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The Impact of Transcranial Photobiomodulation on the Bilateral Dorsolateral Prefrontal Cortex in Enhancing Convergent Thinking and Stroop Test

Javier Peña[1] | Makii Muthalib[2,3] | Roger E. Beaty[4] | Irune Pérez[1] | Agurne Sampedro[1] | Olaia Lucas-Jiménez[1] | Naroa Ibarretxe-Bilbao[1] | Natalia Ojeda[1]

[1]Department Psychology, Faculty of Health Sciences, University of Deusto, Bilbao, Basque Country, Spain | [2]SilverLine Research, Oxford, UK | [3]EuroMov, Univ. Montpellier, Montpellier, France | [4]Department Psychology, Pennsylvania State University, Pennsylvania, USA

Correspondence: Javier Peña (javier.pena@deusto.es)

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ABSTRACT

Transcranial photobiomodulation (tPBM) has been employed for cognitive enhancement in healthy individuals. This study aimed to investigate the effects of tPBM applied bilaterally over the dorsolateral prefrontal cortex (DLPFC) on convergent thinking (CT), divergent thinking (DT), and the Stroop test. Additionally, we explored whether Stroop performance mediates the effect of tPBM on creativity. In this double-blind, between-subjects study, 56 healthy participants were randomly assigned to either the tPBM or sham group. tPBM was administered using near-infrared light (810 nm, 40 Hz; 50% duty cycle) over the right and left DLPFC for 20 min. Creativity was assessed at baseline and during stimulation using the Unusual Uses (UU) and Picture Completion (PC) for DT, and the Remote Associates Test (RAT) for CT, and the Stroop test. ANCOVA, controlling for baseline scores, revealed that the tPBM group scored significantly higher than the sham group on the RAT ($F = 6.15$, $p = 0.016$) and Stroop ($F = 4.89$, $p = 0.031$). However, no significant differences were observed for DT. The findings suggest that tPBM may be effective in enhancing CT, but its effect does not appear to be mediated by improvements in Stroop performance. These results indicate that tPBM could be a promising tool for cognitive enhancement in the healthy population.

1 | Introduction

Creativity is a fundamental cognitive ability that enables individuals to generate novel and valuable ideas (Runco and Jaeger 2012), playing a critical role in human adaptation, innovation, and problem-solving across diverse fields such as art, science, and technology. It is often conceptualized as comprising two primary subdomains (Zhang et al. 2020): convergent thinking (CT) and divergent thinking (DT). CT involves the ability to derive a single, correct solution to a well-defined problem through logical reasoning and deduction (Zmigrod et al. 2015). In contrast, DT is characterized by the capacity to explore multiple possible solutions to open-ended problems, relying on flexibility, originality, and the generation of a wide range of ideas (Guilford 1967).

Investigating the neural mechanisms underlying creative processes, including both CT and DT, can provide critical insights into how different brain regions and networks interact to facilitate creativity.

Evidence from neuroimaging studies indicates that creativity relies on a complex interaction of multiple brain networks, rather than activity within isolated regions (Beaty et al. 2019). More concretely, creative ability has been positively associated with both the intrinsic connectivity of the Default Mode

Network (DMN) and its functional coupling with the executive control network (ECN) (Beaty et al. 2016). The DMN mainly facilitates idea generation while the ECN guides, constrains, and refines processes generated by the DMN to align with the objectives of the creative task (Beaty et al. 2016). Although there is evidence of the DMN's implication in processes of creative idea evaluation and integration of diverse information from distant brain regions (Luchini et al. 2025). The ECN, encompassing mainly the dorsolateral prefrontal cortex (DLPFC) and parietal regions, is critical for tasks requiring focused attention, inhibitory control, and goal-directed processing, which are essential for CT and the selective refinement of creative ideas (Zhang et al. 2020). The DLPFC plays a pivotal role in creativity, particularly in cognitive processes such as CT and DT (Li et al. 2022), which are integral to creative performance (Zhang et al. 2020). This evidence has catalyzed interest in the use of transcranial electrical stimulation (tES) over the DLPFC as a means of enhancing creative abilities. Studies applying anodal transcranial direct current stimulation (tDCS) (Cerruti and Schlaug 2009; Metuki et al. 2012) and random noise stimulation (tRNS) (Peña, Sampedro, et al. 2021; Peña et al. 2022, 2019) over the left DLPFC have demonstrated improvements in CT tasks, likely by enhancing goal-oriented cognition and associative reasoning pathways.

On the other hand, the effects of tES over the DLPFC on DT are more variable (Chen et al. 2024). While some studies have reported that stimulation with tDCS (Zmigrod et al. 2015; Xiang et al. 2021; Colombo et al. 2015) and tRNS (Peña, Sampedro, et al. 2021; Peña et al. 2019) over the left DLPFC can improve certain aspects of DT such as the fluency dimension, results are generally less robust and consistent compared to CT tasks (Chen et al. 2024). One possible explanation is that DT may benefit less from stimulation of the DLPFC due to the open-ended and expansive nature of the task, which likely demands a distinct balance between inhibitory control and cognitive flexibility compared to CT tasks.

Almost all the studies that used noninvasive brain stimulation for creative enhancement have used tES or repetitive transcranial magnetic stimulation (rTMS) (Chen et al. 2024; Cortes et al. 2023). Recently, transcranial photobiomodulation (tPBM) has emerged as a promising tool for cognitive enhancement both in healthy and neurological populations (Salehpour et al. 2018). tPBM is a noninvasive neuromodulation technique that utilizes near-infrared light to influence brain activity, primarily through its effects on mitochondrial function and cerebral blood flow (Hennessy and Hamblin 2017), which can be considered a form of neurovascular modulation (Hosseini and Bikson 2021). A widely supported mechanism of action involves the absorption of near-infrared photons by cytochrome c oxidase in neuronal mitochondria, which enhances mitochondrial oxidative metabolism and increases cellular ATP availability (Karu 1988). In addition, tPBM has been shown to increase bioavailable nitric oxide (NO), via endothelial and neuronal NO synthases within the cerebral vasculature, resulting in vasodilation and increased regional cerebral blood flow (Tian et al. 2016), enhancing oxygen delivery. These effects collectively contribute to increased metabolic and hemodynamic support to the brain. Additional effects include strengthening antioxidant defenses (Lu et al. 2017) or the stimulation of neurotrophic factors (Xuan et al. 2015), highlighting its neuroprotective and regenerative properties (Wong-Riley et al. 2005). tPBM is mechanistically distinct from tES and rTMS in that it modulates mitochondrial bioenergetics rather than directly applying electric or magnetic fields to cortical tissue, a difference that may confer important advantages for large-scale cognitive network modulation (Peña et al. 2023). By contrast, tDCS and rTMS primarily influence neuronal function through shifts in transmembrane potentials and synaptic efficacy, with spatial effects largely constrained to superficial cortical regions (Beaty et al. 2014; Shofty et al. 2022). Relative to tES, tPBM does not rely on current flow through the scalp and skull, reducing interindividual variability related to coil or electrode configuration, skull properties, and baseline cortical excitability (Sunavsky and Poppenk 2020). Additionally, tPBM presents practical and safety-related advantages that strengthen its translational relevance. Compared to rTMS, tPBM is nonthermal, noninvasive, low risk, and well tolerated, with virtually no serious adverse events and does not induce scalp muscle activation, and has a substantially lower risk of adverse events such as seizures (Takeuchi et al. 2020; Borwick et al. 2020) while also allowing simultaneous EEG acquisition without electromagnetic interference (Salehpour et al. 2018; Ly et al. 2017).

As far as the authors are aware, only our previous study has used tPBM for creative thinking enhancement (Brosnan and Wiegand 2017). In this study, tPBM was applied over the main hubs of the DMN, and findings suggested a significant improvement in DT, but not in CT. These results are in line with previous research, indicating that the DMN is highly related to DT processes (Mitchell 2010; Hommel et al. 2011; Loftus et al. 2015; Friehs and Frings 2018).

As previously stated, the DLPFC, as a primary hub of the ECN, has been implicated in Stroop performance and interference resolution (Parris et al. 2021; Becker and Cabeza 2022; Peña Sampedro, GÓmez-Gastiasoro, et al. 2021). Neuroimaging studies have provided substantial evidence for the involvement of this region during Stroop task execution (Faul et al. 2007). Altogether, previous research suggests that Stroop performance and creativity are correlated (Torrance 1966), and they share at least some neural underpinnings, including the DLPFC. Regarding brain stimulation studies that have investigated Stroop performance, evidence shows that tDCS over the DLPFC results in improved Stroop task performance (Mednick 1962; Becker and Cabeza 2023), although there is also evidence of no significant effect (C. J. S. T. R. O. O. P. Golden 2001). Previous studies have shown that tPBM over the DLPFC improves executive function using offline protocols (Blanco et al. 2017; O'Donnell et al. 2022), but as far as the authors are aware, none of the previous studies have investigated the online effects of tPBM over the bilateral DLPFC can induce changes in Stroop performance.

On the other hand, commonly used measures of CT (Remote Associates Test [RAT]) and DT (Alternative Uses Task) are language-dependent measures of creativity. To address this limitation, Becker and Cabeza recently developed a language-independent Remote Associates task (LI-RAT) (C. J. Golden 1978), which uses image-based stimuli to enhance external validity. Previous studies examining the effects of noninvasive brain stimulation on CT have exclusively used verbally based RAT. In this study, we sought to include an additional language-independent measure of CT (LI-RAT) for two main objectives: first, to assess whether bilateral stimulation of the DLPFC using tPBM induces changes in a visually based CT task, and second, to provide CT evidence free from linguistic and cultural biases, enabling cross-cultural comparisons between studies.

Therefore, the aim of this study was to investigate if tPBM over left and right DLPFC produces a significant improvement in both verbal and visual CT. As exploratory additional hypotheses, we expect a significant improvement in both verbal and visual DT and Stroop performance. Additionally, we also tested this exploratory aim: If the effect of tPBM on creativity was mediated by improvements in Stroop performance. Our specific hypotheses are the following: (1) tPBM over the bilateral DLPFC will enhance CT in both verbal and visual CT tasks; (2) exploratory hypothesis that tPBM over the bilateral DLPFC will improve the fluency dimension of both verbal and visual DT tasks; (3) exploratory hypothesis that tPBM over the bilateral DLPFC will improve the interference score from the Stroop task performance, reflecting enhanced inhibitory control and this improvement in Stroop will act as a mediator of the effect of tPBM on CT and DT improvement.

2 | Methods

2.1 | Statistical Power and Sample Size Estimation

The sample size calculation was based on a previous study using tPBM over the DMN on DT (Preacher and Hayes 2008). Using the G*Power 3 software (IBM corp 2015), a sample size of 56 subjects, 28 in each group, was enough to attain an effect size of $f = 0.38$ to detect differences in DT and CT with 80% power and a 5% level of significance.

2.2 | Participants

We recruited 56 healthy and native Spanish-speaking volunteers (aged 18 years or above) from the general population, based on the power analysis. There were no restrictions on gender or handedness of participants.

Participants did not receive any course credit or monetary compensation for participating in the study. The study obtained ethical approval from the Research Ethics Committee of The University of Deusto (Ref: ETK-8/21–22).

All volunteers provided written informed consent to participate in the study and they were free to withdraw at any time. All experimental procedures were conducted in accordance with the Declaration of Helsinki (2013).

2.3 | Design and Procedure

This randomized double-blind, sham-controlled, parallel-group between-subjects design study consisted of one single session. The participants were randomly (block randomization) assigned to one of the two groups ($n = 28$ in each group): real tPBM device and sham device with a computer generated randomization (www.randomizer.org). To ensure a double-blind design, the active and sham devices were physically indistinguishable and identified only by specific codes unknown to the evaluator. Although sex and age were not stratified a priori, the distribution of these variables between groups was analyzed. Both participants and experimenters remained blind to the stimulation condition throughout the study.

After signing the consent form, baseline creativity assessment was carried out before starting the tPBM session. The order of the task administration was fixed. First, the Stroop test was administered (45 s for each of the three conditions). Then subjects had 2 min and 45 s to complete the RAT. Afterwards, LI-RAT was administered and they were asked to give an answer to each item in 7 s. Then DT tasks (UU and PC) from the Torrance Test of Creative Thinking Test were administered. First UU and finally PC (2 min for each task).

During the application of tPBM (or placebo), the participants carried out the parallel versions of RAT, LI-RAT, UU, and PC in a counterbalanced order. We assessed the blinding efficacy by asking participants to answer the following sentence: “Please, tell us if you think you were receiving real stimulation, no stimulation (placebo) or you do not know?”

2.4 | tPBM

We used the “Vielight Neuro Gamma” tPBM device (Neuro Gamma, Toronto, Canada) in this study. The device consists of a controller and a headset with four light-emitting diode (LED) modules, but for this study only 2 LEDs were used on the bilateral DLPFC. The Neuro Gamma delivers painless, noninvasive, nonthermal, non-laser, pulsed (40 Hz; 50% duty cycle), near-infrared light (810 nm wavelength), through the 2 non-laser LEDs over a 20-min session. The LEDs were positioned over the left and right DLPFC (F3 and F4, according to the EEG 10–20 system). The power density output of each LED was 100 mW/cm2. The sham device was used for the sham group. The sham is indistinguishable from the intervention to the participants. It has an optical sensor which prompts the device to switch off after the headset is in contact with the scalp for 3 s.

2.5 | Measures

2.5.1 | Visual Divergent Thinking

PC subtest from *The Torrance Test of Creative Thinking* (Lee and Therriault 2013) was included in the study. We included two different forms (Form A and B) for the baseline and poststimulation assessments. We measured three dimensions based on two raters: fluency, originality, and flexibility. We converted fluency, originality, and flexibility measures to z-scores to obtain PC composite based on the whole sample mean and standard deviation of each assessment point. The inter-rater reliability ranged from 0.96 to 0.99. The internal consistency was good (Cronbach's alpha = 0.88).

2.5.2 | Verbal Divergent Thinking

UU subtest from *The Torrance Test of Creative Thinking* (Lee and Therriault 2013) was included in the study. We included two different forms (Form A and B) for the baseline and poststimulation assessments. We measured three dimensions based on two raters: fluency, originality, and flexibility. We converted fluency, originality, and flexibility measures to z-scores to obtain UU composite based on the whole sample mean and standard deviation of each assessment point. The inter-rater reliability ranged from 0.89 to 0.99. The internal consistency was good (Cronbach's alpha = 0.93).

2.5.3 | Verbal Convergent Thinking

The Spanish version of the RAT (Nijstad et al. 2010) 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 was based on 30 items. Participants had 2 min and 45 s to write down as many correct items as possible. The items were presented on 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).

2.5.4 | Visual Convergent Thinking

The LI-RAT is a more recent instrument developed to measure CT without the influence of language (Fink and Benedek 2014). In order to do this, participants are presented with two images and are instructed to find a target object connected to both cues. Unlike in the RAT, the relationship is not purely conceptual; rather, one of the cues is connected conceptually while the other is connected perceptually. For instance, when presented with a bowling ball (perceptual) and a palm tree (conceptual), participants are intended to respond "coconut". In the present study, 20 different items were presented in the pretest and posttest, coming up to a total of 40 items. Each pair of items were presented on a laptop screen (15.6 in.) and participants had 7 s to give an answer.

2.5.5 | Stroop Test

The Spanish paper-based adaptation (Kounios and Beeman 2014) of the original Stroop test (Beaty et al. 2015) was used. It consists of three different conditions in which participants are presented with (1) color words printed in black ink, (2) crosses (XXXX) printed in colors, and (3) color words printed in inks that do not match their meaning. In the first condition, participants are instructed to read the words, while in the other two they are asked to name the ink color. Importantly, due to the color-word interference, in the third condition participants must suppress their automatic reading response to correctly perform the task. Participants were given 45 s to verbalize as many items as possible and were instructed to self-correct in case of errors. The number of responses was recorded. The interference measure was calculated: Interference = color-word score − [(word * color) / (word + color)] and analyzed. Higher scores reflect higher cognitive inhibition performance. The Stroop test has demonstrated high internal consistency, with a Cronbach's alpha of 0.80.

2.6 | Statistical Analyses

Baseline characteristics were compared using X^2 test for categorical data and ANOVA test for continuous variables. ANCOVA was used to compare poststimulation scores (controlling for baseline scores) between the two groups for each of the creativity variables. Effect size (n_p^2) was also calculated. To examine whether the association between tPBM and creative improvement was mediated by the improvement in Stroop performance, linear regression models were fitted using bootstrapped mediation procedures included in the PROCESS SPSS macro (Mayseless et al. 2015). IBM SPSS software version 23.0 (Ellamil et al. 2012) was used for statistical analyses. All tests were two-tailed and the significance level was set at 0.05.

3 | Results

3.1 | Baseline Characteristics

There were no significant differences in any of the variables at baseline including age, sex, years of education, and handedness (See Table 1).

TABLE 1 | Participant characteristics of the tPBM and sham groups at baseline.

	tPBM	**Sham**		
	Mean ± SD	**Mean ± SD**	**Statistic**	***p* value**
Age	29.13 ± 11.80	27.48 ± 10.74	F (1,56) = 0.31	0.579
Years of education	14.58 ± 2.93	14.86 ± 2.56	F (1,56) = 0.12	0.732
Gender: *n* (%) Females	15 (51.7%)	16 (55.2%)	X^2 (1, N = 58) = 0.07	0.792
Edinburgh handedness	43.11 ± 43.76	46.35 ± 43.24	F (1,56) = 0.06	0.804

Abbreviations: SD, standard deviation; tPBM, transcranial photobiomodulation.

3.2 | Effects of tPBM on Creativity

The CT (RAT and LI-RAT) and DT (Unusual Uses and Picture Completion) scores at baseline and online results are displayed in Table 2.

ANCOVA results (online comparisons controlling for baseline scores) are shown in Table 3. Regarding CT, results suggest that RAT was significantly higher during tPBM compared to sham, indicating a moderate effect size ($n_p^2 = 0.098$). LI-RAT, on the other hand, did not show any significant effects. Similarly, verbal and visual DT scores were not statistically significant.

As secondary analyses, we analyzed subdimensions of both UU and PC (See Tables 4 and 5). Preliminary exploratory results suggest that tPBM produced a significant improvement in the visual fluency domain ($n_p^2 = 0.085$) although it must be interpreted cautiously. The rest of the DT subdomains were not significant.

TABLE 2 | Creativity scores of the tPBM and sham groups at baseline and during stimulation.

		tPBM	Sham
		Mean ± SD	**Mean ± SD**
RAT	Baseline	7.25 ± 2.93	9.07 ± 4.26
	During stimulation	9.75 ± 3.27	9.29 ± 3.27
LI-RAT	Baseline	5.50 ± 3.34	6.36 ± 3.52
	During stimulation	6.29 ± 3.13	6.54 ± 3.24
Total UU	Baseline	−0.08 ± 0.93	0.08 ± 0.84
	During stimulation	−0.09 ± 0.88	0.09 ± 0.99
Total PC	Baseline	−0.05 ± 0.87	0.05 ± 0.92
	During stimulation	0.13 ± 0.80	−0.13 ± 1.00

Abbreviations: LI-RAT, number of correct answers in Language-independent Remote Associates Test; PC, Picture Completion from Torrance Test of creative thinking; RAT, number of correct answers in Remote Associates Test; SD, standard deviation; tPBM, transcranial photobiomodulation; UU, Unusual Uses from Torrance Test of Creative Thinking.

The correlation among the baseline creative scores is displayed in Table 6. LI-RAT and RAT were not significantly correlated, whereas RAT was significantly related to both verbal and visual DT.

3.3 | Effects of tPBM on Stroop Performance

ANCOVA results indicated that tPBM produced a significant effect ($F = 4.89$, $p = 0.031$, $n_p^2 = 0.085$) on the Stroop interference scores compared to sham (marginal means ± standard error: 8.95 ± 1.08 vs. 5.58 ± 1.08, respectively).

3.4 | Stroop Improvement Mediation Analysis

Given that tPBM produced a significant improvement in Stroop interference scores, we proceeded to analyze if the effect of tPBM on verbal CT and the fluency subdomain of DT was partially mediated by the improvement in Stroop performance. Results indicated that there was no significant mediation effect for any of the analyses performed (bootstrapped 95% confidence interval for indirect effect on verbal CT: −0.50–0.36 and fluency subdomain of DT: −0.19–0.30), so the improvement in Stroop interference performance did not significantly explain the improvement in RAT nor in fluency DT during tPBM.

3.5 | Blinding

Our results suggest that participants were not able to guess between real and sham conditions [$\chi^2(2, N = 56) = 4.39$, $p = 0.085$]. From the real tPBM group, 42.9% guessed that they had received stimulation, 39.3% guessed they had received the placebo, and 17.9% were undecided. From the sham group, 35.7% guessed that they had received the placebo, 21.4% that they had received stimulation, and 42.9% were undecided.

4 | Discussion

The present study showed that tPBM stimulation over the right and left DLPFC can enhance verbal CT and Stroop performance. Although we also expected to find a significant effect in visual CT (LI-RAT), results were not significant. Similarly, we only found a small effect on the fluency dimension of visual DT.

TABLE 3 | Differences between the tPBM and sham groups during stimulation in convergent and divergent thinking scores after controlling for baseline scores.

	tPBM	Sham			
	Marginal mean ± SE	**Marginal mean ± SE**	**F**	***p***	n_p^2
RAT	10.31 ± 0.46	8.72 ± 0.46	5.74	0.020	0.098
LI-RAT	6.32 ± 0.60	6.50 ± 0.60	0.04	0.833	
Total PC	0.16 ± 0.80	−0.16 ± 0.12	3.34	0.073	
Total UU	0.04 ± 0.14	−0.04 ± 0.14	0.16	0.688	

Abbreviations: n_p^2, Eta partial squared; PC, Picture Completion from torrance test of creative thinking; SE, standard error; tPBM, transcranial photobiomodulation; UU, Unusual Uses from torrance test of creative thinking.

TABLE 4 | Divergent thinking subdomain scores (Fluency, originality, and flexibility) of tPBM and sham groups at baseline and during stimulation.

		tPBM	Sham
		Mean ± SD	**Mean ± SD**
UU fluency	Baseline	8.11 ± 3.57	8.57 ± 2.94
	During stimulation	9.04 ± 3.13	9.75 ± 3.45
UU originality	Baseline	5.68 ± 3.31	6.11 ± 2.42
	During stimulation	6.57 ± 3.18	7.43 ± 3.26
UU flexibility	Baseline	5.75 ± 2.07	6.18 ± 2.06
	During stimulation	6.68 ± 2.11	6.86 ± 2.30
PC fluency	Baseline	6.79 ± 2.30	7.11 ± 2.22
	During stimulation	7.25 ± 1.86	6.68 ± 2.33
PC originality	Baseline	2.79 ± 1.60	2.61 ± 1.73
	During stimulation	3.14 ± 1.86	2.50 ± 1.73
PC flexibility	Baseline	5.96 ± 1.99	6.43 ± 1.97
	During stimulation	6.43 ± 1.68	6.18 ± 2.23

Abbreviations: PC, Picture Completion from torrance test of creative thinking; SD, standard deviation; tPBM, transcranial photobiomodulation; UU, Unusual Uses from torrance test of creative thinking.

TABLE 5 | Differences between the tPBM and sham groups in UU, and PC subdomains under stimulation scores after controlling for baseline scores.

	tPBM	Sham	F	p	n_p^2
	Marginal mean ± SE	**Marginal mean ± SE**			
UU fluency	9.19 ± 0.46	9.59 ± 0.46	0.37	0.547	
UU originality	6.70 ± 0.52	7.30 ± 0.52	0.67	0.416	
UU flexibility	6.79 ± 0.37	6.75 ± 0.37	0.01	0.932	
PC fluency	7.37 ± 0.26	6.56 ± 0.26	4.94	0.031	0.085
PC originality	3.11 ± 0.31	2.54 ± 0.31	1.61	0.210	
PC flexibility	6.56 ± 0.31	6.05 ± 0.31	1.32	0.255	

Abbreviations: n_p^2, Eta partial squared; PC, Picture Completion from torrance test of creative thinking; SE, standard error; tPBM, transcranial photobiomodulation; UU, Unusual Uses from torrance test of creative thinking.

TABLE 6 | Baseline correlation matrix of creative scores.

	RAT	LI-RAT	Total PC	Total UU
RAT	1	0.14	0.29*	0.43**
LI-RAT		1	−0.13	0.11
Total PC			1	0.39*
Total UU				1

Abbreviations: LI-RAT, Language-Independent Remote Associates Test; PC, Picture Completion from torrance test of creative thinking; RAT, number of correct answers in remote associates test; UU, Unusual Uses from torrance test of creative thinking.

The significant verbal CT improvement during tPBM stimulation of the bilateral DLPFC is consistent with previous tES studies revised in a meta-analysis (Chen et al. 2024), including tDCS (Cerruti and Schlaug 2009; Metuki et al. 2012), and tRNS (Peña, Sampedro, et al. 2021; Peña et al. 2022). This effect is likely due to the role of the DLPFC in supporting executive functions critical for CT tasks that require systematic reasoning and logical problem-solving (Jung et al. 2013).

More specifically, the positive effect of DLPFC stimulation with tPBM on verbal CT but not on general DT may be due to its effect on reinforcing pathways involved in focused and goal-oriented cognitive processes. Zhang et al. (Zhang et al. 2020) posited that the left DLPFC and the left inferior frontal gyrus (IFG) play a pivotal role in transitioning between metacontrol states, specifically shifting from a flexible to a more persistent cognitive approach. The authors suggest that these two routes operate distinctly in DT and CT; the persistence route appears to predominate in CT, likely facilitating systematic and effortful exploration within a limited set of categories (Frings et al. 2018). Further supporting evidence for this relationship is found in the correlation between working memory and executive functioning with CT, as opposed to DT (Jung et al. 2013). Nonetheless, RAT problems can be solved in more than one way. Prior research indicates that they may be resolved through an insight-based process, often described as a sudden "Aha moment" accompanied by limited awareness of the underlying cognitive mechanisms (Teymoori et al. 2023). This type of solution has been linked to inwardly focused attention (Blanco et al. 2017). In the present study, however, we cannot determine whether participants predominantly relied on insight or on a more deliberate analytical strategy, as they were not directly asked to report how they reached their answers. Future research could address this issue more directly by recording the type of solution strategy used after each RAT item and/or use functional neuroimaging to determine the level of cognitive load used to achieve the solution.

Regarding visual CT, as far as the authors are aware, this is the first noninvasive brain stimulation study to include a nonverbal version of RAT (LI-RAT). Therefore, we cannot make any direct comparison with previous studies. A possible reason for the negative results in LI-RAT but significant improvement in RAT may be that, unlike in the RAT, the relationship between items in LI-RAT is not purely conceptual; rather, one of the cues is connected conceptually while the other is connected perceptually. Therefore, it is possible that both tests are measuring not exactly the same cognitive processes. Nevertheless, as the effects of noninvasive brain stimulation on LI-RAT scores have not been previously investigated, further research is needed to elucidate the mechanisms underlying performance on this new CT task.

Our results indicated that tPBM did not produce significant effects on originality and flexibility subdomains of DT, whereas a significant improvement was found in the visual fluency dimension. However, this exploratory result must be interpreted cautiously. Although some previous tES studies reported a significant effect on DT (Zmigrod et al. 2015; Xiang et al. 2021; Colombo et al. 2015), meta-analytical findings suggest that evidence for DT enhancement with DLPFC stimulation is less consistent than for CT (Chen et al. 2024). The present results may reflect the prominent role of the DLPFC in the ECN for tasks requiring focused attention, inhibitory control, and goal-directed processing, rather than in idea generation, which numerous neuroimaging (Beaty et al. 2019, 2016; O'Donnell et al. 2022; Baumert et al. 2020; Vanderhasselt et al. 2006; Huang et al. 2024) and noninvasive brain stimulation research (Brosnan and Wiegand 2017; Hommel et al. 2011) have more consistently associated with the DMN.

In the present study, the improvement in Stroop performance with an online tPBM protocol aligns with previous tES research targeting prefrontal regions using both tDCS (Parris et al. 2021; Kim et al. 2019; Lange et al. 2017) and tPBM (Başaran et al. 2022; Lee et al. 2024). However, there is also evidence indicating a lack of significant improvement on Stroop tasks following tDCS over the left DLPFC (Buitenweg et al. 2019). Additional support for the DLPFC's involvement in Stroop task performance comes from studies employing rTMS, which show that high-frequency stimulation of the left DLPFC can improve Stroop performance [69]. Collectively, these findings highlight the DLPFC's essential role in supporting the cognitive control mechanisms required for successful Stroop task completion. An interesting finding of our study was that we could not find empirical evidence for a mediating effect of Stroop interference on tPBM's influence on verbal CT. As previously suggested, other cognitive processes, such as working memory and other executive functions, may partly underlie this tPBM stimulation effect on CT. Future studies could clarify the mediational mechanisms through which tPBM impacts higher-order cognitive processes, such as creativity.

The improvement of both creativity and Stroop performance through tPBM of the bilateral DLPFC holds significant clinical relevance in the treatment of various neurological and psychiatric disorders that rely on the ECN. Cognitive inhibition, a key component of executive function, is often impaired in conditions such as depression [70], anxiety disorders [71], and neurodegenerative diseases [72]. By enhancing Stroop performance, tPBM may offer a safe noninvasive approach to ameliorate symptoms and improve overall cognitive functioning in these patient populations. For instance, in major depressive disorder, where cognitive rigidity is a common feature, tPBM-induced improvements in Stroop performance could potentially lead to more adaptive thinking patterns, enhanced problem-solving abilities, and better emotional regulation [73], ultimately contributing to symptom reduction and improved quality of life. Furthermore, the clinical application of tPBM for improving Stroop performance extends beyond mental health disorders. In the context of aging and age-related cognitive decline, enhancing Stroop performance could help older adults maintain their ability to adapt to new situations, learn new skills, and navigate complex environments [74]. This has implications for preserving independence and quality of life in the elderly population [75].

Although the present study yielded some interesting findings, several limitations should be acknowledged. First, since we stimulated both the left and right DLPFC simultaneously with tPBM, we are unable to isolate the specific effects of each hemisphere on the observed outcomes. Second, we exclusively used a 40 Hz frequency during tPBM, which precludes us from determining whether different pulse rates might yield distinct effects on creativity and Stroop performance. Similarly, there is limited knowledge regarding the optimal tPBM dose and ways to determine, including the NIR LED power density, wavelengths, frequency and size, skin color, ideal number of sessions, and the combination of stimulated areas. Third, the study relied on an unpaid convenience sample, which may limit the generalizability of the findings to the broader population. Additionally, given that all tasks were administered at two time points, practice effects may vary by task, even after controlling for baseline performance via ANCOVA. Lastly, while significant improvements were observed in the RAT, the visual DT task exhibited a pattern of improvement during tPBM, but these changes did not reach statistical significance. This may be due to limited statistical power caused by the sample size, potentially leading to an underpowered result. In sum, this study involved a single stimulation session in healthy participants without assessing functional or long-term outcomes. Further research is required in clinical populations, educational contexts, and longitudinal designs to test sustainability, generalizability, and practical significance.

The future of tPBM holds significant promise for advancing noninvasive brain stimulation techniques in enhancing cognitive performance in healthy individuals and the possible influence on clinical populations as discussed earlier. Future research directions may focus on optimizing tPBM stimulation dosing parameters, including frequency, wavelength, power density, and treatment duration, to maximize therapeutic efficacy. Additionally, the development of more sophisticated and miniaturised light delivery systems and wearable devices could facilitate long-term, home-based tPBM interventions, potentially expanding its accessibility and clinical utility. Integrating tPBM with other neuroimaging and neuromodulation techniques, such as functional near-infrared spectroscopy, functional magnetic resonance imaging, or electroencephalography, may provide valuable insights into its effects on brain function and connectivity, enabling more targeted and personalized treatment approaches.

5 | Impact on Education

The present findings may carry potential implications for the learning and teaching of creativity and in general executive control. The selective enhancement of CT and Stroop performance through tPBM over the right and left DLPFC highlights the role of executive control processes in structured problem-solving and logical reasoning. In educational contexts, this suggests that creativity training should not be limited to the promotion of divergent idea generation, but could also potentially incorporate opportunities to strengthen analytical and evaluative skills that support CT. Our study may provide a potential neurocognitive basis for developing teaching strategies that more deliberately balance activities fostering exploratory thinking with tasks that encourage systematic reasoning, and pave the way to introducing a simple and noninvasive way to help enhance these creative thinking skills through tPBM. Such an approach could potentially help students not only to generate novel ideas but also to refine and implement them effectively, thereby supporting a more comprehensive cultivation of creativity within the classroom.

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Ethics Statement

The study obtained the ethical approval from the Research Ethics Committee of Deusto University (Ref: ETK-8/21–22).

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

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

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