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Enhancement of Divergent Creative Thinking After Transcranial Near-Infrared Photobiomodulation Over the Default Mode Network

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ABSTRACT

Transcranial photobiomodulation (tPBM) has been used for cognitive enhancement in healthy people. However, its effect on creativity has not been investigated. The default mode network (DMN) is associated with divergent thinking (DT; but not convergent thinking, CT), and also with anxiety, which in turn has been negatively related to creativity. We aimed to use tPBM over the DMN to assess the effect on DT compared to sham. Additionally, we assessed the possible mediating effect of anxiety between tPBM and DT. In this single-blind, between-subjects study, 58 healthy participants were randomly assigned to tPBM or sham group. tPBM was applied using near-infrared light (810 nm, 40 Hz; 50% duty cycle), through light-emitting diode devices combining transcranial plus intranasal PBM over the cortical nodes of the DMN for 20 min (240 J/cm^2 in total). DT and CT were assessed before (baseline) and after tPBM with the Unusual Uses (UU), Picture Completion (PC) and Remote Associates test (RAT). ANCOVA (post-stimulation controlling for baseline) results showed that tPBM group had significantly higher scores compared to sham in total UU, PC, and total DT. tPBM may be effective for DT enhancement. The lack of effect on CT reveals a specific link between DMN and DT.

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Keywords
Transcranial photobiomodulation; creativity; default mode network; divergent thinking

Introduction

Creativity is a highly valued characteristic in the current society due to its link with accomplishments in different fields, including workplace organization (Agars, Kaufman, & Locke, 2007; Samani, Abdul Rasid, & Bt Sofian, 2015), music composition (Collins, 2005), academic achievement (Gajda, Karwowski, & Beghetto, 2017), or scientific progress (Wilcox, Cortese, Baravelli, & Skjaerven, 2018). Therefore, the enhancement of creativity is a highly valued aim (Pick & Lavidor, 2019).

Traditionally, creativity has been defined as the ability to produce ideas and products that are both original and effective (Runco & Jaeger, 2012). Scientific literature on creativity has consistently differentiated between divergent thinking (DT) and convergent thinking (CT). DT has been previously defined as the ability to generate multiple alternative and novel solutions to a single problem while simultaneously establishing remote associations between unrelated concepts from distant categories (Guilford, 1967), whereas CT involves finding a single solution to a problem in a deductive way (Sharon Zmigrod, Colzato, & Hommel, 2015).

Neuroimaging and creativity

The neuroscience of creativity has attempted to disentangle the neural underpinnings of both DT and CT. In this context, several studies have supported the idea that DT is mostly associated with the default mode network (DMN) (Beaty et al., 2014; Jung, Mead, Carrasco, & Flores, 2013; Kühn et al., 2014; Mayseless, Eran, & Shamay-Tsoory, 2015; Shofty et al., 2022; Sunavsky & Poppenk, 2020; Takeuchi et al., 2020), although there is also strong evidence suggesting that creativity emerges from the synchronization of three cortical networks: the DMN, salience network, and the executive control network (Beaty et al., 2018; Beaty, Benedek, Barry Kaufman, & Silvia, 2015; Beaty, Benedek, Silvia, & Schacter, 2016). The DMN includes the medial prefrontal cortex, inferior parietal lobes, posterior cingulate cortex, and medial temporal lobes (Andrews-Hanna, Reidler, Sepulcre, Poulin, & Buckner, 2010; Spreng, Stevens, Chamberlain, Gilmore, & Schacter, 2010), and is suggested to be involved in several cognitive processes, including episodic memory, mental simulation, mind wandering, semantic memory retrieval or semantic integration (Andrews-Hanna, Smallwood, & Spreng,

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2014; Beaty, Seli, & Schacter, 2019; Buckner, Andrews-Hanna, & Schacter, 2008; Kleinmintz, Ivancovsky, & Shamay-Tsoory, 2019; Raichle, 2015; Spreng, Gerlach, Turner, & Schacter, 2015; Volle, 2018; Wu et al., 2015; Zabelina & Andrews-Hanna, 2016). All these cognitive processes are related to the so-called generation phase of the two-fold model of creative thinking (Kleinmintz, Ivancovsky, & Shamay-Tsoory, 2019), which consists in the activation through a semantic network in order to combine unrelated categories in an original way. For example, there is evidence suggesting that the brain regions involved in episodic memory typically exhibit increased activity during the creative thinking process (Ellamil, Dobson, Beeman, & Christoff, 2012). Additional evidence comes from patients with hippocampal damage, who show an impairment in both episodic memory and DT tasks (Duff, Kurczek, Rubin, Cohen, & Tranel, 2013). In another study, an episodic-specificity induction was able to enhance DT performance but not CT (Madore, Addis, & Science, 2015). A recent study proposed an integrated theoretical framework that describes how creative ideas arise across four distinguishable stages of memory search, including episodic memory (Benedek, Beaty, Schacter, & Kenett, 2023). In sum, all these results indicate that episodic memory retrieval contributes to DT.

Another important cognitive process that is related to both the DMN and creativity is mind wandering. The activity of the DMN is increased during mind wandering (Gusnard, Akbudak, Shulman, & Raichle, 2001; Jung, Mead, Carrasco, & Flores, 2013) and there is evidence suggesting that it is correlated positively with creativity (Preiss, Cosmelli, Grau, & Ortiz, 2016). More specifically, some authors suggest that DT might benefit more from mind wandering than CT (Madore, Addis, & Science, 2015; Murray, Liang, Brosowsky, & Seli, 2021). There is also evidence suggesting the opposite way, including a reduction in mind wandering after inhibiting the medial prefrontal cortex with cathodal transcranial electrical stimulation (tES, see also next section), but only among men (Bertossi, Peccenini, Solmi, Avenanti, & Ciaramelli, 2017).

Results from functional magnetic resonance imaging studies suggest that functional connectivity of various areas involving the DMN supports higher DT performance, including DT tasks such as the alternate uses task (Beaty et al., 2014; Takeuchi et al., 2012). There is also evidence of a correlation between greater DT and greater fractional anisotropy values on nodes of the DMN (Takeuchi et al., 2010a). Similarly, gray matter volume of different nodes of the DMN has been associated with creativity (Buckner, Andrews-Hanna, & Schacter, 2008; Kühn et al., 2014; Sunavsky & Poppenk, 2020). On the other hand, CT is often associated with the main hub of the cognitive (executive) control network, the dorsolateral prefrontal cortex (Gonen-Yaacovi et al., 2013; Martin et al., 2018; Takeuchi et al., 2010b Zhang, Sjoerds, & Hommel, 2020), instead of the DMN.

Transcranial electrical stimulation and creativity

Along with neuroimaging studies, there have been several studies aiming to improve creativity through tES (see Weinberger, Green, & Chrysikou, 2017) for a review). Most studies have targeted brain areas related to the cognitive control network (Colombo, Bartesaghi, Simonelli, & Antonietti, 2015; Grabner, Krenn, Fink, Arendasy, & Benedek, 2018; Lustenberger, Boyle, Foulser, Mellin, & Fröhlich, 2015; Peña et al., 2021; Peña, Sampedro, Ibarretxe-Bilbao, Zubiaurre-Elorza, & Ojeda, 2019; Zmigrod, Colzato, & Hommel, 2015), whereas a few targeted single brain areas of the DMN, mainly posterior parietal cortex (Ghanavati, Nejati, & Salehinejad, 2018; Ghanavati, Salehinejad, Nejati, & Nitsche, 2019; Peña et al., 2022). These studies found a significant improvement in the originality dimension in visual tasks, a result that is consistent with the idea of the role of the DMN on DT. Importantly, however, they only targeted a single brain region instead of stimulating the entire DMN. More recently, in a unique study carried out by Shofty et al. (2022). in epilepsy patients implanted with cortical electrodes, the authors used direct cortical electrical stimulation in these awake patients to disrupt individually identified regions of the DMN while performing a DT task. They found that the temporary inhibition of DMN nodes using direct cortical stimulation produced a decreased fluency performance in a verbal DT task. Additional evidence of the relationship between the DMN and creativity comes from studies that used DT training (Fink et al., 2015, 2018). In the first study (Fink et al., 2015), DT training was linked to changes in activity of regions from the DMN. In the second study (Fink et al., 2018), the successful training of verbal DT was followed by functional connectivity changes not only in the DMN but also in the sensorimotor/auditory network, and the attention network.

Transcranial photobiomodulation and creativity

To our knowledge, no previous studies have used transcranial photobiomodulation (tPBM) in the field of creativity. This technique (tPBM) has recently emerged as a promising tool for cognitive enhancement (Lee, Ding, & Chan, 2023; Salehpour et al., 2018) and it involves exposing neural tissue to light wavelengths

that usually range from red to near-infrared (NIR) (600 to 1100 nm) (Hennessy & Hamblin, 2017). The main action mechanism of tPBM seems to be the excitation of mitochondrial cytochrome c oxidase (Karu, 1988), which in turn may enhance the metabolic capacity (Saucedo et al., 2021) and the anti-inflammatory and antioxidant responses of the neurons, among other responses (Salehpour et al., 2018). tPBM could also work through neurovascular modulation (Arora et al., 2021; Bahr-Hosseini & Bikson, 2021). tPBM has been used to treat several neurological and psychological disorders. For example, previous studies found that tPBM improves cognition in traumatic brain injury (Stevens et al., 2022), Alzheimer disease (Cardoso, Lopes Martins, & da Silva, 2020), ischemic stroke patients (Berman, Halper, Nichols, Lundy, & Huang, 2017; Maksimovich, 2015; Saltmarche, Naeser, Ho, Hamblin, & Lim, 2017), depression (Cassano, Petrie, Hamblin, Henderson, & Iosifescu, 2016) and autism disorders (Ceranoglu et al., 2022).

According to a meta-analysis (Salehpour et al., 2019), there is also evidence of cognitive enhancement in healthy people after tPBM. For example, Barrett & Gonzalez-Lima, (2013) found that a single session of tPBM (1064 nm for 8 min) over the right prefrontal cortex (FP2 according to the 10–20 EEG system) significantly improved attention and memory. Using very similar stimulation parameters, other authors (Hwang, Castelli, & Gonzalez-Lima, 2016) also found significant improvement of both attention and memory. Similarly, Blanco, Saucedo, and Gonzalez-Lima (2017) also found that a single 8-min session of 1064 nm tPBM over the lateral prefrontal cortex region (FP2, F4, and F8 according to the 10–20 EEG system) produced a significant enhancement of learning-related cognitive function. Chan, Lee, Yeung, and Hamblin (2019) applied tPBM (633 and 870 nm) over the forehead and posterior midline (FP1 and FP2) in a single 7.5-min session and found a significant effect on inhibition ability, selective attention and category fluency. However, there is also evidence of a lack of significant effect of tPBM over the left prefrontal cortex on verbal cognition (Fink et al., 2018).

Prior studies using tPBM have targeted single brain areas within larger networks (e.g., DMN). However, a recent study (Zomorrodi, Loheswaran, Pushparaj, & Lim, 2019) showed it is possible to target and modulate neuronal oscillations from the entire DMN with tPBM (810 nm, 20 min) by stimulating the main subdivisions of the DMN: the ventral medial prefrontal cortex, the posterior cingulate cortex, precuneus, dorsal medial prefrontal cortex, lateral parietal cortex and the entorhinal cortex (Zomorrodi, Loheswaran, Pushparaj, & Lim, 2019). Despite the hypothesized link between the DMN and DT, to our knowledge, no previous studies have attempted to stimulate the entire DMN to test whether DMN positively affects DT in healthy adults. It thus remains unclear whether reported effects of prior studies reflect the targeted engagement of single DMN regions (e.g., angular gyrus) or the broader engagement of the larger network.

Common neural underpinnings and relationship between creativity and anxiety

We also assessed a potential mediator of the DMN-creativity link: state anxiety. There is evidence suggesting that the DMN partially underlies anxiety. More concretely, the medial prefrontal cortex seems to be involved in anxiety (Gusnard & Raichle, 2001; Zhao et al., 2007). Similarly, it has been reported that high trait anxiety is associated with reduced thickness in some main brain hubs of the DMN such as the medial prefrontal cortex (Hu & Dolcos, 2017; Kühn, Schubert, & Gallinat, 2011; Spampinato, Wood, De Simone, & Grafman, 2009) or the precuneus (Miskovich et al., 2016). A possible reason for the involvement of the DMN on anxiety may be due to its role in emotion regulation (Schilbach, Eickhoff, Rotarska-Jagiela, Fink, & Vogeley, 2008; Sylvester et al., 2012). Previous attempts to reduce anxiety by stimulating the DMN with tPBM suggest that it is possible (Chao, 2019; Saltmarche, Naeser, Ho, Hamblin, & Lim, 2017). On the other hand, previous studies suggest that anxiety is negatively related with creativity (Byron & Khazanchi, 2011; Daker, Cortes, , 2020). Therefore, considering the common neural underpinnings with tPBM, and the positive previous attempts trying to reduce anxiety levels, we also assessed state anxiety to explore if any change in anxiety mediates the possible effect of tPBM to the DMN on creativity.

Therefore, the current study aimed to investigate the effects of tPBM (810 nm) of the entire DMN on creativity categories after a single 20-min session in healthy adults, by analyzing the change in DT and CT scores. Based on the previously mentioned literature, we hypothesized that tPBM (compared to sham) would enhance DT scores (including fluency, originality, and flexibility subdimensions, as well as total DT scores), but not CT. Additionally, we also hypothesized that the effect of tPBM of the DMN on DT would be partially mediated by its positive effect on reducing anxiety level.

Material and methods

Statistical power and sample size estimation

Given that there were no previous studies using tPBM on creativity, the sample size calculation was based on

a previous study using other transcranial noninvasive electrical technique that investigated the effect on DT (Peña et al., 2021). Using the G*Power 3 software (Faul, Erdfelder, Lang, & Buchner, 2007), a sample size of 58 subjects, 29 in each group, was sufficient 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.

Participants

We recruited 58 healthy and native Spanish-speaking volunteers from the general population (mainly from the university but also from the general population through social media advertising), based on the power analysis. Inclusion criteria were being 18 years old or above. There were no restrictions on gender or handedness of participants. Exclusion criteria were (a) previous history of brain surgery and (b) history or presence of neurological disorder or injury (epileptic or convulsive seizure, brain stroke, severe brain injury).

Participants did not receive any course credit or monetary compensation for participating in the study. The study obtained the ethical approval from the Research Ethics Committee of XXX (Ref: XXX). 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).

Design and procedure

This randomized single-blind, sham-controlled, parallel-group mixed-design study consisted of a single session. The study design and procedures are specified in Figure 1. The participants were randomly assigned to one of the two groups ($n = 29$ in each group): real tPBM and sham. A computer-generated randomization was used to assign groups (www.randomizer.org). All participants were blind to the stimulation group condition, since no perception was felt on the scalp and there was no visual indication of the device being on or off. The experimenter was not blind since they had to turn the device on to start the stimulation.

After signing the consent form, baseline creativity assessment was carried out before starting the real or sham stimulation (see Figure 1). Following previous NIBS studies with a similar methodology (XXXX), subjects had 2 min and 45 s to complete the RAT and 2 min for Unusual Uses (UU) and Picture Completion (PC) subtests from the Torrance Test of Creative Thinking.

After 20 min of tPBM, the participants carried out the parallel versions of RAT, UU and PC in a counterbalanced order. We assessed the blinding efficacy 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?."

tPBM

For tPBM, we used the "Vielight Neuro Gamma" device (Vielight Inc., Toronto, Canada) in this study. This portable low-level light delivery device administers NIR light to the brain both transcranially and intranasally (see Figure 2). The device consists of a controller, a nasal applicator, and a head set with four light-emitting diode (LED) modules. The Neuro Gamma delivers painless, noninvasive, non-thermal, non-laser, pulsed (40 Hz; 50% duty cycle), NIR light (810 nm wavelength) through five non-laser LEDs over

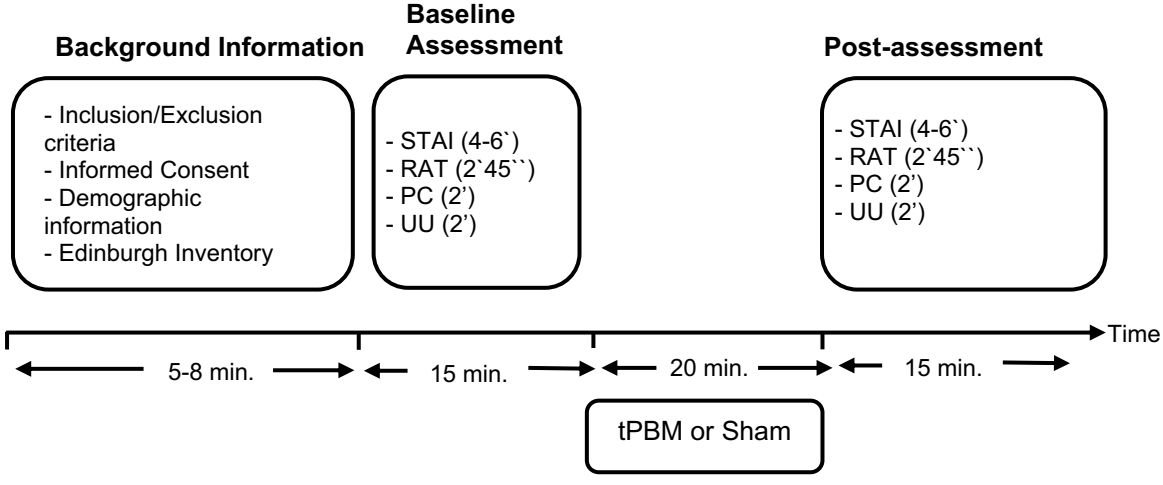

Figure 1. Study design. Note: Schematic representation of the experimental procedure for the creativity assessments (RAT = Remote Associates Test; PC = Picture Completion Task; UU = Unusual Uses.

Figure 2. Transcranial photobiomodulation device positioning (Vielight Inc.). Note: Photographs of Vielight Inc. "Neuro gamma" illustrating correct device positions for treatment, and corresponding targeted default mode network (DMN) subdivisions.

a single 20-min session (Zomorrodi, Loheswaran, Pushparaj, & Lim, 2019). The LEDs were positioned over the main subdivisions of the DMN (see Figure 2). More specifically, diodes were positioned using the International 10-20 system of scalp electrodes location. The middle point of the top of the head was stablished by the cross point between the center line from the nasion (bridge of the nose) to inion (occipital protuberance) and the line from the top on an ear to the other. For the location of the FZ diode, it was placed 20% away from the middle point in the frontal direction. For the location of the P3 and P4 diodes, they were placed 20% away from the middle point in the occipital direction (El Khoury, Mitrofanis, & Henderson, 2019). The power density output of the nasal applicator was 25 mW/cm^2, anterior LED was 75 mW/cm^2, and three posterior LEDs, 100 mW/cm^2. Over the set-time of 20 min, the energy dose to the brain (both headset and intranasal applicator) equaled 240 J/cm2 (Zomorrodi, Loheswaran, Pushparaj, & Lim, 2019). This tPBM device, with a 20-min NIR stimulation session at the specified power densities, has been successfully and safely implemented in previous studies (Chao, 2019; El Khoury, Mitrofanis, & Henderson, 2019; Saltmarche, Naeser, Ho, Hamblin, & Lim, 2017; Zomorrodi, Loheswaran, Pushparaj, & Lim, 2019). For the sham group, the device was placed on the head for 20 min but not turned on. During the tPBM administration, participants were instructed to keep their eyes closed and sit still in a chair.

Creativity measures

Divergent thinking (the Torrance Test of Creative Thinking)

The Unusual Uses (UU) and Picture Completion (PC) subtests from *orrance Test of Creative Thinking* (Torrance, 1967) were included in the study. The UU is a verbal task that requires participants to write down as many uncommon uses for everyday objects as they can. In this study, "Tin Cans" and "Cardboard Boxes" were used; the PC is a visuospatial task that presents incomplete shapes and requires participants to draw as many sketches using the shapes as possible. We included two different forms (Form A and B) for the baseline and post-stimulation assessments. We measured three dimensions for both UU and PC: fluency (total number of responses), originality (statistical infrequency of responses in the sample) and flexibility (total number of categories of responses; e.g., faces or objects). We converted both UU and PC fluency, originality and flexibility measures to *z*-scores to obtain PC and UU composites. The internal consistency was good for both UU (Cronbach's alpha = 0.93) and PC (Cronbach's alpha = 0.88). Finally, a total DT composite score was created based on fluency, originality, and flexibility scores from UU and PC (Cronbach's alpha = 0.83). We also calculated the percentage of original responses based on fluency scores (number of

original responses × 100/total number of correct responses) for both UU and PC.

Convergent thinking (Remotes Associates Test, RAT)

The Spanish version (Ledesma-González, 2018) of the RAT (Mednick, 1962) was administered. Two different forms of the test were used for the baseline and during stimulation assessment. In the RAT, participants were asked to identify a word that is associated (either forming a compound word or semantically related) with three cue words (e.g., *cream-skate-water*; correct answer = *ice*). 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 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).

Anxiety

The anxiety level was assessed using the State Trait Anxiety Inventory (STAI) (Spielberger, Gorsuch, Lushene, Cubero, & adaptación española, 1999). In this study, we used the STAI state (STAI-S) subscale. It consists of 20 items with a 4-point scale (0–3 points) and a final score ranging from 0 to 60. A higher score indicates a higher level of anxiety.

Statistical analyses

Baseline characteristics were compared using X^2 test for categorical data and ANOVA test for continuous variables. ANCOVA was used to compare post-stimulation scores (controlling for baseline scores) between the three groups for each of the creativity variables. Effect size (n_p^2) was also calculated. IBM SPSS software version 23.0 (IBM Corporator Released, 2015) was used for statistical analyses. All tests were two-tailed and the significance level was set at 0.05. Bonferroni–Holm was used to correct multiple comparisons.

Results

Baseline characteristics

There were no significant differences between the real and sham groups in any of the variables at baseline including age, sex, years of education, and handedness (see Table 1). The mean age of the general sample was 28.31 years (standard deviation = 11.21) and 14.74 completed years of education (standard deviation = 2.69). The 46.6% of the general sample was male and 53.4% was female.

Effects of tPBM on DT and CT scores

The total DT and CT scores at baseline and post-treatment are displayed in Table 2. ANCOVA results (post-treatment comparisons controlling for baseline scores) are shown in Table 3, and Figure 3 shows change score distributions in verbal DT (UU), visual DT (PC), and total DT (post-treatment minus baseline). Results showed significant differences between both groups in verbal DT (total UU) with a medium effect size (n_p^2 = 0.10), indicating a higher performance after tPBM compared to sham. The visual DT (total PC) score was also significant and indicated that tPBM produced higher performance than the sham group, showing a large effect size (n_p^2 = 0.14). Finally, the total DT score was significantly higher after tPBM compared to sham with a large effect size (n_p^2 = 0.24).

As expected, tPBM did not show any significant effect on CT (RAT).

Effects of tPBM on DT subdomains

Regarding verbal DT subdomains, the results suggest that the originality dimension was significantly higher after tPBM compared to sham (see Table 4), indicating a large effect size (n_p^2 = 0.15). The effects on PC showed significant differences in fluency, with a medium effect size (n_p^2 = 0.13). Regarding the percentage of original responses, there was a significantly higher percentage of original responses in UU (F = 5.90, p = .018) after tPBM (Marginal mean = 75.23, Standard Error = 3.73)

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

Note: Abbreviations: tPBM = transcranial photobiomodulation; SD = standard deviation.

Table 2. Creativity scores of tPBM and sham groups at baseline and post-stimulation.

		tPBM	Sham
		Mean ± SD	Mean ± SD
RAT	Baseline	7.21 ± 2.77	7.24 ± 3.94
	Post	8.79 ± 2.85	8.07 ± 3.80
UU Fluency	Baseline	9.34 ± 3.25	8.24 ± 3.25
	Post	10.38 ± 3.67	8.37 ± 3.67
UU Originality	Baseline	6.28 ± 2.99	6.14 ± 3.06
	Post	7.97 ± 4.02	5.38 ± 3.43
UU Flexibility	Baseline	6.69 ± 2.55	6.38 ± 2.21
	Post	7.31 ± 2.43	6.14 ± 2.49
PC Fluency	Baseline	5.00 ± 2.52	5.07 ± 2.57
	Post	6.14 ± 2.86	4.97 ± 2.07
PC Originality	Baseline	2.00 ± 1.53	2.44 ± 1.99
	Post	2.97 ± 1.80	2.21 ± 1.34
PC Flexibility	Baseline	4.55 ± 2.15	4.28 ± 1.94
	Post	5.41 ± 2.42	4.48 ± 2.03
Total UU	Baseline	0.08 ± 0.94	−0.08 ± 0.92
	Post	0.27 ± 0.96	−0.27 ± 0.87
Total PC	Baseline	0.02 ± 0.84	−0.02 ± 0.96
	Post	0.22 ± 1.01	−0.22 ± 0.74
Total DT	Baseline	0.03 ± 0.75	−0.03 ± 0.72
	Post	0.25 ± 0.78	−0.25 ± 0.62
Anxiety	Baseline	14.34 ± 6.89	15.35 ± 6.59
	Post	11.41 ± 7.94	13.24 ± 5.75

Abbreviations: tPBM = transcranial photobiomodulation; SD = Standard deviation; Verbal RAT = number of correct answers in Remote Associates Test; PC= Picture Completion from Torrance Test of Creative Thinking; UU= Unusual Uses from Torrance Test of Creative Thinking.

Table 3. Differences between the tPBM and sham groups in convergent and divergent thinking post-stimulation scores after controlling for baseline scores.

	tPBM	Sham	*F*	*p*	n_p^2
	Marginal Mean ± SE	**Marginal Mean ± SE**			
RAT	8.80 ± 0.54	8.06 ± 0.54	0.95	0.334	0.02
Total UU	0.21 ± 0.12	−0.21 ± 0.12	6.15	0.032	0.10
Total PC	0.24 ± 0.11	−0.24 ± 0.11	9.19	0.012	0.14
Total DT	0.22 ± 0.08	−0.22 ± 0.08	17.15	0.004	0.24

Abbreviations: tPBM = transcranial photobiomodulation; 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.

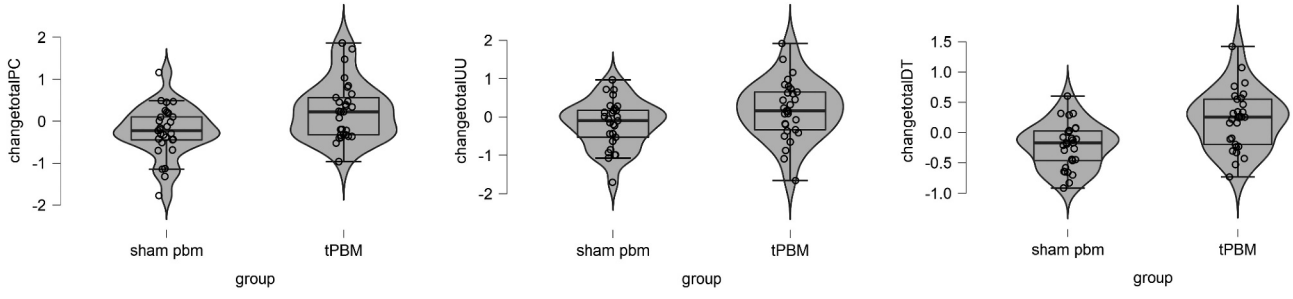

Figure 3. Change scores (post-stimulation minus baseline scores) in total PC, total UU, and total DT of sham and tPBM groups.

compared to sham (Marginal mean = 62.39, Standard Error = 3.73). However, PC did not show significant differences in the percentage of original responses (F = 0.41, p = .525).

Effects of tPBM on anxiety

ANCOVA results (F = 0.73, p = .397) indicated that tPBM over the DMN (Marginal mean = 11.79, SE = 0.89) did not significantly affect anxiety levels compared

Table 4. Differences between the tPBM and sham groups in divergent thinking subdomains post-stimulation scores after controlling for baseline scores.

	tPBM	Sham	*F*	*p*	n_p^2
	Marginal Mean ± SE	**Marginal Mean ± SE**			
UU Fluency	9.89 ± 0.49	8.87 ± 0.49	2.14	0.149	0.04
UU Originality	7.92 ± 0.47	5.43 ± 0.47	9.66	0.018	0.15
UU Flexibility	7.22 ± 0.37	6.23 ± 0.37	3.47	0.204	0.06
PC Fluency	6.16 ± 0.30	4.94 ± 0.30	8.21	0.030	0.13
PC Originality	3.03 ± 0.28	2.15 ± 0.28	4.78	0.132	0.08
PC Flexibility	5.30 ± 0.27	4.60 ± 0.27	3.36	0.144	0.06

Abbreviations: tPBM = transcranial photobiomodulation; 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.

to sham (Marginal mean = 12.87, SE = 0.89). Therefore, we did not test further mediation analyses for the mediation effect of anxiety hypothesis.

Blinding

Our results suggest that participants were not able to guess between real and sham conditions [$\chi^2(1, N = 57) = 3.69$, $p = .158$]. From the real PBM group, 34.5% guessed that they had received stimulation, 27.6% guessed they had received the placebo and 37.9% were undecided. From the sham group, 25.0% guessed that they had received the placebo, 57.1% that they had received stimulation and 17.9% were undecided.

Discussion

The primary novel goal of the current study was to investigate if tPBM over the main hubs of the DMN of healthy subjects improves creative thinking – specifically, DT (but not CT) – compared to sham. The secondary objective was to test if reduction in anxiety would partially explain the improvement in DT. The results supported the first hypothesis, whereas they did not support the second hypothesis, which suggests that tPBM of the DMN subdivisions enhances creativity specifically in DT without any confounding effects of anxiety.

Regarding the effects on DT, results showed that tPBM over the DMN significantly enhanced total scores in verbal DT (UU) with a medium effect size and visual DT (PC) and total DT, showing a large effect size. Results in UU were mainly due to the significant enhancement in the originality dimension, whereas PC improvement was mainly due to fluency improvement. The effects of tPBM on fluency and originality, both visual and verbal, are consistent with previous neuroimaging studies that reported that the DMN is associated with DT (Beaty et al., 2014; Jung, Mead, Carrasco, & Flores, 2013; Kühn et al., 2014; Mayseless, Eran, & Shamay-Tsoory, 2015; Shofty et al., 2022; Sunavsky & Poppenk, 2020; Takeuchi et al., 2020). In this context, several cognitive processes (such as mind wandering or episodic memory) have been related to the activation of the DMN and creativity and may be partially mediating this relationship. More concretely, as previously described, the DMN is activated during mind wandering (Gusnard, Akbudak, Shulman, & Raichle, 2001; Jung, Mead, Carrasco, & Flores, 2013) and it is related to DT but not CT (Madore, Addis, & Science, 2015; Murray, Liang, Brosowsky, & Seli, 2021). However, the relationship between mind wandering and DT is not always supported. For example, negative rumination (a kind of mind wandering) can generate anxiety (Nolen-Hoeksema, 2000), which in turn may negatively affect creativity (Byron & Khazanchi, 2011; Daker, Cortes, 2020). Similarly, there is also evidence suggesting that mind wandering during creative idea generation may be negatively related to creativity (Hao, Wu, Runco, & Pina, 2015). Given that we have not assessed mind wandering in this study, we cannot draw any conclusion, but future studies could investigate if the effect of tPBM over the DMN on DT is partially mediated by mind wandering.

Like mind wandering, episodic memory has been repeatedly related to creativity and the DMN (Beaty, Benedek, Silvia, & Schacter, 2016). According to some authors, the idea generation process that occurs during DT tasks might be partially due to the retrieval and reconstruction of specific episodic details (Madore, Thakral, Beaty, Addis, & Schacter, 2019). In other words, a possible mechanism of the role of DMN on DT might be the flexible retrieval of memories (Andrews-Hanna, Reidler, Huang, & Buckner, 2010; Shofty et al., 2022), involving areas of the DMN that supports the generation of unique and novel associative ideas while inhibiting those that are more mundane

which in turn could lead to greater originality (Fink et al., 2010; Mayseless, Eran, & Shamay-Tsoory, 2015). However, as previously mentioned, creativity emerges from the synchronization between the DMN and other networks, such as the executive control network (Beaty, Benedek, Silvia, & Schacter, 2016; Beaty, Cortes, & Zeitlen, 2021) and salience network (Abraham, Rutter, Bantin, & Hermann, 2018). Therefore, although the current study shows the involvement of the DMN on both visual and verbal DT, we cannot consider that it underlies DT in an independent way but integrated with other brain networks.

Previous literature suggest that tPBM may help the brain switch from a state of mind-wandering (DMN) to a state of focused attention (salience and central executive networks) more readily (Mitrofanis & Henderson, 2020), which may additionally help in understanding the improvement in DT tasks. However, given that we have not included any neurophysiological measure, we cannot assure that it was the case in our study, and it remains as a possible additional explanation of the results. Studies assessing the effect of tES on creativity and functional connectivity suggest that it is possible to increase the delta band connectivity between the posterior cingulate cortex and the inferior parietal cortex after real stimulation but not with sham (Koizumi, Ueda, Li, & Nakao, 2020). Similarly, other authors observed that tES of the inferior frontal gyrus produced changes in the power levels of the resting state beta frequency bands, which was increased by anodal tES and was associated with better performance in creativity (Hertenstein et al., 2019).

Additionally, in order to discard a general cognitive effect of tPBM, we also tested if tPBM would enhance CT scores on the RAT. As expected, based on previous literature suggesting the higher relationship between CT and the executive control network instead of the DMN (Zhang, Sjoerds, & Hommel, 2020), we did not find a significant effect on CT. This negative result, to some extent, reinforces the idea of the specific role of the DMN on the idea generation phase of the two-fold model of creativity (Kleinmintz, Ivancovsky, & Shamay-Tsoory, 2019) instead of the evaluation process phase, whereas the executive control network constrains these ideas to meet task-specific goals.

As far as the authors are aware, this is the first study testing tPBM on creativity through the stimulation of the DMN – and the first study to stimulate the entire network – so direct comparisons with previous studies are not possible. However, we can put these results in context when we compare them with tES studies on creativity that targeted single regions within the DMN. For example, studies that stimulated the posterior parietal cortex, a hub of the DMN have also shown a significant effect mainly on the originality dimension of DT (Ghanavati, Nejati, & Salehinejad, 2018; Ghanavati, Salehinejad, Nejati, & Nitsche, 2019; Peña et al., 2020a, 2020b), particularly in visual tasks. An additional advantage of tPBM compared to tES is the lack of adverse effects of the former. A recent study that used direct cortical stimulation in awake patients during surgery demonstrated a causal link between the DMN and creativity (Shofty et al., 2022). In this study, authors temporarily inhibited individually identified regions of the DMN while performing a verbal DT task, finding the opposite pattern of results compared to the current study. In that study, the temporary inhibition (deactivation) of DMN nodes decreased fluency performance, whereas in our study, the stimulation (activation) of the DMN produced higher performance in both verbal and visual DT tasks. Since the authors included only a verbal DT task (Shofty et al., 2022), we cannot compare the results obtained on visual DT.

Contrary to predictions, tPBM over the DMN did not show any significant effect on anxiety levels (Chao, 2019). Given that we did not find any positive effect on anxiety state levels, we could not test if the effect of tPBM on creativity was partially mediated by the reduction of anxiety. Therefore, we could not confirm our second hypothesis.

There are several limitations in the current study that must be acknowledged. First, the measures for DT (UU and PC) included only one item per timepoint and the time was limited to 2 min, which might explain the lack of significant results in UU fluency and flexibility. Having more time to respond could have produced more responses and therefore potentially discriminated between the sham and tPBM effects. Secondly, the RAT measure included in the present study was based mostly on associative items, but it also contains compound items. Therefore, we cannot conclude if the null effect found was due to association processes or insight solution. Third, we cannot assure that the first test administered after the stimulation has the same effect as the last one. Related to this limitation, we do not know if the effect on DT would have been different if the assessment was carried out during the tPBM instead of immediately after. Also, the effects have been found immediately after tPBM, so we cannot determine if the effects are maintained over the time. However, previous research using tPBM of the motor cortex region has shown modulation of cortical excitability of up to 30

min after stimulation, which was similar to the excitability modulation after tES (Song et al., 2021), so we would assume a similar time course of after-effects to be seen after our tPBM protocol of the DMN regions. In this window of opportunity, we expect the effect to be the same whether immediately after or 10–15 min later. The light may also reach adjacent brain areas other than the intended to stimulate, so we cannot rule out that our results may have been affected. Future studies should also test if repeated tPBM sessions boost cognitive and/or creative enhancement more than a single session in order to find an optimal dose of tPBM. Finally, although the effects have been observed after a single session of tPBM we cannot conclude if more "doses" may produce a higher effect on creativity. The optimum tPBM NIR wavelength applied also remains unknown.

The present study results add evidence to the effects of tPBM on cognition, extending previous studies that used tPBM on healthy adults and observed an enhancement of cognitive functioning (Salehpour et al., 2019). Altogether, these results of tPBM on cognitive functioning in healthy people, and people with neurological or psychiatric diseases, open up new possibilities of research in fields that may have a positive impact on different aspects of human cognition and behavior. Furthermore, future studies may test if the improvement in DT is partially mediated by the effect on other cognitive functions, such as memory, mind wandering, processing speed or executive functioning. Future studies should also include neuroimaging techniques in order to investigate the possible neurophysiological effects of tPBM.

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No potential conflict of interest was reported by the authors.

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Data availability statement

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

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