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## Accelerating Creativity: Effects of Transcranial Direct Current Stimulation on the Temporal Dynamics of Divergent Thinking

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### ABSTRACT

Transcranial direct current stimulation (tDCS) over the dorsolateral prefrontal cortex (DLPFC) has been shown to enhance divergent and convergent creative thinking. Yet, how stimulation impacts creative performance over time, and what cognitive mechanisms underlie any such enhancement, remain largely unanswered questions. In the present research, we aimed to (1) verify the impact of DLPFC tDCS on both convergent and divergent thinking, and further investigated (2) the temporal dynamics of divergent thinking, focusing on the serial order effect (i.e., the tendency for ideas to become more original and less frequent over time), and (3) any role that cognitive inhibition may play in mediating any effect of stimulation on creative thinking (considering the DLPFC's involvement in driving inhibitory processes that are also relevant for creative thinking). In a within-subjects design, twenty-six participants received three types of cross-hemispheric tDCS stimulation over the DLPFC (left cathodal and right anodal, L-R+; left anodal and right cathodal, L-R-; and sham). Before stimulation, they completed a pre-flanker task measuring cognitive inhibition; during stimulation, they completed the Alternate Uses Task (AUT), Remote Associates Test (RAT), and post-flanker task. Results showed that, compared with the sham stimulation, originality of responses in the AUT was significantly enhanced in the L-R- condition, while no tDCS effect was observed for the RAT. Additionally, compared with the other stimulation conditions, we found a diminished serial order effect in the L-R- condition characterized by an accelerated production of more original ideas. Critically, the L-R- condition was accompanied by better performance on the flanker task. Our findings thus verify that L-R- tDCS over the DLPFC accelerates idea originality also providing tentative clues that inhibition may act as a cognitive mechanism underlying enhancements in divergent thinking resulting from frontal lobe neuromodulation.

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### Introduction

Creative cognition is thought to involve both divergent thinking (DT) and convergent thinking (CT). DT is typically characterized as an association process of idea generation, whereas CT as a selection process that monitors and evaluates ideas (Finke, Ward, & Smith, 1992; Guilford, 1967; Kleinmuntz, Ivancovsky, & Shamay-Tsoory, 2019). Increasing evidence indicates that DT and CT can be enhanced using transcranial direct current stimulation (tDCS) – a noninvasive brain stimulation method that temporarily modulates the firing rate of neurons in specific brain regions – with several studies reporting tDCS-enhanced performance on creative tasks involving DT (Chrysikou et al., 2013; Colombo, Bartesaghi, Simonelli, & Antonietti, 2015; Ghanavati, Salehinejad, Nejati, & Nitsche, 2019; Goel, Eimontaite, Goel, & Schindler, 2015; Green et al.,

2017; Huang, Song, Jiang, Zhao, & Luo, 2021; Ivancovsky, Kurman, Morio, & Shamay-Tsoory, 2019; Kenett, Rosen, Tamez, & Thompson-Schill, 2021; Khalil, Karim, Kondinska, & Godde, 2020; Mayseless & Shamay-Tsoory, 2015; Xiang et al., 2021) and CT (Cerruti & Schlaug, 2009; Chi & Snyder, 2011; Chi & Snyder, 2012; Luft, Zioga, Banissy, & Bhattacharya, 2017; Metuki, Sela, & Lavidor, 2012; Pick & Lavidor, 2019; Ruggiero, Lavazza, Vergari, Priori, & Ferrucci, 2018; Zmigrod, Colzato, & Hommel, 2015).

To date, however, very little is known about how stimulation impacts creative performance over time (i.e., its temporal dynamics) and the cognitive mechanisms underlying enhanced creative thinking (e.g., cognitive inhibition). Regarding the temporal dynamics of DT, a consistent behavioral finding is the so-called serial order effect, or the tendency for ideas to become more

original and less frequent over the course of idea generation (Christensen, Guilford, & Wilson, 1957; Ward, 1968). Research on the serial order effect has typically been concerned with the Alternate Uses Task (AUT), a widely used DT test involving the generation of creative uses for objects (Bai, Mulder, et al., 2021; Guilford, Christensen, Merrifield, & Wilson, 1978). Regarding cognitive mechanisms, cognitive inhibition – one of the subcomponents of executive control (Groborz & Necka, 2003; Hallquist, Geier, & Luna, 2018) – is considered closely related to creativity (Benedek, Franz, Heene, & Neubauer, 2012; Nusbaum & Silvia, 2011), but evidence linking inhibition to DT is mixed.

On one hand, *decreased* inhibition (or disinhibition) was found to contribute to the “release” of controlled processes in both DT (Ivancovsky et al., 2019; Mayseless & Shamay-Tsoory, 2015; Radel, Davranche, Fournier, & Dietrich, 2015) and CT (Chi & Snyder, 2011, 2012; Luft et al., 2017), presumably supporting an increased availability of unfiltered and low-level perceptual information. On the other hand, *increased* inhibition was also found to boost creativity in both DT (Beaty, Christensen, Benedek, Silvia, & Schacter, 2017; Cheng, Hu, Jia, & Runco, 2016; Colombo et al., 2015; Koizumi, Ueda, Li, & Nakao, 2020; Nusbaum & Silvia, 2011; Xiang et al., 2021) and CT (Cerruti & Schlaug, 2009; Metuki et al., 2012; Zmigrod et al., 2015), which may reflect the suppression of common ideas, and in turn facilitate the selection of novel ideas.

To date, however, whether and how cognitive inhibition can be modulated through tDCS to boost creative performance remains unclear. Thus, the present study aims to 1) test the effects of tDCS on CT and DT, 2) isolate the temporal effects of tDCS on DT, and 3) examine whether the effects of tDCS on creative performance relate to underlying modulations of cognitive inhibition.

### Brain stimulation and creative cognition

tDCS is a noninvasive and safe tool that can temporarily and reversibly regulate the excitability of neurons by applying a weak current to a specific area of the scalp. In accordance with the sliding-scale perspective, anodal stimulation increases the neuronal excitability within a targeted brain region while cathodal stimulation reduces it (Nitsche & Paulus, 2000). Although tDCS has been shown to have the potential to improve creativity, a recent review indicates that these results are often moderated by an interaction between stimulation

polarity, stimulation site, and cognitive demand characteristics of the experimental task (Weinberger, Green, & Chrysikou, 2017).

Some researchers have suggested that idea generation, when measured in terms of fluency and reaction times, can be improved by cathodal stimulation over the left prefrontal cortex (PFC; Chrysikou et al., 2013; Chrysikou, Morrow, Flohrschutz, & Denney, 2021) – a region involved in regulatory filtering of bottom-up information, including working memory, language, and attention tasks (Thompson-Schill, Bedny, & Goldberg, 2005). For example, Chrysikou et al. (2013) reported an improvement in reaction times and fluency when generating uncommon but not common uses for objects when following cathodal stimulation over the left prefrontal cortex (PFC). This effect was replicated in a recent large-scale study comparing multiple stimulation montages (unilateral or bilateral stimulation, ventrolateral PFC or occipital cortex; Chrysikou et al., 2021), which demonstrated faster reaction times when generating a single idea from cathodal stimulation over the left ventrolateral PFC. Other studies targeting the inferior frontal gyrus (IFG) – a region involved in controlled retrieval from semantic memory (Grindrod, Bilenko, Myers, & Blumstein, 2008) – found enhanced fluency effects following left cathodal and right anodal stimulation (Hertenstein et al., 2019; Mayseless & Shamay-Tsoory, 2015). Such bilateral stimulation is hypothesized to alter the balance of activation between the two hemispheres, reducing cognitive control and selective retrieval mechanisms (Hertenstein et al., 2019; Mayseless & Shamay-Tsoory, 2015). Altogether, these findings provide some ground for the view that disinhibition benefits creative thinking. More specifically, they tend to be interpreted in terms of a “release” from selective and evaluative memory retrieval processes. The general improvement of creative fluency and reaction times may result from an increased availability of unfiltered and low-level perceptual information following cognitive control disengagement.

On the other hand, a recent review suggested that performance that strongly relies on idea selection, such as in tasks requiring high cognitive demands or goal-directed thinking (e.g., DT idea originality and CT tasks), may be improved by anodal tDCS over the left dorsolateral prefrontal cortex (DLPFC) and frontopolar cortex (Weinberger et al., 2017). When considering several recently published studies (cf. Table 1), it appears that left anodal or left anodal and right cathodal (L+R-) stimulation over the DLPFC can enhance not only fluency but also originality in DT tasks, as well as performance on CT tasks. For instance, Colombo et al. (2015) found enhanced fluency and originality on an AUT with unilateral

**Table 1.** Overview of creativity research conducted by transcranial direct current stimulation (tDCS) technique.

| References                                                            | Tasks                                                                                    | tDCS protocol                    | tDCS parameters | Location of target electrode(s)             | Location of reference electrode(s) | Design & polarity                                                                                        | Sample size                                                                                 | Outcome tasks                               | Findings                                                                                                                                                                                                         |
|-----------------------------------------------------------------------|------------------------------------------------------------------------------------------|----------------------------------|-----------------|---------------------------------------------|------------------------------------|----------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|---------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1. L+ over DLPFC/IFG improved divergent thinking & semantic distance. |                                                                                          |                                  |                 |                                             |                                    |                                                                                                          |                                                                                             |                                             |                                                                                                                                                                                                                  |
| Xiang et al., (2021)                                                  | 1. AUT; 2. Compound remote associates (CRA);                                             | Online; Bilateral                | 1.5 mA, 20min   | DLPFC                                       | N/A                                | Mixed-subjects; L+R-, L-R+, Sham.                                                                        | N=30 for low-trait-anxious (LTA); N=31 for high-trait-anxious (HTA).                        | AUT.                                        | Compared to sham tDCS, L+R- DLPFC enhanced AUT fluency, flexibility, and originality for LTA.                                                                                                                    |
| Koizumi et al., (2020)                                                | AUT.                                                                                     | Offline; Unilateral              | 2mA, 20min      | DLPFC; IPL                                  | N/A                                | Within-subjects; L+ DLPFC & R- IPL.                                                                      | N = 14.                                                                                     | AUT.                                        | Compared to sham tDCS, L+ over DLPFC & R- over IPL enhanced AUT flexibility.                                                                                                                                     |
| Colombo et al. (2015)                                                 | Alternate uses task (AUT).                                                               | Offline; Unilateral              | 1.5 mA, 20 min  | DLPFC                                       | Right orbitofrontal                | Between-subjects; L+, L-, R+, R-, sham.                                                                  | N = 45 for 3 groups (15 for each).                                                          | AUT.                                        | Compared with sham tDCS, L+ or R+ over DLPFC enhanced fluency and originality.                                                                                                                                   |
| Ghanavati et al. (2019)                                               | 1. Verbal fluency (i.e., semantic and phonemic fluency tasks); 2. Five-point test (FPT). | Online; Unilateral               | 1.5 mA, 15 min  | PPC; temporal area; DLPFC                   | Contralateral shoulder             | Within-subjects; anodal left DLPFC (F3), anodal left temporal (T3), anodal right PPC(P4), and sham tDCS. | N = 15.                                                                                     | 1. Verbal fluency; 2. FPT.                  | Compared with sham tDCS, 1. L+ over DLPFC: more words in phonemic fluency task. 2. Both L+ over temporal or DLPFC: more words with semantic fluency task. 3. L+ over DLPFC and R+ over PPC: more unique figures. |
| Green et al. (2017)                                                   | 1. Analogy finding task; 2. Thin slice creativity verb generation task.                  | Offline and Online; Unilateral   | 2 mA, 20 min    | 4*1 HD-tDCS Frontopolar Cortex (AF3)        | FPz, Fz, F7, and FC3               | Between-subjects; L+, Sham.                                                                              | N = 15 for stimulation group; N = 16 for sham group.                                        | Thin slice creativity verb generation task. | Compared with sham tDCS, cue & L+ HD-tDCS enhanced semantic distance of Verb Generation Task.                                                                                                                    |
| Huang et al., (2021)                                                  | A riddle task.                                                                           | Offline Unilateral               | 1 mA, 20 min    | Exp.1: TPJ Exp.2: DLPFC                     | Contralateral orbitofrontal cortex | Within-subject; L+, R+, sham.                                                                            | Exp1: N = 36; Exp2: N = 30.                                                                 | A riddle task.                              | 1. L+ DLPFC increased the novelty index but not the appropriateness index of creative ideas. 2. R+ over TPJ increased both the novelty and appropriateness indexes of creative ideas.                            |
| Kenett et al., (2021)                                                 | 1. Uncommon sentence completion task; 2. Reading span test; 3. Verbal fluency.           | Online; Unilateral               | 1.5 mA, 17 min  | IFG                                         | Contralateral mastoid              | Between-subject; L+, L-, and sham.                                                                       | N = 45 for 3 groups (15 for each).                                                          | Uncommon sentence completion task.          | Compared with sham tDCS, L+ over IFG leads to more appropriate and less novel responses.                                                                                                                         |
| 2. L- over PFC/IFG improved divergent thinking.                       |                                                                                          |                                  |                 |                                             |                                    |                                                                                                          |                                                                                             |                                             |                                                                                                                                                                                                                  |
| Chrysikou et al., (2021)                                              | Pictorial object task.                                                                   | Online; Unilateral               | 1.5 mA, 20 min  | PFC                                         | Contralateral mastoid              | Between-subjects; L- and R-.                                                                             | N = 48 for 6 groups (8 for each).                                                           | Pictorial object uses task.                 | Compared with sham tDCS, L- over PFC enhanced unusual uses fluency and response speed.                                                                                                                           |
| Chrysikou et al., (2021)                                              | 1. Pictorial object uses task; 2. Short-term memory task.                                | Online; Unilateral and bilateral | 1.5 mA, 20 min  | Exp. 1, 2, 3: PFC Exp. 4: occipital cortex. | Contralateral mastoid              | Exp. 1: L-, R-, sham; Exp. 2: L+, R+, sham; Exp. 3: L-R+, R-L+, sham; Exp. 4: L+ O1, R+ O2, sham.        | Exp. 1, 2, 3: N = 60 for 3 groups (20 for each); Exp. 4: N = 66 for 3 groups (22 for each). | Pictorial object uses task.                 | Compared with sham tDCS, L- over PFC enhanced unusual uses fluency.                                                                                                                                              |
| Mayseless & shamay-tsoory (2015)                                      | 1. Verbal fluency task; 2. AUT; 3. Visual figural task (VFT).                            | Online; Bilateral                | 1.5 mA, 22 min  | IFG                                         | N/A                                | Mixed-design; Exp.1: L-R+, sham; L+ R-, sham. Exp. 2: L-, sham; L+, sham.                                | Exp. 1: N = 30 for 2 groups (15 for each); Exp. 2: The same with Exp. 1.                    | AUT.                                        | Exp.1: Compared with sham tDCS, L-R+ IFG enhanced AUT fluency and flexibility; Exp.2: No significance.                                                                                                           |

(Continued)

Table 1. (Continued).

|                                                        |                                                                               |                                             |                |            |                                    |                                                                                |                                                                             |                                                                      |                                                                                                                                                                                        |
|--------------------------------------------------------|-------------------------------------------------------------------------------|---------------------------------------------|----------------|------------|------------------------------------|--------------------------------------------------------------------------------|-----------------------------------------------------------------------------|----------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Ivancovsky et al. (2019)                               | AUT.                                                                          | Online; Unilateral                          | 1.5 mA, 20 min | IFG        | Contralateral supraorbital region  | Mix design; Japan, Israel, anodal, sham; cathodal, sham.                       | N = 60 for 2 groups (30 for each).                                          | The Z score of the sum of the fluency, flexibility, and originality. | Compared with sham tDCS, 1. L- over IFG enhanced creativity; 2. L+ over IFG impaired creativity.                                                                                       |
| Khalil et al. (2020)                                   | 1. AUT; 2. Go-nogo.                                                           | Offline; Bilateral                          | 1 mA, 30 min   | IFG        | N/A                                | L+R-, L-R+.                                                                    | N = 40 for 2 groups (20 for each).                                          | AUT; Go-nogo.                                                        | Compared with L+R- tDCS, L-R+ over IFG enhanced flexibility and originality only when inhibitory control was improved.                                                                 |
| Hertenstein et al. (2019)                              | 1. AUT; 2. CRAT; 3. Wisconsin card sorting task.                              | Online; Bilateral                           | 1 mA, 22 min   | IFG        | N/A                                | Between-subjects; L+R-, L-R+, Sham.                                            | N = 90 for 3 groups (30 for each).                                          | AUT; CRAT.                                                           | Compared with sham tDCS, 1. L-R+ over IFG enhanced the fluency and impaired the number of errors of Wisconsin card sorting task. 2. L+R- over IFG increased the response time of CRAT. |
| 3. L+ over DLPFC/ATL/MTG improved convergent thinking. |                                                                               |                                             |                |            |                                    |                                                                                |                                                                             |                                                                      |                                                                                                                                                                                        |
| Cerruti and Schlaug (2009)                             | 1. RAT; 2. Verbal fluency task (VF).                                          | Online; Unilateral                          | 1 mA, 20 min   | DLPFC      | Right supraorbital region          | Within-subject; Exp1: L+, L-, sham; Exp2: R+, R-, sham.                        | Exp1: N = 18; Exp2: N = 12.                                                 | RAT.                                                                 | Compared with sham tDCS, L+ over left DLPFC enhanced RAT.                                                                                                                              |
| Metuki et al. (2012)                                   | CRA.                                                                          | Online; Unilateral                          | 1 mA, 11 min   | DLPFC      | Contralateral orbitofrontal cortex | Within-subject; L+, sham.                                                      | N = 21 for one group.                                                       | CRA.                                                                 | Compared with sham tDCS, L+ over DLPFC enhanced solution recognition for difficult problems.                                                                                           |
| Zmigrod et al. (2015)                                  | 1. AUT; 2. CRA.                                                               | Online; Bilateral                           | 2 mA, 20 min   | DLPFC; PPC | N/A                                | Within-subject; L+R-, L-R+, sham.                                              | Exp1: N = 14; Exp2: N = 14.                                                 | CRA.                                                                 | Compared with sham tDCS, 1. L+R- over DLPFC enhanced CRA score; 2. L+R- and L-R+ over PPC enhanced insight solutions and impaired analytical solutions.                                |
| Ruggiero et al. (2018)                                 | 1. Divergent thinking test (DTT); 2. RAT; 3. Simple reaction time (SRT) task. | Offline; (RAT/SRT); Online (DTT); Bilateral | 1.5 mA, 20 min | ATL        | N/A                                | Between-subjects; L+R-, L-R+ + Sham                                            | N = 21 for 3 groups (7 for each).                                           | RAT.                                                                 | Compared with sham tDCS, L+R- ATL reduced RAT reaction times (RTs) by 20%.                                                                                                             |
| Goel et al. (2015)                                     | 1. Riddles/Insight task; 2. Phonemic verbal fluency task (PVF).               | Offline; Bilateral                          | 2 mA, 20 min   | MTG; TPJ   | N/A                                | Mixed-design; no stimulation, sham, stimulation, L+MTG & R-TPJ, L-MTG & R+TPJ. | N = 32 for 2 groups (16 for native and 16 for non-native English speakers). | Insight task; PVF.                                                   | Compared with sham tDCS, 1. L+MTG & R-TPJ enhanced insight performance for both groups 2. L-MTG & R+TPJ impaired PVF performance for non-native English speaker                        |
| 4. L- over DLPFC/ATL improved convergent thinking.     |                                                                               |                                             |                |            |                                    |                                                                                |                                                                             |                                                                      |                                                                                                                                                                                        |
| Chi and Snyder (2011)                                  | Matchstick arithmetic problems                                                | Online; Bilateral                           | 1.6 mA, 17 min | ATL        | N/A                                | Between-subjects; L-R+, L- R-, Sham.                                           | N = 60 for 3 groups (20 for each).                                          | Matchstick arithmetic problems.                                      | Compared with sham tDCS, L-R+ over ATL enhanced the scores.                                                                                                                            |
| Luft et al. (2017)                                     | Matchstick arithmetic problems                                                | Online; Unilateral                          | 1 mA, 15 min   | DLPFC      | T7, Cz, and Fp2                    | Between-subjects; L+, L-, and sham.                                            | N=60 for 3 groups (20 for each).                                            | Matchstick arithmetic problems.                                      | Compared with sham tDCS, L- over DLPFC enhanced the resolution rate.                                                                                                                   |

Notes: dorsolateral prefrontal cortex (DLPFC); inferior parietal lobule (IPL); prefrontal cortex (PFC); inferior frontal gyrus (IFG); posterior parietal cortex (PPC); anterior temporal lobe (ATL); middle temporal gyrus (MTG); temporo-parietal junction (TPJ).

anodal stimulation of the left DLPFC. Further, Xiang et al. (2021) found enhanced fluency, flexibility, and originality with left anodal and right cathodal stimulation over the DLPFC. The ability to formulate creative analogies was also found to be facilitated by presenting a cue to “think creatively” (inducing a high cognitive demand state) and administering anodal HD-tDCS over the left frontal pole (Green et al., 2017).

Notably, Huang et al. (2021) found that anodal tDCS over the left DLPFC improved the novelty but not the appropriateness of solutions in a divergent riddle task. One reason for these positive effects might be that top-down, executive processes were amplified through this kind of stimulation, consistent with findings that the DLPFC is involved in executive functions like cognitive control and goal-directed thinking (Beaty, Benedek, Silvia, & Schacter, 2016; Groborsz & Necka, 2003). In support of this conjecture, participants displayed enhanced performance in a primed fluency task with left DLPFC anodal stimulation (Ghanavati et al., 2019). Performance on such fluency tasks has been shown to rely on executive functions and goal-directed processes required to generate more unique responses and avoid response repetition (Murray, 2017). Taken together, these findings suggest that anodal stimulation over the DLPFC is more likely to contribute to originality relative to cathodal stimulation over the left ventrolateral PFC/IFG.

Regarding CT, several studies report a positive effect of left anodal or L+R- tDCS over the DLPFC (Cerruti & Schlaug, 2009; Metuki et al., 2012; Pope, Brenton, & Miall, 2015; Zmigrod et al., 2015). Cerruti and Schlaug (2009) observed an improvement on the Remote Associates Test (RAT) – a CT task that involves finding a single, correct solution (Mednick, 1962) – following anodal stimulation over the left DLPFC, as opposed to sham or cathodal stimulation. Similarly, Zmigrod et al. (2015) reported increased Compound Remote Associates (CRA) scores with left anodal and right cathodal stimulation over the DLPFC. Further, Metuki et al. (2012) and Pope et al. (2015) showed that performance on difficult RAT and math problems was enhanced by anodal tDCS over the left DLPFC more strongly than for easier problem sets. Taken together, these findings suggest that the DLPFC plays a causal role in driving cognitive inhibition, such as in facilitating performance on more cognitively demanding tasks like novel idea generation and problem solving.

Taken together, although the results of previous studies are not entirely consistent, there seems to be a possible dissociative effect between inhibition and activation of the left frontal cortex with tDCS. On the one hand, performance in terms of low cognitive demands (i.e., fluency in DT tasks) was enhanced by left cathodal or L-R+ tDCS over the IFG, suggesting a general release of cognitive inhibition (Chrysikou et al., 2013, 2021; Maysless & Shamay-Tsoory, 2015). Conversely then, performance measured through higher cognitive demands criteria (i.e., originality in DT tasks and accuracy in CT tasks) was enhanced by left anodal or L+R- tDCS over the DLPFC and frontopolar cortex. The latter finding was suggested to be due to an activation of executive processes like the inhibition of irrelevant information (Colombo et al., 2015; Green et al., 2017; Huang et al., 2021; Xiang et al., 2021). Therefore, this study aimed to verify the results of previous tDCS studies, and to test the possible role of cognitive inhibition in determining these brain stimulation effects on creativity performance.

### **Serial order effect and cognitive inhibition**

One of the earliest and most consistent findings in the DT literature is the *serial order effect*. This refers to a temporal phenomenon whereby, over the course of an extended period of idea generation, ideational fluency tends to decrease while originality increases (Acar, Abdulla Alabbasi, Runco, & Beketayev, 2019; Bai, Leseman, et al., 2021; Bai, Mulder, et al., 2021; Beaty, Kenett, Hass, & Schacter, 2019; Beaty & Silvia, 2012; Christensen et al., 1957; Wang, Hao, Ku, Grabner, & Fink, 2017). The serial order effect was originally interpreted as grounded in a process of spreading activation in semantic memory, whereby individuals start by producing many salient (but less original) ideas (i.e., information that is highly related to the DT prompt; e.g., brick: house) before eventually reaching more distant/original associations in memory.

The unfolding of the serial order effect is thought to be influenced by executive functions. For example, two studies with children between four and six years of ages found that executive functions (e.g., mental operations like assembling, combining, or synthesizing the stimulus) usually occurred in the later stages of the AUT and predicted the originality of uses (Bai, Leseman, et al., 2021; Bai, Mulder, et al., 2021). Notably, recent behavioral and neural evidence has consistently found that increased (but not decreased) cognitive inhibition diminished serial order effect. For example, Beaty and Silvia (2012) found that individuals with higher levels

of fluid intelligence (Gf) – a facet of intelligence tied to executive control (Frith et al., 2021; Kane & Engle, 2002) – would tend to produce more original ideas earlier in a DT task. Similarly, individuals with stronger cognitive inhibition abilities, who may inhibit obvious ideas more efficiently even at the earlier stages of a DT task, showed no change in upper alpha activity from an early to a late stage of idea generation (Wang et al., 2017). Alpha power has been consistently observed during creative thinking, which potentially reflects executive aspects of creative thought, such as inhibition of goal-irrelevant stimuli (i.e., common ideas), internal attention (target-directed), controlled retrieval (original ideas), and evaluative processes (Benedek, 2018; Rominger et al., 2019). Thus, these results ultimately allude to the possible effect of inhibitory abilities in diminishing the serial order effect of DT, flattening the curve of originality over time.

### **The present research**

Though previous evidence regarding neuromodulation and creative cognition is mixed, a relatively consistent finding is that tasks requiring higher cognitive demands benefit more strongly from anodal tDCS over the left DLPFC (Weinberger et al., 2017). Moreover, effects on creative performance following bilateral stimulation to the frontal cortex (Mayseless & Shamay-Tsoory, 2015; Peña et al., 2021; Xiang et al., 2021) appear superior to those from unilateral stimulation (Mayseless & Shamay-Tsoory, 2015). In line with these findings, the present study adopted a bilateral tDCS protocol targeting the DLPFC. This choice was motivated by accounts detailing the contributing role of the DLPFC in driving inhibitory control (Kim, Johnson, & Gold, 2014) and response selection processes (Lesh, Niendam, Minzenberg, & Carter, 2011), both being important functions for creative thinking. Also, several studies have found that stimulating the left DLPFC, compared with a sham condition, could enhance creative performance (Colombo et al., 2015; Ghanavati et al., 2019; Koizumi et al., 2020; Metuki et al., 2012; Pope et al., 2015; Xiang et al., 2021; Zmigrod et al., 2015). Additionally, some creativity and brain stimulation studies have adopted a between-subjects approach (stimulation vs. sham; Chrysikou et al., 2013; Colombo et al., 2015; Green et al., 2017) or mixed designs (stimulation 1 vs. sham 1 and stimulation 2 vs. sham 2; Ivancovsky et al., 2019; Mayseless & Shamay-Tsoory, 2015) when incorporating both experimental and sham conditions. Here, we adopt a within-subjects design to attenuate

behavioral effects from participants responding differently to the various stimulation conditions (cf. Huang et al., 2021; Xiang et al., 2021; Zmigrod et al., 2015).

We administered three types of cross-hemispheric tDCS stimulation over the DLPFC to each participant, across multiple lab sessions – left cathodal with right anodal (L-R+), left anodal with right cathodal (L+R-), and sham stimulation. Participants then completed in the AUT and RAT during online stimulation. To examine whether DLPFC stimulation affects the temporal dynamics of DT, we assessed the serial order effect by analyzing the quantity (fluency) and quality (mean originality) of DT responses over time. Additionally, we assessed cognitive inhibition by administering both an online and offline flanker task (before stimulation). Our rationale was that any behavioral effects on creative performance would be modulated by enhancements in inhibitory control.

We hypothesized that AUT originality and RAT scores would be enhanced under L+R- stimulation, accompanied by an increase in cognitive inhibition, which would be evidenced by improved performance on the flanker task (Hypothesis 1). In support of this proposal, left anodal tDCS over the DLPFC has been reported to benefit creative tasks with high cognitive demands (Weinberger et al., 2017). Meanwhile, prior work has also demonstrated advantages of bilateral/cross-hemispheric stimulation, as opposed to only stimulating one hemisphere (Mayseless & Shamay-Tsoory, 2015). AUT originality and RAT have been proposed to rely on some common cognitive processes (i.e., selection, goal-direction, and inhibition of irrelevant conceptual recombination; Kleinmintz et al., 2019; Mednick, 1962), suggesting that the same stimulation montage may benefit performance on both tasks. Further, previous studies have consistently shown that left cathodal or L-R+ stimulation over the prefrontal cortex can enhance ideational fluency, an effect that has then been hypothesized to be driven by a reduction of cognitive inhibition (Chrysikou et al., 2013, 2021; Hertenstein et al., 2019; Mayseless & Shamay-Tsoory, 2015). We thus hypothesized that the L-R+ stimulation would lead to increased fluency and decreased cognitive inhibition (Hypothesis 2). Finally, we hypothesized that the L+R- condition will involve a reduction in the serial order effect, characterized by an accelerated production of more original ideas (Hypothesis 3). We based this last hypothesis on previous accounts of the serial order effect being moderated by executive control constructs like cognitive inhibition (Cheng et al., 2016; Wang et al., 2017) and Gf (Beaty & Silvia, 2012).

## Materials and methods

### Participants

Thirty native Chinese participants were recruited from a Midwest Chinese university and written informed consent was collected prior to participation. Four participants did not complete all three sessions. The final sample consisted of 26 participants (10 males, aged 18 to 24 years old,  $M = 19.31$ ,  $SD = 1.98$ ). All participants were right-handed, had normal or corrected-to-normal vision, and were free from any history of psychiatric or neurological disorders. The study was approved by the local ethics committee.

### Material

#### Experimental paradigms

**Alternate uses task (AUT).** The AUT (Guilford et al., 1978) was adopted to assess DT. Participants were asked to verbalize as many “unusual” and “original” object uses as possible for two common objects within 8 min (4 min per object). A microphone was used to record responses and event windows were set at each minute of the AUT to explore the presence of a serial order effect, consistent with an approach adopted in past research (Wang et al., 2021). Three object lists were used, counterbalanced across sessions (list1: can, pencil; list2: box, chopsticks; list3: newspaper, spoon). Responses were evaluated in terms of fluency (number of responses), flexibility (number of categories), and originality (novelty of responses). Three graduate students, who did not participate in the experiment and who were blind to the experimental purpose, were recruited as raters. After being instructed on the score standards, they first reviewed all the answers and subsequently completed a pre-evaluation. Raters discussed responses that varied widely in their creativity ratings to ensure that they were familiar with the scoring criteria and to increase consistency across scoring standards. Additionally, to avoid repetition and potential order effects, the order of presentation of each answer was randomized between raters.

An objective scoring method was used to evaluate originality values (Torrance, 1974). Possible uses for each object were collected from all participants and compiled in terms of their frequency. A score of two was assigned if the frequency of a response was equivalent to less than 2% of all participants for a specific object; a score of one if its frequency was between 2% and 4.99%; and a score of zero if 5% or more participants

listed it (Mayseless & Shamay-Tsoory, 2015). Total scores for each list were calculated based on the average scores for the two included items. To examine the serial order effect, we adopted a previously developed approach (Hao et al., 2014). Mean originality scores were calculated (Eq. 1) at each time block (t1, 0–1 min; t2, 1–2 min; t3, 2–3 min; t4, 3–4 min), also controlling for the influence of fluency on total originality. In Equation 1,  $n$  indicates the number of responses, while  $O_i$  indicates the originality score of a single response.

$$\text{Originality} = \frac{\sum_{i=1}^n O_i}{n} \quad (\text{Eq.1})$$

**Remote associates test (RAT).** The RAT is a well-known task that is typically used to examine CT (Mednick, 1962; Zmigrod et al., 2015). Forty-eight items (including 3 practice items) were taken from a set of 135 RAT problems found in the Chinese adaption of the RAT (Xu, 2016). The 45 test items (solution rate from 45%–55%) were divided into three lists and counterbalanced across sessions, with each list including 15 items and taking about 5 min to complete. Each trial began with the presentation of three prime words on a computer screen (e.g., “board [板]”, “hole [洞]”, and “color [色]”). Participants were then instructed to find a common association between the three primes and to press the spacebar immediately after reaching a solution (e.g., “black [黑]”). They were then asked to write down the solution on an answer sheet. Participants were allowed a maximum of 20s to answer each question. Two dependent measures were recorded: response times (RTs) and accuracy (one correct answer = one point).

**Flanker task.** The flanker task (Eriksen & Eriksen, 1974) was used to assess cognitive inhibition. The task included two types of stimuli: congruent trials (CO) (> > > or < < < <) and incongruent trials (IN) (> > < > or < < > <). Participants were asked to respond – as quickly and accurately as possible – to the middle arrow, by pressing the “F” key when viewing a right-facing arrow and the “J” key when viewing a left-facing arrow. Keyboard responses were given with the index finger of each hand. A single block was adopted, including 160 trials per participant (80 CO and 80 IN), and requiring about 4 min to complete. Consistent with past work (Nozari, Woodard, & Thompson-Schill, 2014; Zmigrod, Zmigrod, & Hommel, 2016), we expected longer RTs and decreased accuracy for IN compared to CO trials. This phenomenon, known as the interference effect, is an established indicator of cognitive control

efficiency, calculated by subtracting the RTs in CO trials from those in IN trials (RTs of IN – RTs of CO trials) (Nozari et al., 2014; Zmigrod et al., 2016).

### Questionnaire on subjective experiences of tDCS

To account for the potential impact of stimulation experience on experimental manipulation, participants were asked to indicate their subjective experiences regarding symptoms of discomfort (e.g., headache, neck pain, scalp pain, tingling, itching, burning sensation, skin redness, sleepiness, trouble concentrating, and acute mood change). Scores were collected on a 4-point Likert scale (1 = no, 2 = mild, 3 = medium, 4 = severe; Brunoni et al., 2011). Subjective experience reports were collected after the stimulation and were later combined for each item into total scores. The subjective experience questionnaire was modeled in accordance with past studies (Xiang et al., 2021; Zmigrod et al., 2015, 2016).

### tDCS

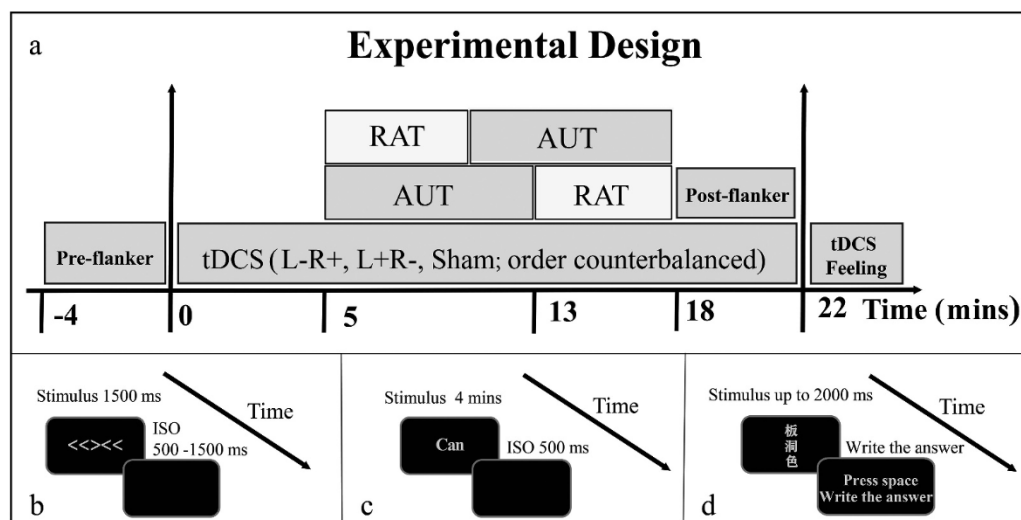
tDCS was applied through 2 saline-soaked square sponge electrodes (25 cm<sup>2</sup>) placed bilaterally over the DLPFC (F3 and F4), in line with the international 10–20 system for EEG electrode placement. The intensity of stimulation was set at 1.5 mA (cf., Chrysikou et al., 2013; Colombo et al., 2015; Mayseless & Shamay-Tsoory, 2015; Xiang et al., 2021) and delivered for 22 min (with a 30s ramp up and 30s ramp down) via a NeuroConn DC-Stimulator Plus device (NeuroConn, Ilmenau, Germany). The sham condition was applied using an 8-s ramp up, 44s of stimulation, and a 5-s ramp

down to produce the same sensation as active condition (NeuroConn, 2014). Participants were administered bilateral tDCS stimulation with alternating electrode polarity in accordance with each experimental condition.

### Procedure

An a priori power analysis was conducted to determine the sample size for a repeated measures ANOVA with three measurements by using G\*Power 3.1. This revealed the need for a sample of at least 19 to attain a large effect size ( $f = 0.40$ ; cf. Ghanavati et al., 2019) and detect differences in creativity (95% power and a 5% level of significance; cf. Ghanavati et al., 2019). Thus, we recruited more than the required 19 participants to attain more reliable effects.

In this study, each participant completed three sessions (2 stimulation, 1 sham), separated by intervals of at least 48 hours and carried out at consistent times of the day. Before the experiment, participants came to the laboratory to familiarize themselves with the experimental tasks. Following instruction, participants completed the practice trials for the flanker task. The practice continued until performance stabilized (accuracy and RTs below 5% of the variation in the last task), as sufficiently fast (average RTs below 700 ms) and accurate (above 80% of correct responses). This standard has been previously used to stabilize task performance (Radel et al., 2015). Participants then completed practice trials for the RAT (3 items) and AUT (1 item, e.g., cup).



**Figure 1.** (a) Overall experimental design. (b) Eriksen flanker task paradigm. (c) AUT paradigm. (d) RAT paradigm. Each session started with a pre-flanker task, followed by a 22 min tDCS session (L-R+, L+R-, Sham; order counterbalanced). Participants then performed the AUT and RAT (in a counterbalanced fashion) before completing the post-flanker task. Delivery of tDCS was ended following the post-flanker task, then participants completed a subjective experiences questionnaire. Note: the Chinese characters “板”, “洞”, and “色” in (d) represent “board”, “hole”, and “color” in English.

The experiment began with a pre-flanker task, followed by tDCS (counterbalanced across participants). Participants completed the AUT and RAT (counterbalanced across participants) after 5 min of tDCS, since the cortical excitability changes from tDCS are typically observed only after 3–5 min of stimulation (Nitsche & Paulus, 2000). Then, the post-flanker task was administered during stimulation. After tDCS stimulation, participants completed the subjective experience questionnaire. (see Figure 1).

### Statistical analysis

All the data analyses were conducted using the statistical package SPSS for Windows, version 22 (IBM, SPSS, Inc., Chicago, IL). To estimate the effect of tDCS on performance in the AUT and RAT, a single factor repeated measures analysis of variance (ANOVA) was carried out on the dependent variables (i.e., fluency, flexibility, originality, and mean originality for the AUT; RTs and accuracy for the RAT), with stimulation type (L-R+, L-R-, sham) as within-subject factor. To estimate the effect of tDCS on the serial order effect, a two-factor repeated measures ANOVA was carried out on mean originality for the AUT, with stimulation type (L-R+, L-R-, sham) and time block (t1, t2, t3, t4) as within-subject factors. All results from the repeated-measures ANOVAs were Greenhouse–Geisser corrected if the sphericity assumption was violated. Post-hoc multiple comparisons were performed using Bonferroni-adjusted corrections. The alpha level was 0.017 (0.05/3) when the Bonferroni correction was applied. Additionally, to quantify evidence for the null hypothesis, Bayes factors were calculated (Wagenmakers et al., 2018). A Bayes factor of  $BF_{01} < 1$  indicates no evidence in support of  $H_0$ , a  $BF_{01}$  between 1 to 3 indicates anecdotal evidence, and a  $BF_{01}$  between 3 and 10 indicates moderate evidence (Wagenmakers et al., 2018).

## Results

### Effects of tDCS on AUT

Inter-rater reliability on the AUT was operationalized via intraclass correlations (ICCs) across the three raters. ICCs ranged from .69 to 1.00 for the creativity measures (fluency, flexibility, originality, and mean

originality). ICCs between .75 and 1.00 are considered “excellent” while ICCs between .60 and .74 are considered “good” (Cicchetti, 1994). Table 2 shows the descriptive statistics of the mean score of AUT fluency, flexibility, originality, mean originality as a function of stimulation type.

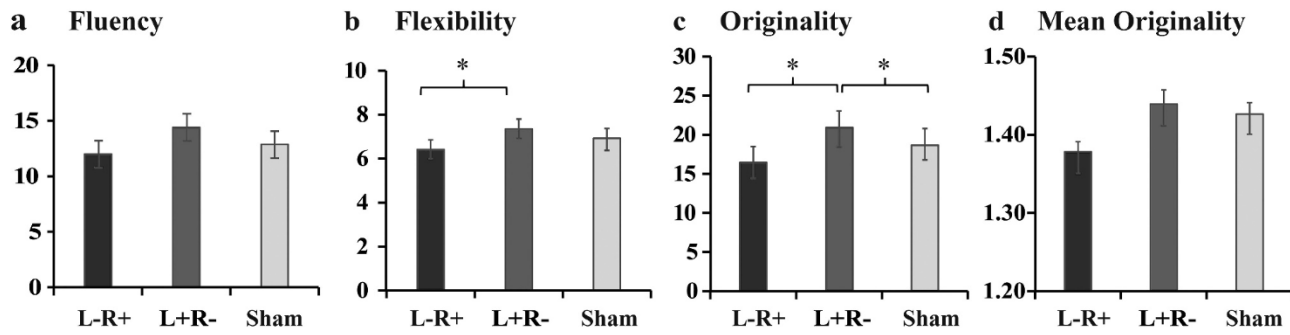
To assess the effects of tDCS over the DLPFC on creative performance, four repeated measures ANOVAs were conducted separately for AUT fluency, flexibility, originality, and mean originality, with stimulation type (L-R+, L-R-, sham) as a within-subjects factor. A main effect of stimulation type was found for AUT fluency,  $F(2, 50) = 4.83$ ,  $p = .018$ ,  $\eta_p^2 = .162$ , flexibility,  $F(2, 50) = 5.70$ ,  $p = .009$ ,  $\eta_p^2 = .186$ , originality,  $F(2, 50) = 5.00$ ,  $p = .019$ ,  $\eta_p^2 = .167$ , but not mean originality,  $F(2, 50) = .874$ ,  $p = .418$ ,  $\eta_p^2 = .034$ . Consistent with Hypotheses 1, pairwise comparisons revealed a significant enhancement effect in the L-R- condition compared to the sham condition, but only for originality ( $p = .038$ ,  $d = 0.25$ ). Additionally, there were significant differences between L-R- and L-R+ conditions on AUT flexibility ( $p = .028$ ,  $d = 0.43$ ) and originality ( $p = .049$ ,  $d = 0.25$ ) (Figure 2). However, no significant differences were found between the L-R+ and sham condition across all performance measures on the AUT ( $ps > .05$ ). Hypothesis 2, holding that L-R+ stimulation should lead to increased fluency compared to sham, was not supported by the present data.

The null effect of tDCS on AUT performance between the L-R- and sham conditions was calculated across fluency, flexibility, and mean originality via Bayes factors. The analysis revealed medium support for the null hypothesis for flexibility and mean originality, and weak support for fluency (Bayes Factors for  $H_{01}$ : flexibility = 3.89, mean originality = 7.723, fluency = 1.14). In other words, odds are at least 3:1 in favor of the null hypothesis being true for flexibility and mean originality, but the degree of support for the null hypothesis in terms of fluency is weaker.

The null effect of tDCS on AUT performances between the L-R+ and sham conditions was also calculated across all AUT dimensions via Bayes factors. The analysis revealed medium support of the null hypothesis for originality, mean originality, and fluency, and very weak support for flexibility (Bayes

**Table 2.** Mean scores of AUT fluency, flexibility, originality, mean originality, and mean reaction times (RTs) and accuracy on the RAT as a function of stimulation type (Mean  $\pm$  Standard deviation).

|      | AUT          |             |               |                  | RAT         |             |
|------|--------------|-------------|---------------|------------------|-------------|-------------|
|      | Fluency      | Flexibility | Originality   | Mean Originality | RTs (ms)    | Accuracy    |
| L-R+ | 12.00 (6.16) | 6.22 (2.06) | 17.06 (10.36) | 1.38 (.31)       | 4430 (2037) | 9.04 (2.16) |
| L-R- | 14.42 (6.33) | 7.35 (2.28) | 21.62 (11.70) | 1.44 (.24)       | 4988 (2674) | 8.35 (2.30) |
| Sham | 12.87 (6.20) | 6.98 (2.55) | 18.82 (10.25) | 1.42 (.24)       | 4352 (1906) | 9.23 (1.88) |



**Figure 2.** Performance on the AUT as a function of stimulation condition. (a) Fluency. (b) Flexibility. (c) Originality. (d) Mean originality as a function of stimulation type. Error bars represent the standard error. \*  $p < .05$ .

Factors for  $H_{01}$ : originality = 4.28; mean originality = 5.86, fluency = 3.88, flexibility = 0.83). Odds are at least 3: 1 in favor of the null hypothesis between the L-R+ and sham conditions for originality, mean originality, and fluency, but no evidence to support the null hypothesis was found for flexibility.

Thus, only the L+R- stimulation led to improved originality scores when compared to a sham condition. No other measure of AUT performance demonstrated a significant modulation due to brain stimulation. However, weak support for the null hypothesis in terms of fluency scores between the L+R- and sham conditions might reflect that a degree of improvement may have been present, albeit non-significant in the present analyses.

### Effects of tDCS on RAT

To assess effects of stimulation type on RAT performance, two repeated measures ANOVAs were conducted for RTs and accuracy separately, with stimulation type as the within subject factor. Table 2 shows the descriptive statistics for RTs and accuracy in the RAT as a function of stimulation type. Results showed that the main effect of stimulation was not significant for both accuracy ( $F(2, 50) = 1.63$ ,  $p = .207$ ,  $\eta_p^2 = .061$ ) and RTs ( $F(2, 50) = .96$ ,  $p = .381$ ,  $\eta_p^2 = .038$ ). Additionally, the null effect of tDCS on RAT performance between the L+R- and sham and between L-R+ and sham conditions was calculated via Bayes factors, revealing medium (Bayes factors for  $H_{01}$ : RTs, L-R+ vs. sham = 7.68; accuracy, L-R+ vs. sham = 7.97; L+R- vs. sham = 3.31) and close to medium ( $H_{01}$ : RTs, L+R- vs. sham = 2.64) support of the null hypothesis. Thus, we did not observe an enhancement of RAT performance, in terms of RTs and accuracy. The results of RAT in hypothesis 1 were not supported.

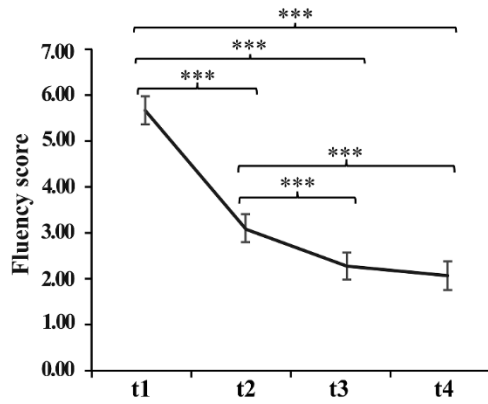
### Effect of tDCS on serial order effect

We next examined whether stimulation impacted the temporal dynamics of DT via the serial order effect. In line with previous approaches, participants with an average originality score of zero on two AUT items for either t3 or t4 were not included (Beatty & Silvia, 2012; Wang et al., 2017). This procedure ensured an optimal representation of the serial order effect. Overall, data from seven participants was excluded this way. Table 3 shows the temporal distribution of mean fluency and originality scores on the AUT as a function of stimulation type and time block.

We conducted three repeated measures ANOVAs, with stimulation type (L-R+, L+R-, sham) and time block (t1, t2, t3, t4) as within-subjects factors, separately for AUT fluency, originality, and mean originality. Results showed that, for fluency, a main effect of time block was found to be significant,  $F(3, 54) = 50.91$ ,  $p < .001$ ,  $\eta_p^2 = .739$  (Figure 3). More specifically, as time increased participants produced fewer responses, a finding consistent with past research (Beatty & Silvia, 2012; Wang et al., 2017). Regarding tDCS effects, for fluency, a main effect of stimulation type as well as an interaction effect between stimulation type and time block were not found,  $ps > .05$ . Brain stimulation therefore did not statistically affect the fluency trend between the three conditions. For originality, main effects were observed for

**Table 3.** Mean AUT scores of fluency, originality, and mean originality in the serial order effect as a function of stimulation type and time block (Mean  $\pm$  Standard deviation).

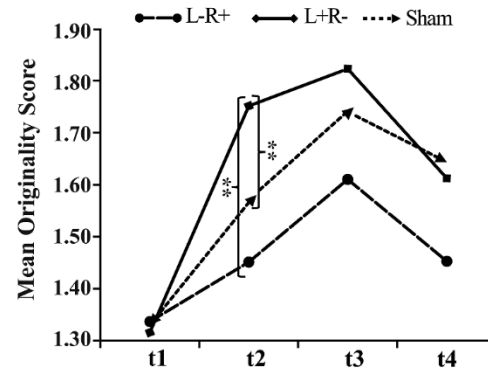
|                  |      | t1          | t2          | t3          | t4          |
|------------------|------|-------------|-------------|-------------|-------------|
| Fluency          | L-R+ | 5.32 (2.18) | 3.29 (1.56) | 2.79 (1.78) | 2.47 (1.87) |
|                  | L+R- | 6.46 (2.18) | 3.78 (1.93) | 3.08 (1.78) | 3.04 (1.66) |
|                  | Sham | 6.11 (2.65) | 3.32 (1.68) | 2.75 (1.49) | 2.66 (1.43) |
| Originality      | L-R+ | 7.14 (3.61) | 4.98 (2.97) | 4.32 (2.89) | 3.71 (3.05) |
|                  | L+R- | 8.68 (3.87) | 6.53 (3.32) | 5.45 (3.13) | 5.09 (3.37) |
|                  | Sham | 8.04 (4.30) | 5.37 (2.93) | 4.65 (2.44) | 4.38 (2.52) |
| Mean Originality | L-R+ | 1.34 (.37)  | 1.45 (.34)  | 1.61 (.37)  | 1.45 (.49)  |
|                  | L+R- | 1.32 (.30)  | 1.75 (.17)  | 1.80 (.20)  | 1.61 (.41)  |
|                  | Sham | 1.33 (.38)  | 1.57 (.20)  | 1.74 (.26)  | 1.64 (.35)  |



**Figure 3.** Fluency score as a function of time. Error bars represent the standard error. \*\*\* $p < .001$ .

stimulation type,  $F(2, 36) = 4.257$ ,  $p = .035$ ,  $\eta_p^2 = .191$ , and time,  $F(3, 54) = 18.808$ ,  $p < .001$ ,  $\eta_p^2 = .511$ . No interaction effect was found between stimulation type and time,  $F(6, 108) = .141$ ,  $p = .981$ ,  $\eta_p^2 = .008$ .

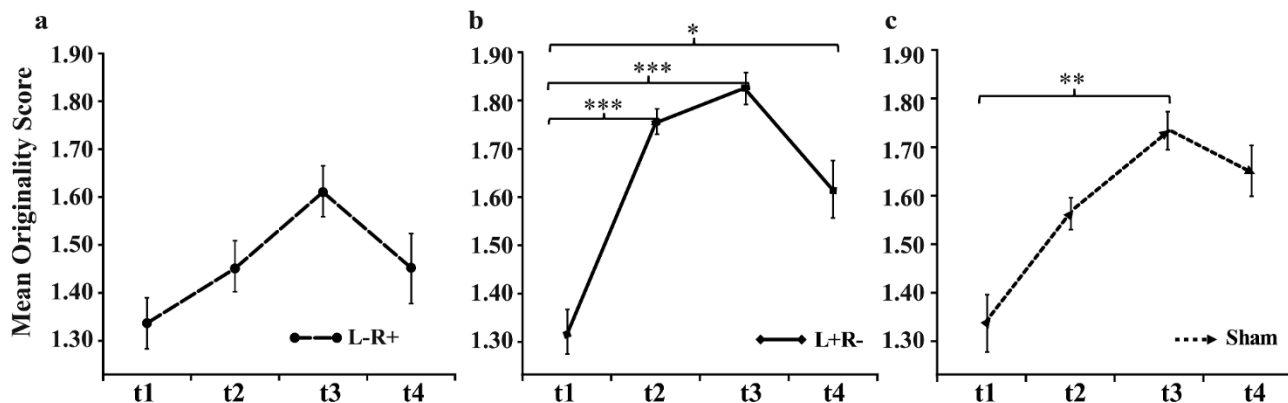
Importantly, originality decreased over time in all three stimulation conditions due to the confounding influence of fluency. After controlling for fluency, the main effect on mean originality scores was significant for both time block,  $F(3, 54) = 11.654$ ,  $p < .001$ ,  $\eta_p^2 = .393$ , and stimulation type,  $F(2, 36) = 4.629$ ,  $p = .023$ ,  $\eta_p^2 = .205$ . Replicating past work, participants produced more unique responses as time increased on a given trial (Beaty & Silvia, 2012; Hass, 2017; Wang et al., 2021). Mean originality scores in each of the last three time-blocks were all found to be significantly higher than those in the first time-block,  $ps < .05$ . Though the interaction effect was not significant,  $F(6, 108) = 1.316$ ,  $p = .274$ ,  $\eta_p^2 = .068$ , we conducted further analysis to understand potential effects of tDCS on serial order effect.



**Figure 5.** Mean originality score as a function of time and stimulation type. The results reflect the diminished effect of L-R+ stimulation over DLPFC on the serial order effect. \*\* $p < .01$ .

We thus conducted separate repeated measures ANOVAs for mean originality in each condition, with time as a within-subjects factor. The results showed that, for the L+R- condition, the mean originality scores at t2, t3, and t4 were higher than those at t1 ( $ps < .05$ , see Figure 4b). For the sham condition, the only significant difference was between t3 and t1, with the results favoring t3 ( $p = .002$ ,  $d = 1.27$ , see Figure 4c). However, in the L-R+ condition, no significant serial order effect was found in terms of mean originality scores ( $ps > .05$ ; see Figure 4a). Taken together, these results indicated that both the L+R- and sham condition corroborate the serial order effect in terms of mean originality scores. Consistent with Hypothesis 3, the serial order effect appeared earlier in the L+R- condition (i.e., t2) than in the sham condition (i.e., t3) and, interestingly, it extended to t3 and t4.

To assess whether specific stimulation montages can diminish the serial order effect, four repeated measures ANOVAs were run on mean originality scores across the



**Figure 4.** Mean originality score as a function of time block and stimulation type. The results reflect the diminished effect of L-R+ stimulation over DLPFC on the serial order effect. (a) L-R+ condition. (b) L+R- condition. (c) Sham condition. Error bars represent the standard error. \*\*\* $p < .001$ ; \*\* $p < .01$ ; \* $p < .05$ .

**Table 4.** Mean reaction times (RTs) and accuracy in the flanker task as a function of pre-/post-flanker, trial condition, and stimulation type (Mean  $\pm$  Standard deviation).

|              |      | RTs (ms)       |                |                     | Accuracy   |             |                     |
|--------------|------|----------------|----------------|---------------------|------------|-------------|---------------------|
|              |      | Congruent      | Incongruent    | Interference Effect | Congruent  | Incongruent | Interference Effect |
| Pre-flanker  | L-R+ | 490.44 (70.82) | 557.37 (75.24) | 66.93 (29.36)       | .99 (.01)  | .97 (.04)   | -.03 (.04)          |
|              | L-R- | 478.08 (47.50) | 549.33 (49.83) | 71.26 (24.24)       | 1.00 (.00) | .96 (.04)   | -.04 (.04)          |
|              | Sham | 484.95 (61.45) | 551.67 (65.83) | 66.71 (35.00)       | 1.00 (.01) | .96 (.04)   | -.04 (.04)          |
| Post-flanker | L-R+ | 489.82 (74.29) | 550.66 (63.22) | 60.84 (34.42)       | .99 (.01)  | .95 (.04)   | -.04 (.04)          |
|              | L-R- | 477.61 (54.08) | 532.67 (56.73) | 55.06 (25.26)       | .99 (.02)  | .94 (.04)   | -.04 (.04)          |
|              | Sham | 479.34 (62.30) | 547.52 (71.84) | 68.18 (36.36)       | .96 (.20)  | .91 (.19)   | -.04 (.04)          |

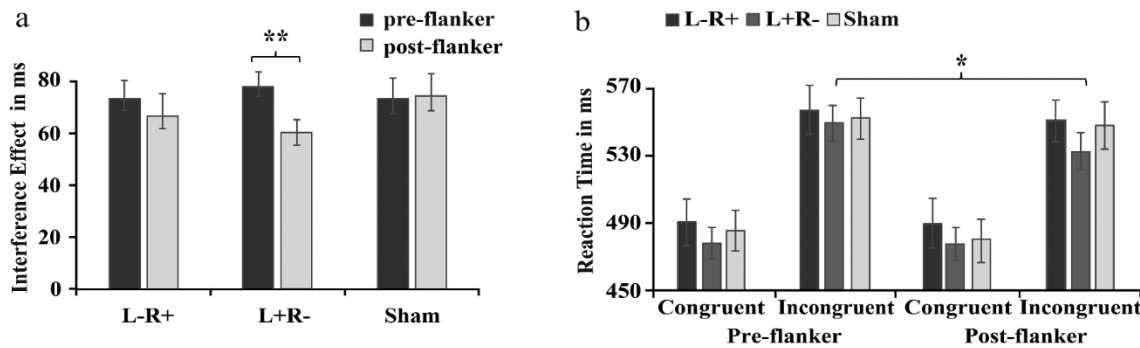
four time blocks separately, with stimulation type as a within-subjects factor. The analysis revealed a significant main effect of stimulation type on mean originality only in t2,  $F(2, 36) = 7.96$ ,  $p = .004$ ,  $\eta_p^2 = .307$ . As predicted by hypothesis 3, the L+R- stimulation enhanced mean originality. Specifically, the mean originality scores at t2 were significantly higher in the L+R- condition than in the L-R+ and sham conditions,  $ps < .01$  (see Figure 5).

### Flanker task results

Next, we assessed flanker performance as a function of stimulation condition to test whether cognitive inhibition may account for enhanced creative performance. All the participants' flanker task data ( $N = 26$ ) was used in the analysis. Before analyzing RTs, we removed several outlier data points, including responses that were too short (below 200 ms), too long (above 1200 ms), or that included errors (lost data .6%), as they may not reflect true reaction processes (Zmigrod et al., 2016). Table 4 shows the mean reaction times (RTs) and accuracy in terms of pre-/post-flanker task, trial condition, and stimulation condition. To test for changes in cognitive inhibition, we analyzed data for the interference effect, accounting for differences between congruent and incongruent conditions

Repeated measures ANOVAs were performed on the interference effect values, with stimulation type (L-R+, L-R-, sham) and time (pre-flanker, post-flanker) as within-subjects factors. Results exposed a significant main effect of time,  $F(1, 25) = 7.66$ ,  $p = .010$ ,  $\eta_p^2 = .235$ . Moreover, there was a significant interaction effect between stimulation type and time,  $F(2, 50) = 3.37$ ,  $p = .043$ ,  $\eta_p^2 = .119$ . Follow-up analyses further revealed that only in the L+R- condition was there a lower interference effect for the post-flanker compared to the pre-flanker task,  $p = .003$ ,  $d = -.654$  (Figure 6a). As predicted in hypothesis 1, these results are suggestive that L+R-stimulation enhanced cognitive inhibition. Hypothesis 2, holding that L-R+ stimulation will decrease cognitive inhibition, was not supported.

We then assessed the effect of congruency in flanker performance. Two repeated measures ANOVAs were separately run for RTs and accuracy, with congruency, stimulation type, and time as the within-subjects factors. A main effect of congruency was observed on both RTs and accuracy,  $F(1, 25) = 178.178$ ,  $p < .001$ ,  $\eta_p^2 = .877$ ;  $F(1, 25) = 47.61$ ,  $p < .001$ ,  $\eta_p^2 = .656$ . Crucially, we found a significant interaction effect between congruency, time, and stimulation type on the RT measures,  $F(2, 50) = 3.37$ ,  $p = .043$ ,  $\eta_p^2 = .119$ . Only the L+R- condition showed a significant interaction effect with congruency

**Figure 6.** The results of Flanker task. (a) Interference effect as a function of stimulation type and pre/post-flanker. (b) Response time as a function of stimulation type, congruency, and pre/post-flanker. Error bars represent the standard error. \*\* =  $p < .01$ , \* =  $p < .05$ .

and time,  $F(1, 25) = 10.45$ ,  $p = .003$ ,  $\eta_p^2 = .295$ . Specifically, RTs on post-flanker tasks were shorter than RTs on pre-flanker for incongruent trials,  $p = .022$ ,  $d = -.31$  (Figure 6b). No other significant effects were found, indicating that the improvement in cognitive inhibition was specific to the L+R- condition.

### Mediation analysis

We further used the lavaan package in R (3.6.1) for multilevel analysis to examine the mediation effect of cognitive inhibition on the relationship between stimulation type and originality. Standard errors were computed based on the MLR approach. All the participants' data ( $N = 26$ ) was used in the analysis.

We used the change scores, calculated as the pre-measured interference effect minus the post-measured interference effect, to represent the change in cognitive inhibition (deltaE in Table 5). To avoid any possible confounding results caused by using different scales for each individual measurement, all variables were standardized. The results were consistent with that of the variance analysis. Compared with the sham group, L+R- stimulation enhanced cognitive inhibition ( $p = .006$ ) and originality ( $p = .017$ ), though the correlation between cognitive inhibition and originality was not significant ( $p = .136$ ).

### Control analyses: tDCS experience, creativity task order, and practice effects

To check for a potential confounding influence subjective experience of undergoing a tDCS procedure (e.g., discomfort), several repeated measures ANOVAs were conducted for the feelings score, with stimulation type (L-R+, L+R-, sham) as a within-subjects factor. Importantly, we found no effect of tDCS condition on subjective experience,  $F(2, 50) = .176$ ,  $p = .787$ ,  $\eta_p^2 = .007$ , suggesting that the experience of tDCS did not adversely impact the present data.

Additionally, to test for an order effect in the task presentation, six repeated measures ANOVAs were run with stimulation type (L-R+, L+R-, sham) as the within-subjects factor and task order (AUT-RAT/RAT-AUT) as the between-subjects factor. ANOVAs were run for AUT fluency, flexibility, originality, and mean originality, as well as RAT accuracy, and RTs. No significant interaction or main effect was observed for any of the dependent variables,  $ps > .05$ . Thus, task order did not noticeably influence the effect of tDCS stimulation type on task performance.

Finally, we tested for a potential practice effect by conducting six repeated measures ANOVAs with stimulation type (L-R+, L+R-, sham) and task session (first session, second session, and third session) as within-subjects factors. AUT fluency, flexibility, originality, and mean originality, in addition to RAT accuracy and RTs, were dependent variables. No significant

**Table 5.** Mediation analyses of cognitive inhibition between stimulation type and originality.

|                     | Estimate | Std.Err | z-value | P(> z ) | Std.lv | Std.all |
|---------------------|----------|---------|---------|---------|--------|---------|
| Level 1 [Within]:   |          |         |         |         |        |         |
| Regressions:        |          |         |         |         |        |         |
| z_deltaE ~          |          |         |         |         |        |         |
| L-R+                | 0.307    | 0.263   | 1.167   | 0.243   | 0.307  | 0.146   |
| L+R-                | 0.718    | 0.263   | 2.726   | 0.006   | 0.718  | 0.341   |
| z_Originality ~     |          |         |         |         |        |         |
| L-R+                | -0.133   | 0.130   | -1.020  | 0.308   | -0.133 | -0.124  |
| L+R-                | 0.328    | 0.137   | 2.394   | 0.017   | 0.328  | 0.306   |
| z_deltaE            | -0.096   | 0.065   | -1.491  | 0.136   | -0.096 | -0.190  |
| Intercepts:         |          |         |         |         |        |         |
| z_deltaE            | -0.342   | 0.186   | -1.836  | 0.066   | -0.342 | -0.344  |
| z_Originality       | 0.000    |         |         |         | 0.000  | 0.000   |
| Variances:          |          |         |         |         |        |         |
| z_deltaE            | 0.901    | 0.144   | 6.245   | 0.000   | 0.901  | 0.912   |
| z_Originality       | 0.216    | 0.042   | 5.098   | 0.000   | 0.216  | 0.849   |
| Level 2 [Between]:  |          |         |         |         |        |         |
| Intercepts:         |          |         |         |         |        |         |
| z_Originality       | -0.065   | 0.193   | -0.336  | 0.737   | -0.065 | -0.075  |
| Variances:          |          |         |         |         |        |         |
| z_Originality       | 0.740    | 0.226   | 3.279   | 0.001   | 0.740  | 1.000   |
| Defined Parameters: |          |         |         |         |        |         |
| IND <sub>L-R+</sub> | -0.030   | 0.032   | -0.919  | 0.358   | -0.030 | -0.028  |
| IND <sub>L+R-</sub> | -0.069   | 0.053   | -1.308  | 0.191   | -0.069 | -0.065  |

Note: Std.lv = standardization of latent variables; Std.all = standardization of all variables; deltaE = Z (pre-measured interference effect)-Z (post-measured interference effect); z\_deltaE = Z score of deltaE; z\_Originality = Z score of originality of creativity; IND<sub>L-R+</sub> = Indirect effect of condition L-R+; IND<sub>L+R-</sub> = Indirect effect of condition L+R-.

interaction or main effect was observed for any of the dependent variables,  $ps > .05$ . These results indicate that session order did not significantly influence the effect of tDCS stimulation on task performance.

## Discussion

This study had three aims: 1) to retest the effect of tDCS on CT and DT, 2) to examine how brain stimulation impacts the temporal dynamics of creative performance, and 3) to assess the cognitive mechanisms underlying enhanced creative thinking (e.g., cognitive inhibition). Using a within-subjects design – with two stimulation conditions and a sham condition administered to each participant – we found a tDCS-induced enhancement of idea originality in DT. This last finding is partly consistent with hypothesis 1, predicting that AUT originality would be enhanced under L+R- stimulation. In addition to corroborating some (but not all) prior findings with this stimulation montage (Colombo et al., 2015; Xiang et al., 2021), we show that DLPFC stimulation affects temporal trends of idea production (i.e., the serial order effect). Consistent with our hypothesis 3, L+R- stimulation to the DLPFC resulted in a diminished serial order effect, evidenced by more original ideas being produced earlier during DT. Critically, though we did not provide direct evidence of a mediation effect of cognitive inhibition between stimulation and originality, we show that this tDCS-enhancement effect was accompanied by decreased cognitive inhibition. Our study thus provides a first clue toward identifying a possible causal role of executive processes in driving the effects of frontal lobe neuromodulation on DT.

### Effects of tDCS on the AUT

We observed a tDCS-induced improvement in the originality of responses in the AUT, partly replicating recent work by Xiang et al. (2021). A stimulation procedure which is identical to that adopted in the present research was shown to enhance fluency, flexibility, and originality. These results are also consistent with two other studies, where enhanced response novelty was found following unilateral anodal stimulation over the left DLPFC (Colombo et al., 2015; Huang et al., 2021). Recent studies also revealed that transcranial random noise stimulation (tRNS) – a technique similarly believed to increase neuronal excitability – over the left DLPFC resulted in

enhanced performance on verbal AUT (Peña, Sampedro, Ibarretxe-Bilbao, Zubiaurre-Elorza, & Ojeda, 2019). Additionally, left anodal stimulation has also been evidenced to contribute to other creative thinking processes. For example, left anodal tDCS over the frontopolar cortex has been found to enhance association breadth when responding to words cueing for narrow semantic associations, but only in individuals with a high creative potential (Brunye et al., 2015). Further, the ability to formulate creative analogies was facilitated when presenting a cue to “think creatively” and administering anodal HD-tDCS over the left frontal pole (Green et al., 2017).

We did not find evidence for enhanced fluency by L-R+ stimulation over the DLPFC as hypothesized; but rather observed a trend of decreasing fluency and originality (Figure 2), albeit non-significant. This result is incongruent with previous studies that found enhanced fluency with L-R+ stimulation (e.g., Hertenstein et al., 2019; Khalil et al., 2020; Mayseless & Shamay-Tsoory, 2015). This might be due to the different stimulation site that was chosen in the present study (DLPFC but not IFG; cf. Table 1). We suppose that the trend of decreasing fluency and originality might be explained when considering a sliding-scale perspective of tDCS. In such terms, it is thought that while anodal stimulation will boost cortical excitability, cathodal stimulation will reduce it (Nitsche & Paulus, 2000). It would then follow that the opposite montage would have contrasting effects when keeping constant all other properties of the stimulation.

Previous findings point to brain region-specific and polarity-specific differences as important factors determining the relationship between neuromodulation and DT performance. When considering past tDCS studies of creative thinking (Table 1), a majority of them indicate that anodal tDCS over the left DLPFC (Colombo et al., 2015; Ghanavati et al., 2019; Green et al., 2017) or L+R- tDCS over the bilateral DLPFC (Xiang et al., 2021) are likely to enhance originality and fluency. This general agreement between sources seems indicative that the left DLPFC plays a critical role in driving originality and fluency during DT. However, unilateral left cathodal or L-R+ tDCS over the IFG seems to also have the potential of improving AUT fluency (Chrysikou et al., 2013; Ivancovsky et al., 2019; Mayseless & Shamay-Tsoory, 2015), suggesting that the left IFG may also play a role in modulating fluency. Given that the DLPFC relates to both associative abilities and cognitive control (Green et al., 2017; Kim et al., 2014), anodal stimulation may

jointly facilitate the generation of semantic associations and the selection of more original ideas, leading to enhancements of both fluency and originality. On the other hand, the IFG has been implicated in associative thinking, such as in the comprehension of novel verbal expressions (i.e., metaphor; Mashal, Faust, Hendler, & Jung-Beeman, 2007) and engagement in creative writing (Shah et al., 2013). Cathodal stimulation over the left IFG might thus have a “releasing” effect on guided memory searches, benefitting fluency but not originality scores, which depend on the retrieval of distant associations.

The present results, together with past evidence, suggest that enhanced creative performance resulting from active stimulation over the DLPFC may be due to a strengthening of cognitive inhibition during idea production. Improved inhibitory control during DT may allow participants to be more effective at suppressing inappropriate or more obvious ideas, redirecting search processes toward task-relevant goals, and ultimately selecting optimal responses at a faster rate (Beaty et al., 2016; Beaty & Silvia, 2012; Beaty, Silvia, Nusbaum, Jauk, & Benedek, 2014). This explanation is also partly supported by the decreased interference effect in the flanker task when considering the same L+R- tDCS condition (as predicted in hypothesis 1).

### ***Effects of tDCS on the RAT***

We did not observe a significant facilitative effect of tDCS stimulation on RAT performance. This is in contrast with the idea that tDCS over the DLPFC may affect the shared cognitive processes between the AUT and RAT (i.e., idea selection and goal-directed memory search). Most of the past literature on CT involves the adoption of unilateral tDCS stimulation over the DLPFC (Cerruti & Schlaug, 2009; Metuki et al., 2012; Pope et al., 2015), whereas our study used bilateral stimulation. As such, it is plausible that unilateral DLPFC stimulation may be uniquely superior at facilitating CT. Another possibility is that the effect may largely be dependent on problem difficulty, with some studies reporting tDCS-enhanced performance on the RAT and math tasks only on difficult items (Cerruti & Schlaug, 2009; Metuki et al., 2012; Pope et al., 2015). In the present experiment, any facilitatory neuromodulation effects may have been masked as we only used items with medium difficulty. We nevertheless conclude that the specific montages used in the present study, targeting the bilateral DLPFC, as well as the medium difficulty of

items, do not appear to be beneficial for RAT performance, at least when compared to prior work targeting unilateral stimulation of DLPFC.

### ***Effects of tDCS on the serial order effect***

A major goal of the present study was to explore the effects of tDCS on the serial order effect that is commonly observed during creative task performance (Acar et al., 2019; Bai, Leseman, et al., 2021; Beaty et al., 2019; Beaty & Silvia, 2012; Christensen et al., 1957). Investigating the temporal dynamics of cognitive performance may help us gather a deeper understanding of the subtle differences in behavior occurring as a result of tDCS. We predicted (Hypothesis 3) that L+R- tDCS would diminish the strength of the serial order effect. In line with this, we found that only the L+R- stimulation accelerated the production of original ideas (i.e., original ideas occurred earlier) as well as enhanced originality compared to the sham condition, but only at the second minute mark. More importantly, only in this condition did the mean originality scores in the later 3 time blocks continue to be significantly higher than those in the first time block. This improved quality (mean originality) of ideas is conceivably due to an increase in inhibitory resources being made available in this condition, as indexed by the reduced interference effect on the flanker task. These results provide an important extension of past work by linking DLPFC stimulation to the executive control processes underpinning DT, and more specifically to the serial order effect (Beaty et al., 2019; Cheng et al., 2016; Wang et al., 2017).

Research from the broader domain of language production may provide some insight for understanding this attenuation of the serial order effect. Anodal tDCS over the left DLPFC has been demonstrated to improve language production in picture naming tasks, in both healthy (Fertonani, Rosini, Cotelli, Rossini, & Miniussi, 2010; Wirth et al., 2011) and aphasic patients (Baker, Rorden, & Fridriksson, 2010). For instance, Wirth et al. (2011) found that anodal tDCS over the left DLPFC could decrease the semantic interference (SI) effect, leading to faster RTs for linguistic output. The SI effect refers to an increase in the naming latencies of target objects presented simultaneously with a distractor stimulus that shares a semantic relation with the target. As such, presenting a related target-distractor pair (e.g., a target “dog” and distractor “cat”) will tend to result in increased naming latencies than when presenting unrelated pairs (e.g., a target “dog” and distractor “car”). Under the activation by competition hypothesis, it is thought that such an increase naming latency reflects an increase in the cognitive resources

required to resolve an underlying competitive state arising from the spreading activation between related semantic concepts (e.g., Roelofs, 1992).

Therefore, it is possible that findings in Wirth et al. (2011) – where anodal tDCS over the left DLPFC decreased the SI effect – reflect a strengthening of cognitive resources devoted to inhibiting the interfering semantic representations, leading to a faster retrieval of the target. Metzuyanim-Gorlick and Mashal (2016) similarly found that after six sessions of L+R- stimulation (as in the present study), performance on the Hayling task was facilitated. In this task, participants were required to complete sentences with a missing last word by verbalizing either the correct word, testing linguistic skills, or an incorrect word, testing cognitive inhibition abilities. Facilitation was restricted to the suppression condition, indicating that the stimulation is specifically influencing inhibitory resources. The authors therefore suggested that the DLPFC might have a special role in both response selection and the suppression of irrelevant semantic information (Metzuyanim-Gorlick & Mashal, 2016).

Accordingly, modulations of the serial order effect in our study may be due to the increased inhibition of common ideas resulting from enhancements of executive faculties. This process would in turn facilitate the selection of remote and novel ideas via a favored access to weaker semantic associations. This processing advantage seems to distinctively arise from anodal tDCS over the left DLPFC, an important hub responsible for general executive functions and semantic processing more specifically (Green et al., 2017; Kim et al., 2014). Semantic information processing (i.e., controlled retrieval and selection of remote information; Jefferies, 2013) and verbal creativity tasks (Chen et al., 2019; Zhang, Sjoerds, & Hommel, 2020) were found to be closely related to the engagement of the left hemisphere. Thus, when interpreted through the broader literature concerning language production, our findings on the serial order effect would seem to indicate that left DLPFC stimulation is driving a more efficient inhibition of unoriginal semantic knowledge during the early stages of idea generation.

### **Limitations and future directions**

Despite the promising results found in this study, some limitations warrant mentioning. First, the small sample size might limit the generalizability of the findings, which may also explain the lack of significant interactions or correlations for some analyses (e.g., serial order

and stimulation; the correlation between originality and cognitive inhibition). Further research is therefore required to replicate the findings with a larger sample size. Second, the bilateral stimulation adopted in the present study might have increased the balance between right hemispheric and left hemispheric activations. Consequently, the more prominent cortical hemisphere could not be identified, calling for further research to inquire further into the underlying neural dynamics. Additionally, we must advise that any comparisons with other studies adopting unilateral stimulation must be drawn with caution, as previous meta-analyses and review articles (Horvath, Carter, & Forte, 2014; Jacobson, Koslowsky, & Lavidor, 2012; Tremblay et al., 2014; Weinberger et al., 2017) revealed that the effects of tDCS were dependent on its associated parameters, such as electrode position and size (Bikson, Datta, Rahman, & Scaturro, 2010), stimulation polarity (Jacobson et al., 2012), intensity (Batsikadze, Moliadze, Paulus, Kuo, & Nitsche, 2013), duration of stimulation (Nitsche & Paulus, 2001), as well as online versus offline stimulation (Steinberg et al., 2019). Thus, future efforts are encouraged to follow more comprehensive and systematic approaches to test what kind of experimental designs enhance any specific measure adopted to assess creative performance. Finally, to have a better understanding of the neural mechanisms that underlie the effects of tDCS on creative performance, it is crucial that future studies combine electrical stimulation with neuroimaging methods, such as EEG, fNIRS, or fMRI.

### **Conclusion**

Using a within-subjects design, the present study corroborates findings that bilateral stimulation of left anodal and right cathodal tDCS over the DLPFC is beneficial to DT, specifically in terms of boosting the originality of responses. This study also extends our understanding of the role played by the DLPFC in defining the temporal dynamics of creative task performance. We show that online L+R- stimulation over the DLPFC had a selective impact on idea quality and led to a reduction of the serial order effect – one of the more robust findings in the DT literature – by accelerating the production of more original ideas in an AUT. More importantly, though our findings did not provide direct evidence that enhanced cognitive inhibition interacts with the effect of brain stimulation on idea originality, we found enhanced cognitive inhibition abilities were generally accompanied by tDCS-enhancements of idea originality. This finding provides tentative clues that inhibition may play a role

in DT, helping to elucidate the cognitive processes underlying enhancements in DT performance by neuromodulation. We encourage future research to combine electrical stimulation with neuroimaging methods to further characterize the neural mechanisms underlying tDCS effects on creative cognition.

## Disclosure statement

No potential conflict of interest was reported by the author(s).

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