuscript.

Michael A. Nitsche declares that he is a member of the Scientific Advisory Board of Neuroelectrics®.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.brs.2018.12.003.

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