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Stimulating Creativity: Modulation of Convergent and Divergent Thinking by Transcranial Direct Current Stimulation (tDCS)

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Creativity has been conceptualized as involving 2 distinct components; divergent thinking, the search for multiple solutions to a single problem, and convergent thinking, the quest for a single solution either through an analytical process or the experience of insight. Studies have demonstrated that these abilities can be improved by cognitive stimulation, mood, and meditation. This investigation examined whether convergent and divergent thinking can be enhanced by noninvasive transcranial direct current stimulation (tDCS). In different sessions, participants received bilateral stimulation over the dorsolateral prefrontal cortex—DLPFC (Experiment1) and over the posterior parietal cortex–PPC (Experiment2), while performing the Compound Remote Associative task (CRA) assessing convergent thinking and the Alternative Uses Task (AUT) assessing divergent thinking. In Experiment1, anodal-left cathodal-right stimulation over the DLPFC significantly enhanced CRA performance. In Experiment2, stimulations over the PPC significantly increased insight solutions and decreased analytical solutions compared to the no stimulation condition. These findings provide direct evidence for the role of the left DLPFC in convergent and divergent thinking and a mediating role of the PPC in problem-solving behavior, presumably through attentional processes. From a methodological perspective, brain stimulation can be used as a tool to modulate and to explore components of creativity.

Thinking creatively is perhaps one of the most elusive of human abilities. A creative idea can be easily recognized when it enters conscious thought, yet creating with intention and describing how the idea came about is often an extremely challenging, if not impossible, task. Ideas often seem to come out of the blue. In general, creativity can be considered as the formation of novel, original, and high-quality ideas that are also useful and adaptive (Runco, 2014; Runco & Jaeger, 2012; Stein, 1953; Sternberg & Lubart, 1999). However, attempts to explore the mechanism underlying creativity have led researchers to try to unpack this complex concept into more defined and testable components. One of the most influential proposals for breaking down the components of creativity has been to distinguish between convergent and divergent thinking (Guilford, 1967). Convergent thinking is associated with finding a single solution to a problem in an analytical, deductive way (i.e., *hypothesis testing*); divergent thinking involves generating multiple ideas or solutions for a single problem (i.e., *brainstorming*).

Investigating these two components of creativity has given rise to the design of two distinct assessments. A well-established paradigm to examine convergent thinking is Mednick's (1962) Remote Associates Task (RAT) which was later extended to the Compound Remote Associates task (CRA) by Bowden and Jung-Beeman (2003). In this task, each item consists of three unrelated

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words (such as *boot, summer, ground*), where each word can form a compound word or phrase with the fourth, sought-for word (e.g., *camp*). Solving these problems can be misleading, because often many potential solutions can be associated with some, but not all, of the words. Conversely, the domain of divergent thinking involves finding multiple solutions to a single, only loosely-formulated problem. To assess this kind of process, Guilford (1957) developed the Alternate Uses Task (AUT), where participants are asked to list as many different uses of everyday items, such as *brick* or *towel*, as they can. Performance in this task can be measured by means of three scores: flexibility, fluency, and elaboration. Recent studies have shown that there is no correlation between the performance in CRA and AUT tasks (Akbari Chermahini & Hommel, 2010) and some factors (like open-monitoring meditation practice) affect performance in the two tasks differently (Colzato, Ozturk, & Hommel, 2012), thus supporting the idea that the CRA and AUT assess orthogonal components of creativity.

That said, Bowden (1997) provided evidence that participants do not always solve the CRA problems in terms of systematic hypothesis-testing but some of the problems seem to be solved by sudden insight (a *eureka* or *aha* experience). A century ago, Gestalt psychologists already began the discussion about the distinction between solving a problem analytically, through some form of induction and deductive reasoning, and the more intuitive insight approach (Kohler, 1925). These two problem-solving strategies appear to differ in several ways. From a phenomenological perspective, the analytical approach is a gradual process that can be explicitly reported by the solver, but the insight solution seems to appear suddenly, usually after an impasse (Bowden, 1997). In the CRA task, participants can find a solution to a problem either by trial-and-error analysis or by insight (aha moment), and are capable of reliably reporting on their subjective feeling about the strategy they employed for each item (Bowden, Jung-Beeman, Fleck, & Kounios, 2005). Neuroimaging studies have provided evidence that solving a problem with insight differs in terms of neural and cognitive processes from a noninsight approach. This observation raises the possibility that the CRA taps into more than one distinct component of creativity (Jung-Beeman et al., 2004; Kounios & Beeman, 2009). One can speculate that the insight problem-solving strategy shares some of the attributes of divergent thinking, where implicit associations are generated and only the best solution pops up into one's conscious awareness.

Recent research efforts into creativity have generated a number of techniques that have been shown to alter various creativity components, such as cognitive stimulation (Fink et al., 2010), mood manipulation (Isen, Daubman, & Nowicki, 1987), food supplement such as Tyrosine (Colzato, de Haan, & Hommel, in press), and open-monitoring meditation (Colzato et al., 2012). An additional technique that has gained popularity in recent years is transcranial direct current stimulation (tDCS), which has been successfully utilized as a tool to explore and modulate cognitive processes with patients and healthy participants (Kadosh, 2013; Priori, 2003; Zmigrod, 2014). This technique applies low-amplitude direct currents in a specific area of the skull, and is thought to modify the transmembrane neural potential of the underlying brain regions, thus affecting the level of excitability in a polarity-dependent fashion. Anodal stimulation is believed to increase excitability in the targeted brain region while cathodal stimulation reduces excitability (Nitsche et al., 2003; Priori, 2003).

Recently, two studies using tDCS have examined whether the performance of the CRA task can be enhanced. Using a unilateral montage, Cerruti and Schlaug (2009) found that anodal stimulation over the left dorsolateral prefrontal cortex (DLPFC) enhances performance of the CRA task compared to cathodal or sham stimulation of the same region, as well as compared to anodal stimulation over the right DLPFC. However, Metuki, Sela, and Lavidor (2012) failed to replicate these findings, but were able to enhance solution recognition during anodal stimulation over the left prefrontal cortex for the harder CRA problems—an effect that was modulated by trait motivation. Although these studies provide evidence for a role of the left prefrontal cortex in processing CRA problems, the mixed results and lack of information regarding the analytical and insight-led problem-solving strategy behavior leave open questions regarding the underlying processes of creative thinking.

The overarching aim of this study was to investigate the impact of noninvasive brain stimulation in relevant cortical areas on convergent and divergent thinking. Previous studies have provided evidence that CRA solutions can be enhanced with anodal stimulation over the left DLPFC using a unilateral montage (Cerruti & Schlaug, 2009; Metuki et al., 2012). However, given the success of the bilateral montage technique in modulating various cognitive functions such as memory recognition (Jacobson, Goren, Lavidor, & Levy, 2012), semantic processing (Sela, Ivry, & Lavidor, 2012), and insight of nonverbal problems (Chi & Snyder, 2011, 2012), it was reasonable to conducting a bilateral montage, rather than a unilateral one, to replicate the findings for convergent thinking and extend it for divergent thinking. Hence, the first goal was to employ this tDCS method to explore the effects of stimulation over the DLPFC and PPC, two brain regions that have been linked to creativity (Kowatari et al., 2009; Shamay-Tsoory, Adler, Aharon-Peretz, Perry, & Mayseless, 2011). In addition, an extended line of research distinguishes between problem-solving strategies in the CRA task as either analytically or insight-led, with evidence that these two solving behaviors involve different neural networks (Jung-Beeman et al., 2004; Kounios & Beeman, 2009). Nevertheless, this has never been experimentally investigated via means of brain stimulation techniques (for review see Kounios & Beeman, 2014). Thus, the second goal was to explore the effect of tDCS over the DLPFC and PPC on these problem-solving strategies.

METHODS

Participants

In total, 28 native Dutch Leiden University students (five men; M age = 20 years; age range = 18–25 years) took part in the study for course credits or a financial reward. The participants were recruited separately for the two experiments and were naïve to the experimental procedure and purpose of the study. In the first experiment, the stimulation region was the DLPFC, (n = 14), and in the second experiment the stimulation region was the PPC (n = 14). All participants were right handed as assessed by the Edinburgh Inventory (Oldfield, 1971) with normal or corrected-to-normal vision. Exclusion criteria included: history of psychiatric disorders, drug abuse, active medication, pregnancy, or susceptibility to seizures. Participants gave their written informed consent to participate in the study.

Experimental Design

The study comprised of two separate randomized experiments on healthy volunteers: in Experiment 1, participants received tDCS stimulation over the DLPFC and in Experiment 2, participants received stimulation over the PPC. The experiments followed a within-subject design. Each participant underwent three sessions: two sessions with tDCS stimulation, anodal stimulation over the left hemisphere and cathodal stimulation over the right hemisphere (AL-CR) and the other with anodal stimulation over the right hemisphere and cathodal stimulation over the left hemisphere (AR-CL). In addition, each participant also underwent a control session without stimulation, i.e., the participant was not connected to any electrodes or any brain stimulation apparatus. The order of the sessions was counterbalanced across participants. To minimize carryover effects of brain stimulation, the interval between the tDCS sessions was at least 48 hr. The study conformed to the ethical standards of the declaration of Helsinki and was approved by the Ethical Committee of Leiden University.

Materials

CRA

A Dutch version of the CRA was adopted from Akbari Chermahini, Hickendorff, and Hommel (2012). In this task, each problem is consisted with three unrelated words, and participants are asked to find a common associate as a solution (e.g., *crab, pine, sauce* → *apple*). The Dutch version compromises of 30 problems (Cronbach's alpha = 0.85; 9). In addition, the participants were asked to indicate whether the solution was resulted from a more analytical approach or whether the solution had suddenly come to mind (aha moment, see 16). The task was divided into three different sets of problems (10 problems, in 5 min) similarly to Colzato et al. (2012).

AUT

In this task, a common household item was presented, and the participants were asked to list as many possible uses for this item in 2 min, adopted from Colzato et al. (2012). The items that were selected were brick, shoe, newspaper, pen, towel, and bottle. In each session, two different items were presented to the participants. The results were scored on three dimensions, flexibility (number of different categories of the responses), fluency (total number of relevant responses), and elaboration (the amount of details in the responses).

Procedure

The experimental sessions begun with tDCS stimulation (stimulation over the DLPFC in Experiment 1 or over the PPC in Experiment 2) and the session type (AL-CR or AR-CL). After the task was well understood and the tDCS was on for at least 5 min, the participants perform a mini version of the CRA task (a set of 10 problems in 5 min), and AUT task (two words each 2 min). In the control session, participants completed the tasks without being stimulated. The mini versions of the tasks were counterbalanced between sessions and participants.

Transcranial Direct Current Stimulation

tDCS was delivered by means of a DC Brain Stimulator Plus (NeuroConn, Ilmenau, Germany) and was applied through a saline-soaked pair of surface sponge electrodes (5 × 7 cm). The electrodes were placed over F3 and F4 (DLPFC) in the experiment 1 and on P3 and P4 (PPC) in experiment 2, according to the international 10–20 system for EEG electrode placement. The polarity of the electrode was depended on the session. The stimulation lasted 20 minutes with a constant current of 2 mA and with a 15-second fade-in and fadeout.

RESULTS

All participants completed the sessions without major complains or discomfort as measured by the tDCS Adverse Effects Questionnaire (Brunoni et al., 2011). Results from one participant in the CRA task were excluded due to an error in the procedure. The measurements from the two tasks were extracted per participant for each session. For the CRA task, the number of correct items and the number of insight solutions was calculated from the correct answers. A repeated measures ANOVAs were performed on each of the measurements with stimulation type (AL-CR, AR-CL, no-stimulation) as a within-subject factor. For the AUT task, fluency, flexibility and elaboration were scored by two independents judges. Again, a repeated measures ANOVAs were performed on the type of AUT measures with stimulation type (AL-CR, AR-CL, no-stimulation) as a within-subject factor.

Experiment 1: Stimulation Over the DLPFC

Convergent Thinking

The two measures from the CRA task were analyzed using repeated measures ANOVAs with stimulation type (AL-CR, AR-CL, no stimulation) as a within-subject factor. There was a significant main effect on correct responses, $F(2,24) = 6.77$, $p < .005$, $\eta_p^2 = .361$. Post hoc multiple comparison tests showed significantly better performance with AL-CR stimulation than with AR-CL stimulation ($p = .017$) and without stimulation ($p = .001$). In addition, numerically more insight solutions were produced under AL-CR stimulation (see Figure 1), but this effect did not reach the significance level, $F(2,24) = 2.93$, $p = .073$, $\eta_p^2 = .191$. The finding that AL-CR stimulation increases generating solutions to CRA problems is in line with Cerruti and Schlang (2009), who showed that anodal stimulation over the left DLPFC improves performance on the remote associates test.

TABLE 1
AUT scores in Experiment 1, stimulation over the DLPFC

AUT	*AL-CR*	*AR-CL*	*No Stimulation*
Fluency	16.57	14.79	15.64
Flexibility	16.57	13.57	14.07
Elaboration	18.00	15.57	15.64

Divergent Thinking

The three AUT scores were analyzed by means of repeated measures ANOVAs with stimulation type (AL-CR, AR-CL, no stimulation) as a within-subject factor. Although AL-CR stimulations produce numerically higher scores (Table 1), this effect did not reach the significance level in any of the analyses (see Figure 2).

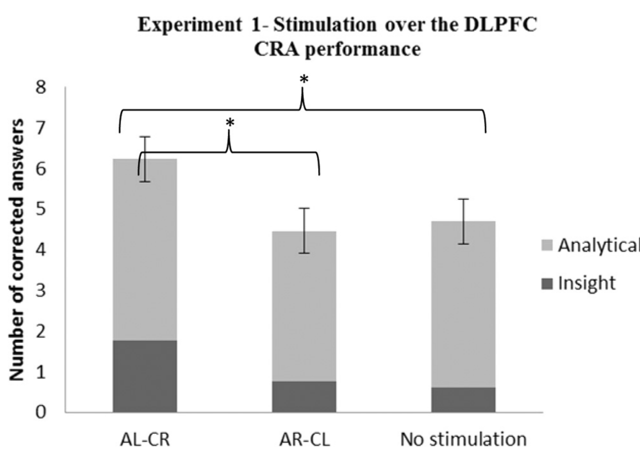

FIGURE 1 CRA performance (insight + analytical) in Experiment 1 as a function of tDCS stimulation over the DLPFC.

Experiment 2: Stimulation Over the PPC

Convergent Thinking

ANOVAs with stimulation type as a within-subject factor found no effect on the number of correct responses but a significant effect on the number of correct insight solutions, $F(2,24) = 3.84$, $p < .05$, $\eta_p^2 = .228$. Post hoc multiple comparison tests showed that the number of insight solutions was significantly higher with AL-CR stimulation ($p = .028$) and with AR-CL stimulation ($p = .038$) than without simulation, indicating that both kinds of PPC stimulation increased insight as a problem-solving behavior (see Figure 3).

Divergent Thinking

No effect was found to be significant in the AUT analyses (see Figure 4).

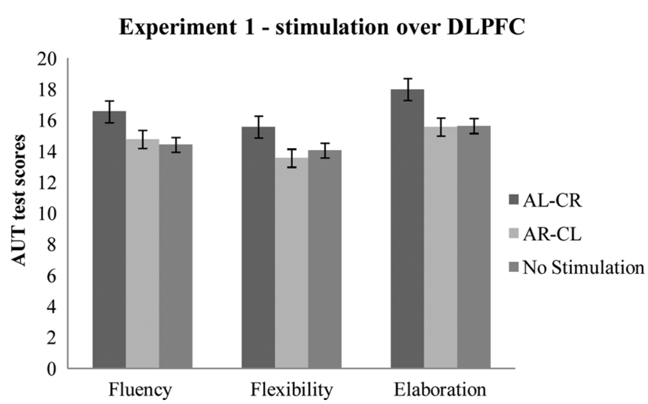

FIGURE 2 AUT performances (fluency, flexibility, elaboration) in Experiment 1 as a function of tDCS stimulation over the DLPFC.

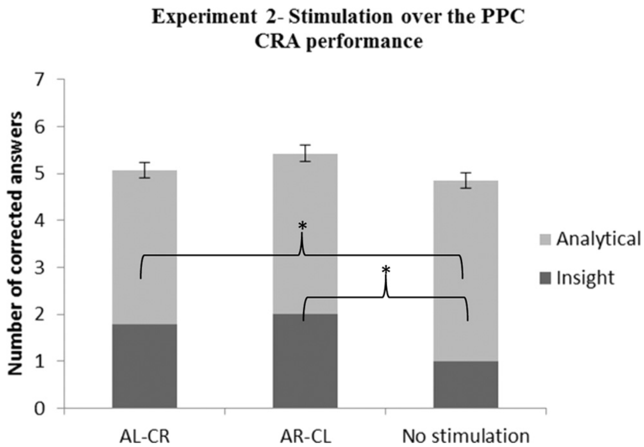

FIGURE 3 CRA performance (insight + analytical) in Experiment 2 as a function of tDCS stimulation over the PPC.

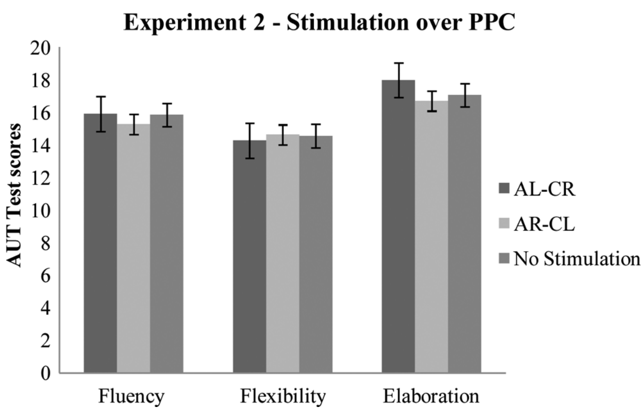

FIGURE 4 AUT performances (fluency, flexibility, elaboration) in Experiment 2 as a function of tDCS stimulation over the PPC.

Relationship Between CRA and AUT Performance

Although AUT performance did not yield significant effects in either of the experiments, its pattern strongly resembles that obtained for the CRA task. One possibility is that the AUT data were noisier than the CRA data (as they rely on just two items per condition instead of 10), which prevented the ANOVA from picking up the effect. Thus AUT (the flexibility score) and CRA data (items correct) were compared to see whether they are differentially affected by the stimulation conditions. Repeated measures ANOVAs were performed with scores (CRA vs. AUT-flexibility) and stimulation type (AL-CR, AR-CL, no-stimulation) as within-subject factors for Experiment 1 and 2. Apart from a less interesting main effect of the scores in both experiments (reflecting the different scales: Experiment1: $F(1,12) = 22.57$, $p < .005$, $\eta^2_p = .653$; Experiment2: $F(1,13) = 65.33$, $p < .001$, $\eta^2 = .834$), there was a main effect of stimulation in Experiment1, $F(2,24) = 5.86$, $p < .005$, $\eta^2_p = .328$. Interestingly, there was not any hint to an interaction between scores and stimulation, $F < 1$, suggesting that brain stimulation affected the two scores in a similar way; see Figure 5.

DISCUSSION

The study had two primary goals: first, to investigate the effect of tDCS on the performance of convergent and divergent thinking, and second, to explore the influence of stimulating a specific region on the problem-solving behavior. With regards to the first goal, the results indicated that CRA performance was enhanced significantly with left-side anodal and right-side cathodal (AL-CR) during DLPFC stimulation (see Figure 1). These results are in line with Cerruti and Schulang (2009), who found enhancement in CRA performance after anodal stimulation over the left DLPFC in a unilateral montage. No such effect was found after PPC stimulation. Thus, this finding provides additional evidence that implicates the left DLPFC with convergent thinking, and suggests ways to enhance it. Moreover, creative problem solving implicates several brain regions and neural networks (for review see Sawyer, 2011). Recent studies have shown that tDCS with opposite polarity over the anterior

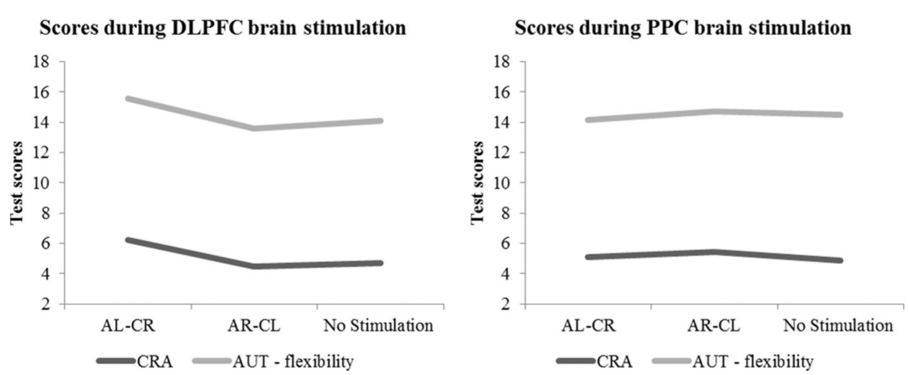

FIGURE 5 CRA scores and AUT flexibility scores in Experiment 1 and 2 as a function of tDCS stimulation over the DLPFC and PPC.

temporal lobes (ATL), i.e., cathodal on the left and anodal on the right, improves performance on nonverbal problems (Chi & Snyder, 2011) and increases the ability to solve very difficult problems such as the nine-dot problem by 40% (Chi & Snyder, 2012). This suggests the involvement of the ATL in nonverbal problem solving. It is possible that both DLPFC and ATL have a role in insight problem solving; alternatively, it might be the case that solving verbal problems involves more frontal regions than non-verbal problems.

The divergent thinking performance as was measured by flexibility, fluency, and elaboration was not significantly affected by the stimulations; however, there was enhancement of the AUT scores during AL-CR stimulation over the DLPFC, in a similar way to the convergent thinking performance (see Figure 2). Nevertheless, Chrysikou et al. (2013) found a modulation effect of unilateral cathodal tDCS over left PFC on uncommon uses of everyday objects compared to cathodal on the right PFC or sham condition, and this effect was only found for uncommon uses of objects. The discrepancy between this effect and the null results in the divergent thinking task might be due to the tDCS montage (unilateral vs. bilateral), the stimulated brain region (DLPFC: F3 & F4 vs. PFC: F7 & F8 according to the international 10–20 system for EEG electrode placement) or the nature of the task (all uses of everyday items vs. uncommon uses of everyday items). In addition, it might be that the data on the divergent thinking task from this study were noisier due to the use of only two items per condition, which might have rendered the analyses as less sensitive. Future research should replicate with different divergent thinking tasks. Given the 2-min intervals for testing divergent thinking in this research and data showing significant benefits of longer testing intervals, this, too, could be adjusted in future research.

The second goal regarded the problem-solving behavior in convergent thinking task during tDCS stimulation. The results reveal that the contribution of insight solutions to CRA performance was significantly higher during stimulation over the PPC (in both AL-CR and CR-AL) compared with the control session (see Figure 3). Given that the PPC is associated with attentional processes (Behrmann, Geng, & Shomstein, 2004) and attention was found to play a prominent role in problem-solving behavior in the remote association task (Ansburg & Hill, 2003) and in attention deployment (Runco, 2004), one can speculate that stimulating this region might affect attentional processes in a way that impairs analytical solutions and thereby promotes insight solutions. In line with this finding, evidence from a clinical study has illustrated that there was a positive correlation between the size of the lesion in the left parietal lobe and the originality scores (Shamay-Tsoory et al., 2011). Moreover, a neuroimaging study has suggested that during practice for creative work, activity in the parietal cortices is suppressed, beginning with suppression of the left parietal followed by the right (Kowatari et al., 2009), which also might explain the observations that both stimulation types modulated the problem-solving behavior. Similar observations of a polarity-independent tDCS-induced impact on specific cognitive processes have also been reported by Zmigrod, Colzato, and Hommel (2014) for stimulus-response integration and by Dockery, Hueckel-Weng, Birbaumer, and Plewnia (2014) for action planning. Thus, this finding provides preliminary evidence for a link between the PPC and problem-solving behavior. Unfortunately, given the use of a bilateral montage, the more prominent cortical hemisphere could not be identified. This calls for further research.

Of particular interest, although the stimulations did not significantly modulate the performance in the divergent thinking task, tDCS stimulations over the DLPFC and the PPC did affect both CRA and AUT performance in a comparable manner. More specifically, as depicted in Figure 5, the stimulation type had a similar effect on the correct response rates of the convergent task and the flexibility scores in the divergent task, for stimulation of both the DLPFC (Experiment 1) and PPC (Experiment 2). Given the considerable evidence that convergent thinking and divergent thinking are distinct components of human creativity (Colzato et al., 2012), this suggests that the manipulations might not target specific components of divergent and convergent thinking but, rather, cognitive operations that these two components share. Indeed, both tasks require the search for a verbally-defined solution to a problem, which is likely to involve cognitive control over memory search (Hommel, 2012)—a process that has also been demonstrated to be sensitive to polarity-independent tDCS effects (Zmigrod et al., 2014). Evidence for overlap has also been found in a study examining the impact of physical exercise on creativity, where both CRA performance and AUT-flexibility were affected by acute exercise (Colzato, Szapora, Pannekoek, & Hommel, 2013). Taken together, these observations suggest that this study did target core mechanisms underlying human problem-solving in general.

In conclusion, this study emphasizes the role of the left DLPFC in creative thinking and the role of the PPC in modulating problem-solving behavior. It provides further evidence that creativity can be enhanced via noninvasive brain stimulation with various montages. Moreover, creativity does not emerge from a single region in the brain (for review see Sawyer, 2011), thus more research is needed to clarify the relationships between the different components of convergent and divergent thinking as well as the relationships between problem-solving strategies. In any case, tDCS appears to be a promising tool for exploring these processes and the brain regions underlying them.

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