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Enhancing Creativity With Combined Transcranial Direct Current and Random Noise Stimulation of the Left Dorsolateral Prefrontal Cortex and Inferior Frontal Gyrus

ABSTRACT

Creativity is a fundamental human accomplishment from scientific advances to composing music. The left dorsolateral prefrontal cortex (DLPFC) and inferior frontal gyrus (IFG) are important metacontrol hubs in flexibility and persistence brain states, respectively. Those hubs are related to divergent thinking, insight problem-solving, and convergent thinking. In this double-blind, between-subjects study, 81 healthy participants were randomly assigned to one of three groups ($n = 27$) that received a combined transcranial direct current stimulation–transcranial random noise stimulation (tDCS-tRNS) protocol with the anode over the left DLPFC and cathode over the left IFG (+DLPFC−IFG), the opposite montage (−DLPFC+IFG), and a sham group (+DLPFC−IFG). Both active tDCS-tRNS groups received 20 min of 1 mA tDCS with 1 mA (100–500 Hz) tRNS. Creativity was assessed before (baseline) and during stimulation with the Unusual Uses, Picture Completion (PC), Remote Association test (RAT), Matchstick Arithmetic (MA), and Nine-dot (ND) problems. Only the +DLPFC−IFG group had significantly higher scores compared with sham in the RAT ($p = .009$), PC fluency ($p = .018$), PC originality ($p = .007$), ND ($p = .007$), and MA ($p = .032$). Overall, −DLPFC+IFG had greater scores in all creativity tests compared with sham. Implications from the metacontrol theory are discussed.

Keywords: transcranial direct current stimulation, transcranial random noise stimulation, creativity, dorsolateral prefrontal cortex, inferior frontal gyrus.

The evolutionary importance of human creativity goes back to pre-historic times when it helped *Homo sapiens* to spread throughout the world more successfully than other human lineages (Zwir et al., 2022). Modern humans demonstrate greater creativity compared with other hominids, such as innovation, flexibility, depth of planning, and related cognitive abilities for symbolism and self-awareness. According to the authors (Zwir et al., 2022), some of the reasons for the evolutionary advantage of creativity, along with self-awareness and cooperative behavior is that they provided greater resilience to aging, injury, and disease (Zwir et al., 2020). Therefore, living longer and healthier may have helped both to speed up spreading modern human lineage around the world and to facilitate the accumulation of knowledge by extending the period of learning. Creativity may have fostered cooperation between individuals, thus promoting behavioral flexibility, technological innovation, and openness to exploration (Zwir et al., 2022).

In modern human society, creativity is associated with positive accomplishments in many different fields such as workplace organization (Agars, Kaufman, & Locke, 2007; Samani, Abdul Rasid, & Bt Sofian, 2015) and scientific progress (Wilcox, Cortese, Baravelli, & Skjaerven, 2018). Consequently, any effort to understand the categories and underlying neural mechanisms of creativity, and ways to increase creativity are highly valued aims (Pick & Lavidor, 2019).

Research in categorizing creativity has mostly focused on divergent thinking (DT), convergent thinking (CT), and insight problem-solving tasks (IPS). DT is usually conceptualized as a type of thinking that allows many new ideas being generated, in a context where more than one solution is correct (Guilford, 1967). Although many studies have used the Torrance Test of Creative Thinking (TTCT; Torrance, 1966) or Alternative Uses Task (Guilford, 1967) to assess DT, there is also evidence suggesting that they partially also involve CT processes (Cortes, Weinberger, Daker, & Green, 2019).

In CT, participants have to primarily find a single solution to a problem in a deductive reasoning way (Zmigrod, Colzato, & Hommel, 2015). A common measure used to assess CT has been the Remote Association test (RAT), although there is also evidence that it may be reflecting DT and IPS at least to some extent (Cortes et al., 2019). For simplicity, in this study we will consider RAT primarily as a CT task and Torrance subtests as DT tasks, although it needs to be taken in mind that both tasks tap also other cognitive processes. IPS tasks are usually solved through sudden insight solutions, sometimes accompanied by an "Aha" experience, such matchstick arithmetic (MA) problems (Aihara, Ogawa, Shimokawa, & Yamashita, 2017; Chi & Snyder, 2011; Di Bernardi Luft, Zioga, Banissy, & Bhattacharya, 2017; Öllinger, Jones, & Knoblich, 2008) or nine-dot (ND) test (Chi & Snyder, 2012; Chu & MacGregor, 2011).

The underlying neural mechanisms of creativity have been investigated using genetic coding (Zwir et al., 2022), neuroimaging (Beaty, Benedek, Barry Kaufman, & Silvia, 2015; Beaty, Benedek, Silvia, & Schacter, 2016; Beaty, Cortes, Zeitlen, Weinberger, & Green, 2021; Beaty, Seli, & Schacter, 2019; Chrysikou, 2019; Gonen-Yaacovi et al., 2013; Sun et al., 2019), and transcranial electrical stimulation (tES) technologies (See Weinberger, Green, & Chrysikou, 2017 for a review). Zwir et al. (2022) identified specific brain regions over-expressing gene sets involved in human creativity unique to modern humans, which included frontal, temporal, and parietal neocortex regions, as well as associated sub-cortical areas important for intuitive insight and evaluation. Results from a meta-analysis of neuroimaging studies (Boccia, Piccardi, Palermo, Nori, & Palmiero, 2015) found that the areas most activated during verbal DT were the left dorsolateral prefrontal cortex (DLPFC), inferior parietal lobule, insula, temporal gyrus (middle and superior), postcentral and supramarginal gyri, and middle occipital gyrus. Results from visual DT suggest a higher activation in the right inferior frontal gyrus (IFG) and DLPFC, the thalamus bilaterally, and left precentral gyrus. The prominent role of the DLPFC and IFG on CT and DT has been recently revised (Zhang, Sjoerds, & Hommel, 2020) along with their relationship with temporal/parietal networks from a metacontrol perspective. More specifically, Zhang et al. (2020) proposed that left DLPFC and left IFG play an important role in switching between metacontrol states based on a flexibility route to a more persistent route. Both routes are suggested to cooperate in a different way in DT and CT (Zhang et al., 2020); the persistence route may dominate CT possibly through the systematic and effortful exploration of a few categories (Nijstad, De Dreu, Rietzschel, & Baas, 2010). Additional evidence for this relationship emerges from the association between working memory and executive functioning with CT but not with DT (Lee & Therriault, 2013). The flexibility route, on the contrary, may be crucial for DT since it is needed to switch between different categories (Zhang et al., 2020). This route is supposed to help DT by having wide attentional focus and change between approaches to the task instead of relying too much on fixed task strategies (Ashby, Isen, & Turken, 1999; Nijstad et al., 2010).

In addition to neuroimaging studies, tES is used to provide more direct causal evidence of specific brain regions on creativity through application of low currents (1–4 mA) via scalp electrodes (Lucchiari, Sala, & Vanutelli, 2018; Weinberger et al., 2017). The most used type of tES in creativity research has been transcranial direct current stimulation (tDCS). This type of stimulation increases more the excitability of the area under positively charged anodal electrode, whereas the excitability decreases more in the area under the cathodal electrode (Jacobson, Koslowsky, & Lavidor, 2012). However, this excitability increase with anodal and decrease with cathodal dichotomy has been more recently questioned, where it is now understood that a mix of excitability increases and decreases on neural structures based on their orientation to the induced electric field is more likely (Hannah, Iacovou, & Rothwell, 2019). Results of tDCS studies on creativity generally indicate an improvement in verbal DT after left anodal/right cathodal tDCS applied to the bilateral DLPFC when compared to left cathodal/right anodal stimulation (Colombo, Bartesaghi, Simonelli, & Antonietti, 2015; Zmigrod et al., 2015). More recently, transcranial random noise stimulation (tRNS) in the high-frequency range (100–500 Hz) has been used as a promising alternative to tDCS. tRNS is a form of tES using random noise that has shown to modulate cortical plasticity (Terney, Chaieb, Moliadze, Antal, & Paulus, 2008).

Although the underlying mechanisms for tRNS are not yet completely understood, there are two main hypotheses. One of the proposed mechanisms of tRNS suggests that the neuronal excitability increases through stochastic resonance, a phenomenon whereby the accumulation of random interference (i.e., noise) can increase the detection of weak stimuli or enhance the information content of a signal (Miniussi, Harris, & Ruzzoli, 2013; Moss, Ward, & Sannita, 2004; van der Groen & Wenderoth, 2016; Ward, 2009). Another possible explanation could be that it would induce a repetitive opening of the Na + channels thus shortening the hyperpolarization phase (Chaieb, Antal, & Paulus, 2015; Terney et al., 2008).

By combining tDCS and tRNS waveforms, it is possible to maintain directionally of current flow between the anode and cathode, thus avoiding polarity change between the anode and the cathode in tRNS (Brevet-Aeby, Mondino, Poulet, & Brunelin, 2019; Dondé, Brevet-Aeby, Poulet, Mondino, & Brunelin, 2019). As such, each electrode sends a mix of both tDCS and tRNS, by adding the random noise stimulation (1 mA) over the direct current stimulation at (1 mA) results in tRNS waveforms being positive (1.5–0.5 mA) thus avoiding tRNS changing polarity from positive to negative (+0.5 to −0.5 mA) in the same electrode without a tDCS offset (Figure 1). Using this hybrid type of tES (tDCS-tRNS) over the DLPFC, some authors found that the left anodal–right cathodal group induced higher scores in both fluency and originality scores of verbal DT compared with sham, but not compared with the opposite montage, which also improved verbal DT (Peña et al., 2021). Their result regarding visual DT suggested that only left cathodal–right anodal group improved visual originality and fluency compared with sham. There is also evidence for verbal DT improvement after tDCS stimulation over the left DLFPC (Colombo et al., 2015; Zmigrod et al., 2015).

However, there are more studies that investigated verbal DT after targeting the IFG with tDCS. Most improvement in verbal DT have been observed after tDCS with the cathode over the left and anode over the right IFG (Hertenstein et al., 2019; Khalil, Karim, Kondinska, & Godde, 2020; Mayseless & Shamay-Tsoory, 2015). Similar results have also been found with the cathode over the left IFG (Chrysikou et al., 2013; Ivancovsky, Kurman, Morio, & Shamay-Tsoory, 2019) and a decreased novelty in responses after anode over the left IFG (Kenett, Rosen, Tamez, & Thompson-Schill, 2021). Another recent study indicated that cathodal tDCS of left ventrolateral prefrontal cortex resulted in an improvement in ideational fluency (Chrysikou, Morrow, Flohrschutz, & Denney, 2021).

Regarding CT, results from tES studies targeting the left DLPFC generally show an improvement after anodal tDCS (Cerruti & Schlaug, 2009; Metuki, Sela, & Lavidor, 2012; Zmigrod et al., 2015), combined tDCS-tRNS (Peña et al., 2021) and tRNS (Peña, Sampedro, Ibarretxe-Bilbao, Zubiaurre-Elorza, & Ojeda, 2019). Another study that targeted the right IFG with anodal tDCS showed significant effects on CT (Hertenstein et al., 2019). Most studies generally show a lack of significant effects on CT obtained by tES studies targeting other brain areas including the ATL (Aihara et al., 2017; Ruggiero, Lavazza, Vergari, Priori, & Ferrucci, 2018).

Finally, the effect of tES on IPS tasks is not completely consistent. Some authors found a significant improvement in MA problems after cathodal left/anodal right tDCS over the ATL (Chi & Snyder, 2011) and

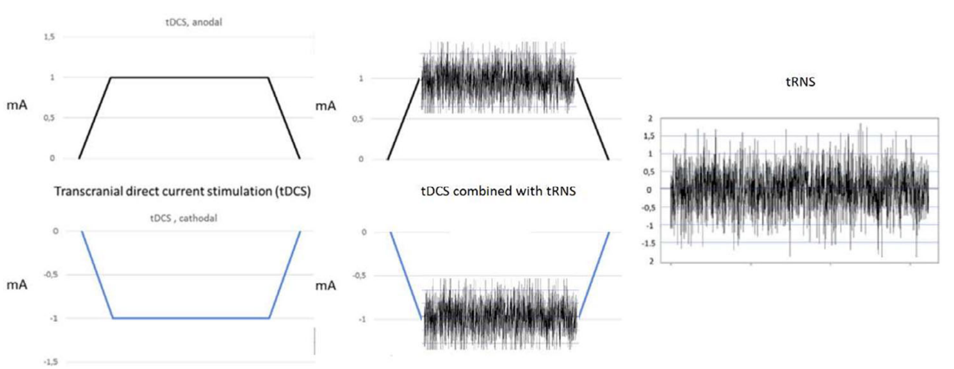

FIGURE 1. Combination of tDCS and tRNS compared with tDCS and tRNS only. [Color figure can be viewed at wileyonlinelibrary.com]

DLPFC (Di Bernardi Luft et al., 2017; Peña et al., 2021), whereas another study did not (Aihara et al., 2017). Regarding the ND problem, cathodal left/anodal right tDCS over the ATL (Chi & Snyder, 2012) as well as cathodal left/anodal right tDCS-tRNS over the DLPFC (Peña et al., 2021) have shown significant improvement.

In sum, although not completely consistent, the previously mentioned literature mainly suggests that anodal tDCS of left DLPFC may increase both CT (Cerruti & Schlaug, 2009; Metuki et al., 2012; Peña et al., 2019, 2021; Zmigrod et al., 2015) and DT (Colombo et al., 2015; Peña et al., 2021; Zmigrod et al., 2015). However, in separate studies, applying cathodal tDCS over the left IFG suggests an increase in DT (Chrysikou et al., 2021; Hertenstein et al., 2019; Ivancovsky et al., 2019; Kenett et al., 2021; Khalil et al., 2020; Kleinmintz et al., 2018; Mayseless & Shamay-Tsoory, 2015). Finally, cathodal left/anodal right tDCS over the ATL (an area adjacent to the IFG; Chi & Snyder, 2011) and cathodal left/anodal right DLPFC (Di Bernardi Luft et al., 2017; Peña et al., 2021) have been related to an improvement in IPS. However, as far as the authors are aware, none of the previous studies have assessed the simultaneous effect of anodal left DLPFC with cathodal left IFG tDCS-tRNS stimulation on different creativity categories (CT, DT, and IPS).

Previous studies indicate that tRNS may provide additional advantages over tDCS, and thus, combining tDCS with tRNS may provide a cumulative effect on creativity categories. For example, Terney et al. (2008) suggested that the effect on tasks based on visual perceptual learning (Terney et al., 2008) and working memory (Murphy, Hoy, Wong, Bailey, & Fitzgerald, 2020) may be larger for tRNS compared with tDCS. Similarly, a meta-analysis (Simonsmeier, Grabner, Hein, Krenz, & Schneider, 2018) showed that the effect of tRNS on language and mathematics was stronger after tRNS compared with tDCS. It is also suggested that tRNS may show longer term effects than tDCS (Berger, Dakwar-Kawar, Grossman, Nahum, & Cohen Kadosh, 2021; Brevet-Aeby et al., 2019; Snowball et al., 2013). Additionally, the possible adverse effects seem to be more bearable after receiving tRNS (Fertonani, Pirulli, & Miniussi, 2011) and tRNS is not as perceptible as tDCS regarding skin perception (Ambrus, Paulus, & Antal, 2010). Therefore, we decided to combine tDCS with tRNS following previous studies to boost the effects of tDCS (Brevet-Aeby et al., 2019; Dondé et al., 2019). We consider this combined tDCS-tRNS protocol allows us to induce greater directionality effects of tDCS with current flow from the anode over the left DLPFC (greater excitatory effects) to the cathode over the left IFG (greater inhibitory effects) and introduce random noise in the high-frequency range (100–500 Hz) to the system with tRNS that has been shown to improve the signal to noise in neuronal information processing.

Therefore, the aim of this exploratory study was to investigate whether a combined tDCS-tRNS with anode over the left DLPFC and cathode over the left IFG (+DLPFC−IFG) improves CT, DT, and IPS. We hypothesize that stimulating left DLPFC may enhance the persistence route and the simultaneous inhibition of left IFG would enhance the flexibility route. To rule out any unspecific directionality effects of this tDCS-tRNS protocol and to check the specific role of both DLPFC and IFG in persistence and flexibility routes, we included another group with the opposite montage with the cathode over the left DLPFC and anode over the left IFG (−DLPFC+IFG) along with a sham group (+DLPFC−IFG). We hypothesize that the +DLPFC−IFG group will enhance CT compared with the sham and −DLPFC+IFG group. The left DLPFC is associated with cognitive control, so we hypothesize that its stimulation would facilitate CT by strengthening the persistence route through the maintenance of focused attention, top-down support for relevant information, manipulation of information in working memory, and inhibition of task-irrelevant information (Fischer & Hommel, 2012; Zhang et al., 2020). We also expect that +DLPFC−IFG will enhance DT to a greater extent compared with the sham and −DLPFC+IFG groups. We hypothesize that the inhibition of left IFG will relax top-down inhibitory constraints and strengthen bottom-up information processing, which is related to the flexibility route during the search for new ideas (Chrysikou, 2019), a central process in DT.

Given that some previous studies have found an effect on IPS with the cathode over the left DLPFC (Di Bernardi Luft et al., 2017; Peña et al., 2021) and other studies over the left frontotemporal areas (Chi & Snyder, 2011, 2012), we hypothesize that both +DLPFC−IFG and −DLPFC+IFG groups would enhance the solution rate on IPS tasks compared with sham. In this way, we will directly compare the effect of inducing greater inhibition of the left IFG with inhibition of the left DLPFC.

MATERIAL AND METHODS

STATISTICAL POWER AND SAMPLE SIZE ESTIMATION

The sample size calculation was based on a previous tES study that investigated the effect of combined tDCS-tRNS over the DLPFC on CT and DT (Peña et al., 2021). Using the G*Power3 software (Faul, Erdfelder, Lang, & Buchner, 2007), a sample size of 81 subjects, 27 in each group, was enough to attain an effect size of $f = 0.38$ (Peña et al., 2021) to detect differences in DT and CT with 85% power and a 5% level of significance.

PARTICIPANTS

Based on the power analysis, 81 healthy and native Spanish-speaking volunteers (aged 18 years or above) were recruited from the general population. There were no restrictions on gender or handedness of participants. Before taking part in the experiment, all participants fulfilled a screening questionnaire for tES contra-indications, including (a) previous history of brain surgery; (b) being pregnant; (c) suffering from frequent or severe headaches or migraines; (d) previous history or presence of neurological disorder or injury (epileptic or convulsive seizure, brain stroke, severe brain injury); and (e) presence of any brain metallic implant.

Participants did not receive any course credit or monetary or compensation for participating in the study. The study obtained the ethics approval from the Research Ethics Committee of Deusto University (Ref: ETK-31/17-18).

All volunteers provided written informed consent to participate in the study, and they were free to withdraw at any time.

Design and procedure

This double-blind, sham-controlled, parallel-group between-subjects design study consisted of one single session. Figure 2 shows the study design and procedure. The participants were randomly assigned to one of

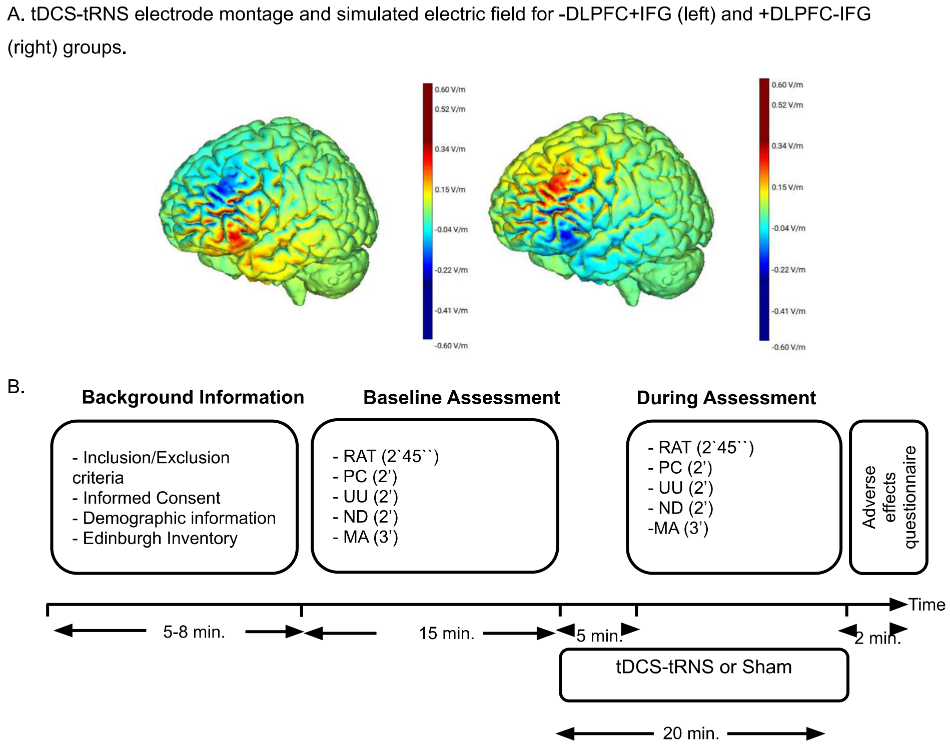

FIGURE 2. Study design and tDCS-tRNS montage. A. Electrode Montages. +DLPFC−IFG stimulation of the electric field according to *Stim Weaver* (Neuroelectrics, Spain) software based on a realistic head model derived from the Finite Element Method (Miranda et al., 2013). Red-yellow colors indicate increased magnitude of the total electric field due to the combined tDCS-tRNS. [Color figure can be viewed at wileyonlinelibrary.com]

the three groups ($n = 27$ in each group): two real stimulation groups (+DLPFC−IFG and −DLPFC+IFG) and one sham group (+DLPFC−IFG). Group assignment was conducted based on a computer-generated randomization software (www.randomizer.org). All raters were blind to stimulation group condition.

After signing the consent form, participants reported sociodemographic information along with hours of sleep, tobacco consumption, and stimulant drinks ingested before the session.

Baseline creativity assessment was carried out before starting stimulation (see Figure 2). Subjects had 2 min and 45 s to complete the RAT and 2 min each for the Unusual Uses (UU), Picture Completion (PC) from the Torrance Test of Creative Thinking and ND problem, and 1 min for each of the three MA problems.

Five minutes after the stimulation started, the subjects performed the parallel versions of RAT, UU, and PC with the same time limitations as the baseline assessment. The order of the version of UU, RAT, and PC was counterbalanced. Afterward, they completed the ND and MA problems. Participants filled the adverse effects questionnaire. In order to study the blinding efficacy, participants were asked to answer the following sentence: “Please, tell us if you think you were receiving real stimulation, no stimulation (placebo) or you do not know?”

APPLICATION OF COMBINED TDCS-TRNS

Combined tDCS-tRNS was delivered by using a wireless battery-operated Starstim8 device (Neuroelectrics Inc., Barcelona, Spain) attached to the back of a neoprene cap that follows the International 10–20 system. In the +DLPFC−IFG group, the anode was placed over the left DLPFC (F3 according to the 10/20 electrode placement EEG-System) and the cathode over the left posterior IFG (close to FT7 as 1/3 of the distance between F7 and C5; Huang et al., 2020; Zheng, Dai, Alsop, & Schlaug, 2016). In the −DLPFC+IFG group, the position of the anode and the cathode was interchanged. Both real tDCS-tRNS groups received 20 min (with 30s ramp-up/down) of 1 mA tDCS with 1 mA of tRNS (high-frequency: 100–500 Hz) via two saline-soaked (5 ml per sponge) circular rubber-sponge electrodes (area of 8 cm^2). In this montage, each electrode sends a mix of both tDCS and tRNS, by adding the random noise stimulation over the direct current stimulation and avoids tRNS changing polarity in the same electrode. The sham group (+DLPFC−IFG montage) received 30 s (with 30s ramp-up/down) of stimulation, which has been shown to provide an adequate placebo stimulation condition. The impedance of the electrodes was checked before and during the tDCS-tRNS application to guarantee that it was maintained below 10 kΩ.

The stimulation protocol was created and monitored using the NIC 2.0 software (www.neuroelectrics.com/products/software/nic2/). Stimulation groups were labeled as “Group A”, “Group B” and “Group C” in the NIC2 software with the double-blind mode enabled. Therefore, the experimenters that applied the stimulation conditions were also blinded.

Creativity measures

The Torrance Test of Creative Thinking

Unusual Uses and PC subtests from *The Torrance Test of Creative Thinking* (Torrance, 1966) were included in the study. We included two different forms (Form A and B) for the baseline and during the stimulation assessments. We measured three dimensions for both UU and PC: fluency, originality, and flexibility.

In the PC task, the participants are asked to complete 10 unfinished figures by drawing additional elements in a paper and pencil task. Fluency referred to the total number of relevant responses and the participants were given 1 point for each figure completed. The originality score was based on the statistical infrequency of each response based on the list of normative data (Torrance, 1966). When responses were classified as original, they were given 1 point. Flexibility was assessed as the number of different ideational categories produced in the pictures, based on the list of categories from the Spanish adaptation of the TTCT (Jiménez, Artiles, Rodríguez, & García, 2007). We converted fluency, originality, and flexibility measures to z-scores to obtain a PC composite. The internal consistency was good (Cronbach’s alpha: 0.77).

In the UU task, participants had to write down as many unusual uses as possible for an item. In the Form A of the test, Cardboard Boxes was used as a stimulus. In the Form B, Tin Cans were used. We measured three dimensions in UU: fluency, originality, and flexibility. Fluency was obtained considering the number of different unusual uses generated (1 point for each response). Originality was based on the statistical unusualness of each response. We used the criteria based on the list of items from the manual (Torrance, 1966). A flexibility score was obtained from the number of different categories represented in the responses. Each different category was given 1 point. We also converted fluency, originality, and flexibility measures to *z*-scores to obtain a UU composite. The internal consistency was good (Cronbach's alpha: 0.85).

Remotes Associates Test

The Spanish version of the RAT (Mednick, 1962) was administered. Two different forms of the test were used for the baseline and during stimulation assessment. In RAT task, participants were asked to identify a word that is associated (either forming a compound word or semantically related) with three cue words. Each form included 30 items, and participants had 2 min and 45 s for write down as many items as possible. The items were presented in the same sheet and participants could go backward and forward if they wished to do so. The internal consistency of the test was high (Cronbach's alpha = 0.81).

Nine-dot Problem

In the ND problem, participants were asked to connect all nine dots using four straight lines without retracing and without removing their pencil from the paper within 2 min time (Knoblich, Ohlsson, Haider, & Rhenius, 1999). Participants attempted to do the task (2 min) both before stimulation and during stimulation. If the participant solved the problem in the first trial, it would not be consider in the statistical analyses.

Matchstick Arithmetic problems

In the MA problems, an incorrect arithmetic statement was displayed using Roman numerals with real matchsticks (e.g., "II," "X" or "IV") and arithmetic operators ("+," "−" or "="). Participants could move only one matchstick to another place in the equation in order to make the equation correct. They have 1 min to solve each equation. Before stimulation, participants were asked to solve three Type A problems, which consisted in moving one matchstick within a specific numeral.

During stimulation (or sham), participants were asked to solve more difficult problems. Based on previous studies (Di Bernardi Luft et al., 2017), the following kinds of problems were included:

Type B: VI = VI + I, Solution: VI = VI**I–**I.
Type C: VI = VI + VI, Solution: VI = VI**=**VI.
Type D: VI = VI + V, Solution: **X**I = VI**=**VI.

We calculated the sum of correct items as well as the individual scores.

Questionnaire of adverse effects

We used a 11-item questionnaire to assess any perceived side effects, including numbness, tingling, skin redness, headache, itching sensation, concentration difficulties, burning, phosphenes, mood change, sore throat, and scalp pain study.

STATISTICAL ANALYSES

Baseline characteristics were compared using the ANOVA test for continuous variables and chi-squared test for categorical data. Correlation among baseline continuous creativity scores (RAT, UU, and PC dimensions) was performed with Pearson's R (or Spearman's Rho when necessary). Following previous suggestions for pre–post randomized designs (Wan, 2021), ANCOVA was used to compare during stimulation scores (controlling for baseline scores) between the three groups for each of the creativity variables. To avoid possible biases due to the sample size, we performed bootstrapping (Efron & Tibshirani, 1986). The number of subsamples generated from within each group (with replacement) was 1000. Effect size (n_p^2) was also calculated. IBM SPSS software version 23.0 (IBM Corp. Released, 2015) was used for frequentist statistical analyses. All tests were two-tailed, and the significance level was set at .05.

Additionally, following previous suggestions (Biel & Friedrich, 2018), Bayesian statistical analyses were also calculated using JASP software (JASP Team, 2020). Bayesian ANCOVAs were conducted to evaluate the relative strength of evidence in favor of the alternative hypothesis (H1) compared with the null hypothesis (H0). A BF_{10} higher than 3 suggests substantial evidence for the alternative hypothesis compared with the null hypothesis, whereas a BF_{10} between 0.33 and 3 indicates data as inconclusive or anecdotal evidence

(Wagenmakers, Love, et al., 2018; Wagenmakers, Marsman, et al., 2018). Finally, a BF_{10} lower than 0.33 indicates substantial support for the null hypothesis.

RESULTS

BASELINE CHARACTERISTICS OF THE THREE GROUPS

As listed in Table 1, there were no significant differences between groups in any of the variables at baseline. Participants were also asked to indicate whether the number of hours slept, number of drinks with stimulants ingested or number of tobacco consumption was less than usual, more than usual or the same as usual. There were no significant differences between the groups in sleeping hours [χ^2 (4, N = 81) = 6.78, p = .148], stimulant drinks (tea, coffee, etc.), [χ^2 (4, N = 80) = 3.16, p = .531], or tobacco consumption [χ^2 (4, N = 81) = 4.94, p = .294].

EFFECTS OF TDCS-TRNS ON RAT, UU, AND PC

The RAT, UU, and PC scores of +DLPFC−IFG, −DLPFC+IFG, and sham groups at baseline and during stimulation are displayed in Table 2. Additionally, the correlation among the creativity measures at baseline (See Table 3) indicates that RAT was not significantly associated with UU or PC measures, whereas both UU and PC dimensions were significantly related to each other, except for the relationship between UU fluency and PC originality.

Table 4 shows the marginal means during stimulation (controlling for baseline scores) and the differences among the groups. There was a significant difference between groups for the RAT. *Post hoc* analyses showed that the +DLPFC−IFG group had significantly higher scores in RAT when compared to the sham group. The rest of the comparisons were not significant.

Regarding PC subdomains, there was a significant difference among the groups in PC fluency. *Post hoc* analyses showed that the +DLPFC−IFG group had significantly higher scores in PC fluency compared with the sham group and −DLPFC+IFG group. The +DLPFC−IFG group had significantly higher scores in PC originality compared with the sham group, but only marginally significant compared with the −DLPFC+IFG group. No significant differences were found between groups for PC flexibility. However, the composite PC score was significantly different between groups. *Post hoc* analyses indicated that the +DLPFC−IFG group (0.27 ± 11) was significantly higher than both sham group (−0.21 ± 0.11, p = .006, BF_{10} = 26.32) and −DLPFC+IFG group (−0.10 ± 0.11, p = .026, BF_{10} = 7.36). Given that both groups increased the number of responses (fluency), it was decided to investigate whether the increase in originality scores was due to an increase in fluency or to more original responses. Based on the fluency scores, we calculated the percentage of original responses (number of original responses * 100/total number of correct responses). There were significant differences in the percentage of original responses [F (2,78) = 3.40, p = .039, n_p^2 = 0.08, BF_{10} = 1.45]. *Post hoc* analyses showed that +DLPFC−IFG group (41.51 ± 25.74)

TABLE 1. Participant Characteristics of the Real (+DLPFC−IFG and −DLPFC+IFG) and Sham tDCS-tRNS Groups at Baseline

	+DLPFC−IFG	−DLPFC+IFG	Sham	Statistic	*p*-Value
	Mean ± *SD*	Mean ± *SD*	Mean ± *SD*		
Age	31.29 ± 11.21	31.11 ± 11.49	28.93 ± 11.70	F (2,77) = 0.34	.715
Years of education	13.70 ± 2.30	13.66 ± 2.63	12.59 ± 2.51	F (2,78) = 1.74	.182
Gender: *n* (%)					
Females	16 (59.3%)	14 (53.8%)	17 (63.0%)	χ^2 (2, N = 80) = 0.46	.795
Number of hours slept	6.75 ± 1.47	6.46 ± 1.40	7.09 ± 1.45	F (2,78) = 1.28	.282
Edinburgh Handedness	67.62 ± 37.35	49.78 ± 50.90	68.11 ± 38.13	F (2,78) = 1.62	.204
Tobacco consumption	0.63 ± 2.37	1.03 ± 3.39	2.59 ± 3.87	F (2,78) = 2.70	.073
Number of stimulants	1.11 ± 0.97	0.93 ± 1.03	1.26 ± 1.19	F (2,78) = 0.66	.522

Note. +DLPFC−IFG = left anode dorsolateral prefrontal cortex-cathode inferior frontal gyrus group; −DLPFC+IFG = left cathode dorsolateral prefrontal cortex-anode inferior frontal gyrus group; *SD* = standard deviation.

TABLE 2. Creativity Scores of the Real (+DLPFC−IFG and −DLPFC+IFG) and Sham tDCS-tRNS Groups at Baseline and During Stimulation

		+DLPFC−IFG	−DLPFC+IFG	Sham	F	p-Value
		Mean ± SD	Mean ± SD	Mean ± SD		
RAT	Baseline	7.33 ± 2.75	7.66 ± 3.15	6.70 ± 2.61	0.59	.559
	During	9.44 ± 3.41	8.00 ± 3.33	6.52 ± 3.30	5.14	.008
UU fluency	Baseline	7.89 ± 3.05	7.85 ± 3.18	6.74 ± 2.36	1.38	.259
	During	8.70 ± 2.79	7.85 ± 3.47	6.56 ± 2.72	3.41	.038
UU originality	Baseline	5.25 ± 2.19	4.63 ± 2.60	3.30 ± 2.40	4.69	.012
	During	5.48 ± 2.97	5.15 ± 3.43	3.78 ± 2.39	2.51	.888
UU flexibility	Baseline	6.07 ± 1.79	5.48 ± 1.88	5.59 ± 1.69	0.83	.439
	During	6.70 ± 2.07	5.59 ± 1.94	5.30 ± 2.31	3.32	.042
PC fluency	Baseline	6.11 ± 2.39	5.67 ± 2.16	5.15 ± 1.74	1.40	.253
	During	6.93 ± 1.75	5.81 ± 1.81	5.52 ± 1.96	4.35	.016
PC originality	Baseline	2.22 ± 1.82	1.56 ± 1.31	1.89 ± 1.39	1.29	.282
	During	2.85 ± 1.70	1.88 ± 1.21	1.59 ± 1.27	5.83	.004
PC flexibility	Baseline	5.11 ± 1.86	4.81 ± 1.90	4.33 ± 1.41	1.37	.260
	During	5.77 ± 1.50	5.30 ± 1.70	4.88 ± 1.78	1.92	.153

Note. +DLPFC−IFG = anodal dorsolateral prefrontal cortex-cathodal inferior frontal gyrus group; −DLPFC+IFG = cathodal dorsolateral prefrontal cortex-anodal inferior frontal gyrus group; PC = Picture Completion from Torrance Test of Creative Thinking; *SD* = standard deviation; UU = Unusual Uses from Torrance Test of Creative Thinking; Verbal RAT = number of correct answers in Remote Associates Test.

TABLE 3. Correlation Among Creativity Measures at Baseline

	RAT	UU fluency	UU originality	UU flexibility	PC fluency	PC originality	PC flexibility
RAT	1	−0.06	0.00	0.12	0.08	−0.10	0.05
UU fluency		1	0.71***	0.77***	0.37***	0.14	0.33**
UU originality			1	0.56***	0.29**	0.24*	0.27*
UU flexibility				1	0.36***	0.24*	0.31**
PC fluency					1	0.42**	0.84***
PC originality						1	0.31**
PC flexibility							1

Note. All correlation coefficients shown are Spearman's Rho except for RAT and UU flexibility. PC = Picture Completion from Torrance Test of Creative Thinking; UU = Unusual Uses from Torrance Test of Creative Thinking. *$p < .05$, **$p < .01$, ***$p < .001$.

produced a significantly higher percentages of original scores ($p = .014$, $BF_{10} = 1.61$) compared with sham (26.14 ± 23.39). There were no significant differences compared with −DLPFC+IFG group (34.19 ± 19.39).

Unusual Uses sub-dimension analyses showed no significant differences in ANCOVA among the groups in UU fluency. However, we will report the *post hoc* analyses as exploratory so we must be cautious with these results. In UU fluency, results suggest that the +DLPFC−IFG group scores were significantly higher than the sham group. The UU originality, UU flexibility, and UU composite scores were not significantly different between groups. Again, although the UU composite score ANCOVA was not significant, we wanted to indicate as an exploratory result that the *post hoc* BF result suggests that there is substantial evidence for the alternative hypothesis in the comparison between the +DLPFC−IFG group and sham group. Regarding the percentage of original responses in UU, results showed that there were no significant differences among the groups [F (2,78) = 0.43, $p = .655$, $n_p^2 = 0.01$, $BF_{10} = 0.15$].

TABLE 4. Differences Between the Real (+DLPFC−IFG and −DLPFC+IFG) and Sham tDCS-tRNS Groups in RAT, UU, and PC Scores During Stimulation After Controlling for Baseline Scores

	+DLPFC−IFG	−DLPFC+IFG	Sham	*F*	*p*	n_p^2	BF_{10}	Comparison group	*Post hoc*	
	Marginal Mean ± *SE*	Marginal Mean ± *SE*	Marginal Mean ± *SE*						*Posthoc p*-value	BF_{10}
RAT	9.33 ± 0.68	7.84 ± 0.55	6.79 ± 0.62	4.96	.009	0.11	5.07	+DLPFC−IFG vs. −DLPFC+IFG	.083	0.76
								+DLPFC−IFG vs. Sham	.009	15.31
								−DLPFC+IFG vs. Sham	.214	0.82
UU fluency	8.44 ± 0.53	7.61 ± 0.54	7.07 ± 0.46	2.28	.109	0.06	0.65	+DLPFC−IFG vs. −DLPFC+IFG	.236	0.41
								+DLPFC−IFG vs. Sham	.036	6.37
								−DLPFC+IFG vs. Sham	.365	0.71
UU originality	4.96 ± 0.59	5.01 ± 0.59	4.44 ± 0.44	0.37	.694	0.01	0.16	+DLPFC−IFG vs. −DLPFC+IFG	.951	0.29
								+DLPFC−IFG vs. Sham	.440	2.43
								−DLPFC+IFG vs. Sham	.380	0.90
UU flexibility	6.47 ± 0.38	5.74 ± 0.32	5.38 ± 0.41	2.60	.081	0.06	0.85	+DLPFC−IFG vs. −DLPFC+IFG	.132	1.47
								+DLPFC−IFG vs. Sham	.036	2.56
								−DLPFC+IFG vs. Sham	.437	0.31
PC fluency	6.60 ± 0.25	5.80 ± 0.26	5.87 ± 0.31	4.23	.018	0.10	2.86	+DLPFC−IFG vs. −DLPFC+IFG	.007	2.27
								+DLPFC−IFG vs. Sham	.035	5.91
								−DLPFC+IFG vs. Sham	.827	0.31
PC originality	2.70 ± 0.30	2.04 ± 0.23	1.59 ± 0.24	5.34	.007	0.12	6.89	+DLPFC−IFG vs. −DLPFC+IFG	.089	2.74
								+DLPFC−IFG vs. Sham	.005	11.40
								−DLPFC+IFG vs. Sham	.147	0.38
PC flexibility	5.60 ± 0.29	5.27 ± 0.29	5.10 ± 0.32	0.84	.436	0.021	0.22	+DLPFC−IFG vs. −DLPFC+IFG	.382	0.45
								+DLPFC−IFG vs. Sham	.216	1.36
								−DLPFC+IFG vs. Sham	.660	0.37

Note. Significance levels were determined using *F* tests based on the bootstrap *SE* estimate for that comparison, rather than using a pooled *SE* estimate. BF_{10} = Bayes factors; +DLPFC−IFG = left anode dorsolateral prefrontal cortex-cathode inferior frontal gyrus group; −DLPFC+IFG = left cathode dorsolateral prefrontal cortex-anode inferior frontal gyrus group; *SE* = standard error; PC = Picture Completion from Torrance Test of Creative Thinking; UU = Unusual Uses from Torrance Test of Creative Thinking; n_p^2 = eta partial squared.

TABLE 5. Differences Between Real (+DLPFC−IFG and −DLPFC+IFG) and Sham tDCS-tRNS Groups in the Percentage of Participants That Solved Matchstick Arithmetic (MA) and Nine-Dot (ND) Problems

	+DLPFC−IFG	−DLPFC+IFG	Sham	χ^2	p	BF_{10}
MA Type B: VI = VI + I	25.0%	34.8%	22.2%	1.06	.590	0.25
MA Type C: VI = VI + VI	37.0%	22.2%	7.4%	6.86	.032	4.49
MA Type D: VI = VI + V	65.0%	52.2%	59.3%	0.73	.693	0.16
ND	25.0%	4.3%	0%	9.94	.007	15.65

Note. BF_{10} = Bayes factors; +DLPFC−IFG = left anode dorsolateral prefrontal cortex-cathode inferior frontal gyrus group; −DLPFC+IFG = left cathode dorsolateral prefrontal cortex-anode inferior frontal gyrus group.

EFFECT OF TDCS-TRNS ON MA AND ND PROBLEMS

The scores on the MA and ND problems are shown in Table 5. For the MA problems, there was only a significant difference among the three groups in the most difficult Type C problem. The percentage of participants that correctly solved the problem was higher in the +DLPFC−IFG group (37.0%) compared with the sham group (7.4%). The rest of MA problems were not statistically significant between groups. The aggregated score showed no significant differences [F (2,79) = 0.97, p = .383].

Regarding the ND problem, several subjects had to be removed from further analyses, which included three participants solved the problem at baseline, and 10 participants already knew the problem. Results showed that the percentage of participants that solved the problem was higher among the +DLPFC−IFG group (25.0%) compared with the sham group (0.0%), which was statistically significant and conclusive.

ADVERSE EFFECTS AND BLINDING

None of the participants reported having experienced any significant adverse effects that made them leave the study. There were no significant differences between the real versus sham groups in minor adverse effects [F (1,78) = 1.80, p = .184]. Moreover, there were no significant differences when comparing the +DLPFC−IFG and −DLPFC+IFG groups separately [F (2,79) = 0.75, p = .477].

We did not find significant differences in stimulation guess between real and sham conditions [χ^2(2, N = 81) = 2.02, p = .364]. From the two real groups, 17% guessed that they had received stimulation, 41.5% guessed they had received the placebo and 41.5% were undecided. From the sham group, 40.7% guessed that they had received the placebo, 29.6% that they had received stimulation, and 29.6% were undecided.

DISCUSSION

The novel findings of this exploratory study were that a combined tDCS-tRNS protocol with anode over the left DLPFC and cathode over the left IFG (+DLPFC−IFG group) simultaneously enhanced CT (RAT), DT (PC fluency and PC originality), and IPS tasks (ND and MA problems) compared with the sham group. Furthermore, Bayesian analyses showed substantial evidence in favor of the alternative hypotheses, which strengthens our traditional statistics. Interestingly, the opposite montage (−DLPFC+IFG) scores in DT, CT, and IPS were mostly in-between the +DLPFC−IFG and sham groups but did not significantly differ from the sham group in any of the scores.

The enhancement in DT (RAT scores) for the +DLPFC−IFG group with anodal stimulation of the left DLPFC is consistent with previous tES studies (Cerruti & Schlaug, 2009; Metuki et al., 2012; Peña et al., 2019, 2021; Zmigrod et al., 2015), as well as neuroimaging studies (Bendetowicz, Urbanski, Aichelburg, Levy, & Volle, 2017; Martin et al., 2018; Zhang et al., 2020). Our combined tDCS-tRNS findings add further evidence of the prominent role of left DLPFC in CT. A possible explanation for this result might be that the left DLPFC exerts top-down control over brain regions involved in stimulus and response processing, enhancing task-relevant information processing and at the same time inhibiting task-irrelevant information (Prutean et al., 2021). It may generate correct responses in spite of the influence of over-learned response trends (Banich, 2009; Botvinick, Carter, Braver, Barch, & Cohen, 2001). Hypothetically, it may therefore facilitate the response selection by assessing the novelty and appropriateness of the response in creativity tasks (Chrysikou, 2019; Kenett et al., 2021; Weinberger et al., 2017). This could be connected to the metacontrol theory since persistence requires to keep on the goal of the task in working by the left DLPFC (Curtis & D'Esposito, 2003; Zhang et al., 2020), and systematic thinking involves that distracting and irrelevant thoughts are blocked out of working memory while attention is fully focused on the task at hand (Nijstad et al., 2010).

Regarding DT, our findings for the greater effect of the +DLPFC−IFG than –DLPFC+IFG group suggest that visual DT performance was strongly affected by the directionality of stimulation from the left DLPFC (anode) to left IFG (cathode), especially on fluency and originality dimensions. Since most of the previous studies have included verbal creativity tasks, it is difficult to compare the current results with previous studies. However, similar to our results, the improvement in visual DT after targeting bilaterally the DLPFC using transcranial alternating current stimulation has been previously shown (Lustenberger, Boyle, Foulser, Mellin, & Fröhlich, 2015). To some extent contrary to our results, there is also evidence of visual DT improvement after cathodal left and anodal right stimulation over the DLPFC (Peña et al., 2021). In this previous study (Peña et al., 2021), tDCS and tRNS were combined as in the present study stimulating left and right DLPFC. One possible reason for this difference may be related to the directionality of the stimulation instead of the areas being stimulated, since the current study stimulated in an anterior–posterior axis, whereas the previous study (Peña et al., 2021) stimulated in a left–right axis. Another possible explanation may be the simultaneous anodal stimulation of the right DLPFC, which might have explained the positive effects on visual DT, in line with a previous neuroimaging meta-analysis (Boccia et al., 2015). However, we cannot draw more decisive conclusions for this result because more research is needed.

Although we did not find a significant main group effect on verbal DT, the exploratory result shows a possible greater effect of the +DLPFC−IFG group on verbal DT compared with sham in the UU test. *Post hoc* Bayesian comparisons also indicated substantial evidence in favor of the alternative hypotheses for UU composite score ($BF_{10} = 5.27$) and UU fluency subdomain ($BF_{10} = 6.37$). Even considering this result with caution, the +DLPFC−IFG montage may enhance verbal DT performance when compared with sham. This specific result is consistent with previous studies that used anodal stimulation over the left DLPFC (Colombo et al., 2015; Peña et al., 2021; Zmigrod et al., 2015) when compared to left cathodal/right anodal stimulation of the DLPFC. As previously mentioned, this stimulation may have boosted the assessment of the novelty and appropriateness of the response in DT tasks (Chrysikou, 2019; Kenett et al., 2021; Weinberger et al., 2017). On the other hand, the simultaneous cathodal stimulation over the left IFG with anodal stimulation of the left DLPFC montage used in this study is also consistent with studies that included only left cathodal tDCS (Chrysikou et al., 2013, 2021; Elisabeth Hertenstein et al., 2019; Ivancovsky et al., 2019; Khalil et al., 2020; Mayseless & Shamay-Tsoory, 2015) and transcranial magnetic stimulation (Kleinmintz et al., 2018) over the left IFG. The improvement in both visual and verbal DT performance with the cathode over the left IFG (Ivancovsky et al., 2019; Mayseless & Shamay-Tsoory, 2015) contrasts with the lack of significant effects on both verbal and visual DT performance during stimulation with cathode over the left DLPFC and anode over the left IFG (−DLPFC+IFG group). Although the neuroimaging evidence of left IFG activation during creativity tasks (Benedek et al., 2014; Ellamil, Dobson, Beeman, & Christoff, 2012; Erhard, Kessler, Neumann, Ortheil, & Lotze, 2014; Gonen-Yaacovi et al., 2013; Kleinmintz et al., 2018; Mayseless, Aharon-Peretz, & Shamay-Tsoory, 2014) might give the impression of being contradictory with these results, a closer inspection suggests that left IFG is mainly active during the evaluation phase of ideas but not during the generation phase (Ellamil et al., 2012; Kleinmintz et al., 2018; Mayseless et al., 2014). Results from tES studies, on the other hand, mostly show that the inhibition of the left IFG with cathodal stimulation (instead of excitation with anodal stimulation) is associated with an improvement in DT tasks. Some authors suggest that the reduction in left IFG activity during the generation phase of original ideas may affect the strictness of the evaluation phase (Kleinmintz et al., 2018) and therefore boost the flexibility route through the enhanced availability of low-level information and facilitation of novel responses via access to widespread associative networks (Ivancovsky et al., 2019; Kenett et al., 2021). Although we cannot determine the differential effect of anodal stimulation of the left DLPFC versus cathodal stimulation of the left IFG from our results, we have been able to compare this montage with the cathode on the left DLPFC and anode on the left IFG (−DLPFC+IFG group). Even taking these results with caution, based on metacontrol theory, the current results may suggest that the enhancement of the persistence route is more sensitive to left DLPFC anodal stimulation (but not cathodal stimulation), whereas the flexibility pathway enhancement seems to be more responsive to cathodal stimulation of left IFG (but not anodal stimulation). However, further research is needed to disentangle the specific role of these core hubs of the creative network as well as the relationship with other brain areas.

Regarding the effects of tDCS-tRNS on IPS, we found significant differences in both the ND and MA problems for the +DLPFC−IFG group compared with sham. The two previous studies that obtained a significant effect on MA after tES used a bilateral montage with cathode on the left DLPFC and anode over the right DLPFC (Di Bernardi Luft et al., 2017; Peña et al., 2021), whereas in the current study, we used a unilateral montage with the anode over the left DLPFC and cathode over the left IFG. This difference in montage may explain the differential results in IPS particularly compared with our previous study (Peña et al., 2021) that used the same tRNS-tDCS parameters. In the present study, although the difference between the two real stimulation groups were not significant, overall the −DLPFC+IFG group performed numerically lower than the +DLPFC−IFG group, but systematically better than the sham group, which is consistent to some extent with previous results (Di Bernardi Luft et al., 2017; Peña et al., 2021). For the −DLPFC+IFG group, the cathode on the left DLPFC may have had a positive effect on IPS tasks, whereas the simultaneous anode over the left IFG may have had a negative effect. A possible reason for this negative effect may be that anodal stimulation of the left IFG may be related to a decrease in the novelty of responses and could have boosted adherence to a typical task completion style (Kenett et al., 2021).

Instead of the traditional anode-excitatory cathode-inhibitory hypothesis of tDCS mechanisms (Lang et al., 2005; Nitsche et al., 2008), alternative explanations for the results obtained in this study may be a mixture of both the montage [close proximity of the anode and cathode electrodes on the left DLPFC/IFG regions; (Garnett, Malyutina, Datta, & Den Ouden, 2015)] and the current flow direction hypothesis (Hannah et al., 2019). By having the anode and cathode electrodes (8 cm^2) in relatively close proximity may have reduced the potential influence of the polarization potential of the opposite polarity electrodes, and thus provided a mixed electric field effect on the underlying cortex and connected networks. However, since the +DLPFC−IFG montage produced consistently greater effects on creativity domains than the opposite montage (−DLPFC+IFG) and sham, the greater influence of the direction of current flow from anode over the DLPFC to the cathode on the IFG may be the crucial difference. According to the current flow direction hypothesis, the effect of tDCS may be more dependent on the current flow direction rather than the specific areas receiving greater excitation or inhibition. Furthermore, the tRNS nested on the tDCS may have also influenced the overall directionality influence, so further studies need to determine the individual and added influence of the two types of tES using modeling and neuroimaging studies.

A possible general explanation for the current results from the metacontrol perspective proposed by Zhang et al. (2020) is that anodal stimulation of the left DLPFC may have boosted the persistence route and concurrent cathodal stimulation of left IFG might have enhanced the flexibility route simultaneously, which in turn may have had a greater positive impact on adaptive metacontrol states. As a consequence, it is possible that this stimulation montage may have made the participants more able to switch between persistence and flexibility pathways during the creativity tasks without producing extreme persistence (related to a too strong top-down bias) nor extreme flexibility (related to too weak top-down bias). According to some authors (Mekern, Sjoerds, & Hommel, 2019), such switching between persistence and flexibility may occur fast, even within one trial.

There are several limitations that require discussion. Firstly, although we used a traditional tES electrodes with two smaller sized sponge-rubber electrodes (8 cm^2), future studies could investigate whether even smaller high definition (HD) tDCS electrodes (3 cm^2) and/or multichannel (i.e., greater than one anode–cathode pair) montages produce more specific and pronounced effects on creativity that has been shown in other executive function cognitive domains (Reinhart, 2017). Secondly, although we considered whether combining tDCS with tRNS will provide cumulative effects on creativity than if used alone, we cannot conclusively confirm whether the results of this study were more due to tDCS or tRNS. Third, the way creativity was measured for both UU and PC included only one item per timepoint. It may partially explain the lack of general significant results in ANCOVA verbal DT analyses. Matchstick problems were assessed also with only one item per type, reducing the reliability of our results. Additionally, the RAT measure used in this study included mostly associative items but also compound items, so we cannot conclude if the positive effect observed was due to insight solution or association processes. Another limitation, which is shared with many tES studies, is the use of different methods, montages, and measures which produce inconsistent results between studies. Therefore, there is a need to develop a tradition of replication and preregistration to test robustness of available findings.

CONCLUSIONS

Using multi-modal tES (tDCS+tRNS) and a unilateral bipolar electrode montage (left DLPC and IFG), we showed that the +DLPC−IFG group induced robust effects on three creativity domains simultaneously (CT, DT, and IPS). These novel results suggest that the directionality effects of tDCS combined with the noise introduced with tRNS over both DLPFC and IFG may have according to the metacontrol theory led to a more efficient switching between persistence (CT) and flexibility (DT and IPS) routes and thus have produced the positive effects found in the three creativity domains examined.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

ETHICS

The study obtained the ethics approval from the Research Ethics Committee of Deusto University (Ref: ETK-31/17–18).

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author.

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