Biological Psychology 207 (2026) 109264

Contents lists available at ScienceDirect

Biological Psychology

journal homepage: www.elsevier.com/locate/biopsycho

Effects of slow oscillatory HD-tDCS on creative cognition and prefrontal cortex activity: A multimodal EEG-fNIRS study

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ARTICLE INFO

Keywords:
Slow oscillatory tDCS
Creativity
EEG
FNIRS
Dorsolateral prefrontal cortex
Medial prefrontal cortex

ABSTRACT

Creativity relies on the dynamic interaction between the default mode (DMN) and frontoparietal control (FPCN) networks, supported by controlled attentional processing and associative strategies. Slow wave activity (SWA: 0.1– 1 Hz) is a critical component of network reorganization during non-REM sleep; while slow oscillatory tDCS (so-tDCS) at 0.75 Hz has been shown to acutely modulate SWA to enhance cognition. This study employed a novel concurrent EEG-fNIRS multimodal imaging approach to investigate whether so-tDCS at 0.75 Hz over the bilateral dorsolateral prefrontal cortex (DLPFC) and medial prefrontal cortex (mPFC) modulates brain oscillations and haemodynamics to promote creativity. Participants ($N = 39$) completed the Unusual Uses and Picture Completion (PC) creative tasks while receiving sham/so-tDCS at 0.75 Hz using a 2 × 1 high-definition (HD) montage with two anodes (F3, F4) and one cathode (Fpz) for 30 min in a double-blind, sham-controlled, crossover experiment. Compared to sham, so-tDCS significantly increased originality in PC ($p = .014$, $g = 0.40$) and was accompanied by sustained increases in oxygenation in the left prefrontal cortex (PFC, $p = .003$). Post-stimulation, functional connectivity (FC) within left PFC was increased and within right was reduced, accompanied by significantly lower SWA in the left PFC. In addition, asymmetrical fNIRS-derived FC patterns were observed: higher left intrahemispheric PFC ($p = .007$), and lower interhemispheric PFC ($p = .015$). These findings suggest that so-tDCS using a HD montage over the bilateral DLPFC and mPFC enhances visual creativity by dynamically adjusting the left PFC resources, which subsequently may trigger downscaling mechanisms.

1. Introduction

In recent years, there has been a growing interest in research on creativity, as it is considered one of the most extraordinary capacities of the human mind (Lustenberger et al., 2015) and described as the most effective and natural solution to the growing complexity of global crises (Runco, 2004). Creativity is defined as an internally driven attention process constrained by a generative goal (Green et al., 2023). According to the dual process model (Benedek & Jauk, 2018), creative cognition relies on two fundamental interacting components: associative strategies that support the formation of new connections between typically unrelated ideas (Beaty & Kenett, 2023; Benedek et al., 2012; Mednick, 1962) and enable the recombination of existing knowledge into novel configurations (Kenett & Thompson-Schill, 2020) based on a structured memory organization (Benedek et al., 2023); and, a controlled attentional processing (Beaty & Silvia, 2012; Frith et al., 2021) that promotes the maintenance of task-relevant information and inhibits interferences (Benedek et al., 2014; Kenett et al., 2018).

The dynamic interplay between these spontaneous and controlled processing in creative cognition has been supported by neuroimaging studies that propose a dynamic crosstalk between the frontoparietal control network (FPCN) and the default mode network (DMN) (Beaty et al., 2015; Chen et al., 2025; Luchini et al., 2025; Sassenberg et al., 2025; Zhuang et al., 2023). FPCN activation during creative task performance is thought to reflect the involvement of top-down processes, essential for maintaining focus and inhibiting distractions during creative tasks (FPCN is involved in controlled processing) (Beaty et al., 2015). Meanwhile, the DMN is linked to internally directed cognitive processes (Zabelina & Andrews-Hanna, 2016) like mind-wandering (Fox et al., 2015), self-generated thought (Bartoli et al., 2024) and associative

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https://doi.org/10.1016/j.biopsycho.2026.109264
Received 12 January 2026; Received in revised form 30 March 2026; Accepted 13 April 2026

thinking (DMN is involved in spontaneous processing) (Marron et al., 2018). Therefore, the core hubs of FPCN and DMN, such as the bilateral dorsolateral prefrontal cortex (DLPFC) and the medial prefrontal cortex (mPFC), respectively, have been proposed as strong neural candidates for the integration of controlled and spontaneous processing during creative thinking (Zhuang et al., 2023).

Further research on the neural basis of creativity has highlighted the role of alpha oscillations (8–12 Hz) in creative thinking (Fink & Benedek, 2014; Stevens & Zabelina, 2019). In particular, frontal alpha synchronization is thought to reflect top-down processing, likely due to the high internal cognitive demands commonly associated with creative thought (Fink & Benedek, 2014). Benedek et al. (2011) found greater alpha synchronization in frontal regions only during creative tasks with high internal processing demands. Similarly, Mazza et al. (2023) reported increased alpha power during the generation of original ideas. However, this increase was observed in central-posterior cortical areas rather than in frontal cortex. Another study by Agnoli et al. (2020) aimed to explore the temporal patterns of alpha oscillations during verbal creativity and how changes in alpha power could account for variations in originality. The study concluded that the higher originality of the responses towards the end of the task was linked to alpha synchronization over frontal, central, temporal, and parietal cortex, and that alpha oscillatory patterns were predictive of the behavioural production of original ideas.

Although not as extensively studied, slower-frequency brain oscillations, such as delta band (1 – 4 Hz) power, have been shown to be associated with greater cognitive flexibility and more uncommon responses (Boot et al., 2017). While higher-frequency oscillations have been associated with more local neural communication, slower oscillations may support creative cognition by facilitating long-range coordination between brain regions involved in creative processing (Stevens & Zabelina, 2019). More specifically, the slow wave activity (SWA: 0.1 – 1 Hz) is most prominent during non-rapid eye movement (NREM) sleep or deep sleep (Fehér et al., 2021). SWA primarily originates in the mPFC and subsequently spreads to other cortical areas travelling mainly through the anterior-posterior axis (Fan et al., 2023) with peak levels between 0.7 – 0.8 Hz (Achermann and Borbély, 1997).

SWA has been associated with enhanced creative processing (Drago et al., 2011; Ritter et al., 2012). In addition, SWA has been linked to better general cognitive performance (Aricò et al., 2010; Wilckens et al., 2018), including executive functions (Munz et al., 2015), learning (Wilckens et al., 2015) and memory (Marshall et al., 2006; Ladenbauer et al., 2016). A possible reason is that SWA promotes synaptic plasticity and supports the synchronization and reorganization of brain dynamics (Ujma et al., 2018; Stevner et al., 2019; Yoshida & Toyoizumi, 2022). It also reflects a state of both local and global high synchrony (Fan et al., 2023) and optimal energy efficiency (Tononi & Cirelli, 2006). In this SWA state, the brain is prepared to reorganize and reconfigure existing knowledge (Abdou et al., 2024), thereby facilitating the formation of remote associations and novel connections (Drago et al., 2011) – both hallmarks of creativity. However, the contribution of SWA to creative cognition remains to be elucidated.

Aiming to benefit from neural and cognitive functioning associated with SWA, various methods have been explored to promote slow oscillations, including non-invasive brain stimulation (NIBS) (refer to Féher et al., 2021 for a review). Although heterogenous outcomes are observed, there is evidence supporting that slow oscillatory transcranial direct current stimulation (so-tDCS) applied during sleep could enhance SWA and memory consolidation. For example, Marshall et al. (2006) had healthy participants complete a learning trial of an associative paired task and then applied so-tDCS at 0.75 Hz on the bilateral DLPFC and simultaneously recorded EEG during sleep. They found an increase in slow oscillatory power during sleep, which was accompanied by a higher number of words recalled the following morning. Ladenbauer et al. (2016) applied the same stimulation protocol during NREM sleep stages 2, 3, and 4, and recorded EEG between stimulation blocks during a 90-minute nap to enhance memory performance and SWA in older adults. The results showed that increased slow oscillatory power during the nap was associated with improved visual memory retention after so-tDCS at 0.75 Hz.

In a similar approach, but in awake participants, Kirov et al. (2009) applied so-tDCS at 0.75 Hz using the same montage as Marshall et al. (2006) and recorded EEG between stimulation blocks during wakefulness. Their results showed an increase in encoding during the learning phase and immediate recall of words in a memory task consisting of learning a list of words, but not in the associative paired task. This was accompanied by temporary increased SWA in frontal areas and a widespread increase in theta activity, and improved encoding performance during both attentive and quiet wakefulness. Given the close relationship between memory and creativity (Benedek et al., 2023), it is reasonable to consider that the application of so-tDCS at 0.75 Hz over the bilateral DLPFC and mPFC may enhance creative thinking.

Despite the growing interest in the neuromodulatory effects of NIBS on both creative performance and EEG oscillatory activity, as far as the authors are aware, only three empirical studies have been conducted to date in order to explore this relationship. First, Hertenstein et al. (2019) applied direct current stimulation (tDCS) over the inferior frontal gyrus bilaterally with the cathode on the left and the anode on the right hemispheres (L-, R+). They observed that enhanced creative thinking was associated with increased neural excitability in right PFC and decreased in left PFC (indexed by a power increase in beta, and delta-theta bands, respectively). Next, the work of Koizumi et al. (2020) assessed creative cognition after tDCS application (anode over F3, cathode over P4) and revealed that higher scores in flexibility were correlated with greater functional connectivity (FC) in delta band between mPFC and the left lateral temporal cortex. Additionally, greater FC in the alpha band between the right lateral temporal cortex and right inferior parietal lobule was found to be positively associated with flexibility. More recently, Camenzind et al. (2025) showed an increase in originality and flexibility scores through transcranial random noise stimulation (tRNS) over the bilateral DLPFC that were linked to changes in alpha coherence. In summary, the available evidence demonstrates significant variability in the stimulation protocols used, the targeted brain areas, and heterogeneous behavioural and EEG outcomes, which makes it challenging to draw consistent conclusions. Therefore, further research is needed to determine the effects of NIBS on brain responses related to creative performance.

An approach that may contribute to obtaining more comparable and generalizable findings is to use a multimodal solution that combines measurements of oscillatory electrical activity (EEG) with neurovascular coupling-related neuroimaging (fMRI blood-oxygen-level-dependent (BOLD) and fNIRS) (Li et al., 2022). Functional near-infrared spectroscopy (fNIRS), in particular, offers a promising complement to EEG, capturing haemodynamic responses with higher spatial resolution than EEG while being more accessible and portable than other fMRI BOLD neuroimaging techniques (Chiarelli et al., 2017). This EEG-fNIRS multimodal approach helps addressing the limitations of each technique alone providing a more comprehensive picture of the neural dynamics involved in NIBS and the creative process.

Research employing fNIRS to investigate the effects of NIBS on creative tasks is limited. Wang et al. (2023) applied tDCS over the bilateral DLPFC (L+, R–) and showed improved creative performance in fluency, flexibility and originality dimensions of the alternative uses task. In this study, higher creativity was associated with increased cortical activation in both the DLPFC and the frontopolar cortex, as well as enhanced interhemispheric and intrahemispheric FC within the PFC. Taken together, these results point to a promising yet largely unexplored area of research, calling for methodological advancements that can capture the complex dynamics of creative brain functioning. To the best of our knowledge, no studies have combined NIBS with hybrid EEG-fNIRS neuroimaging specifically designed to investigate the neural correlates of creativity. Therefore, this study aimed to explore whether so-tDCS at

0.75 Hz over mPFC and bilateral DLPFC during wakefulness can enhance creative cognition. Additionally, using multimodal EEG-fNIRS measurement, the study aims to provide a more comprehensive understanding of how brain electrical oscillations and haemodynamics modulated by so-tDCS support creative processes. Based on the evidence, it is hypothesized that so-tDCS will promote creative thinking and this improvement would be associated to both higher synchronization between bilateral DLPFC and mPFC indexed by greater FC as well as higher slow and alpha power in the PFC.

2. Methods

2.1. Statistical power and sample size estimation

The sample size calculation was based on previous works using tDCS to enhance creativity, as reported in the meta-analysis by Chen et al. (2024). Using G*Power 3.1 software (Faul et al., 2007), a sample size of 39 was sufficient to attain an effect size of $d = 0.5$ to detect differences between so-tDCS and sham sessions with a 90% power and a 5% level of significance.

2.2. Participants

Inclusion criteria included age between 18 and 65 years old, identifying with any gender, and to be Spanish the mother tongue language. Exclusion criteria included: (1) suffer from cognitive alterations; (2) previous history of brain surgery; (3) being pregnant; (4) suffering from frequent or severe headaches or migraines; (5) previous history or presence of neurological disorder or injury (epileptic or convulsive seizure, brain stroke, severe brain injury); and (6) presence of any type of metallic implant in the brain. Participants' average age was 22.74 ± 0.44 years and 15.12 ± 0.24 years of education. Of the total participants, 24 individuals identified with female gender (61.5%) and 15 with male gender (38.5%). Participants indicated using the right hand preferentially to complete daily tasks scoring a mean of −50.51 ± 5.36 (i.e., mostly right-handed) on the Edinburgh Handedness Inventory (Oldfield, 1971).

Participants did not receive any financial compensation for participating in the study. Ethical approval was obtained from the University of Deusto Ethics Committee (Ref: ETK-8/21–22) and was conducted in accordance with theoretical principles for medical research involving human individuals of the Declaration of Helsinki.

2.3. So-tDCS protocol

A StarStim 8 (Neuroelectrics Inc., Barcelona, Spain) was used to provide mild so-tDCS using a high-definition (HD) montage with two anode electrodes (3.14 cm^2) positioned at F3 and F4, and one cathode over Fpz according to the international 10–20 system (see Fig. 1). The total peak current administered through the head was 2 mA with 1 mA applied at F3 and 1 mA at F4, returning through Fpz. Participants received an oscillating current composed of 0.5 mA of direct current

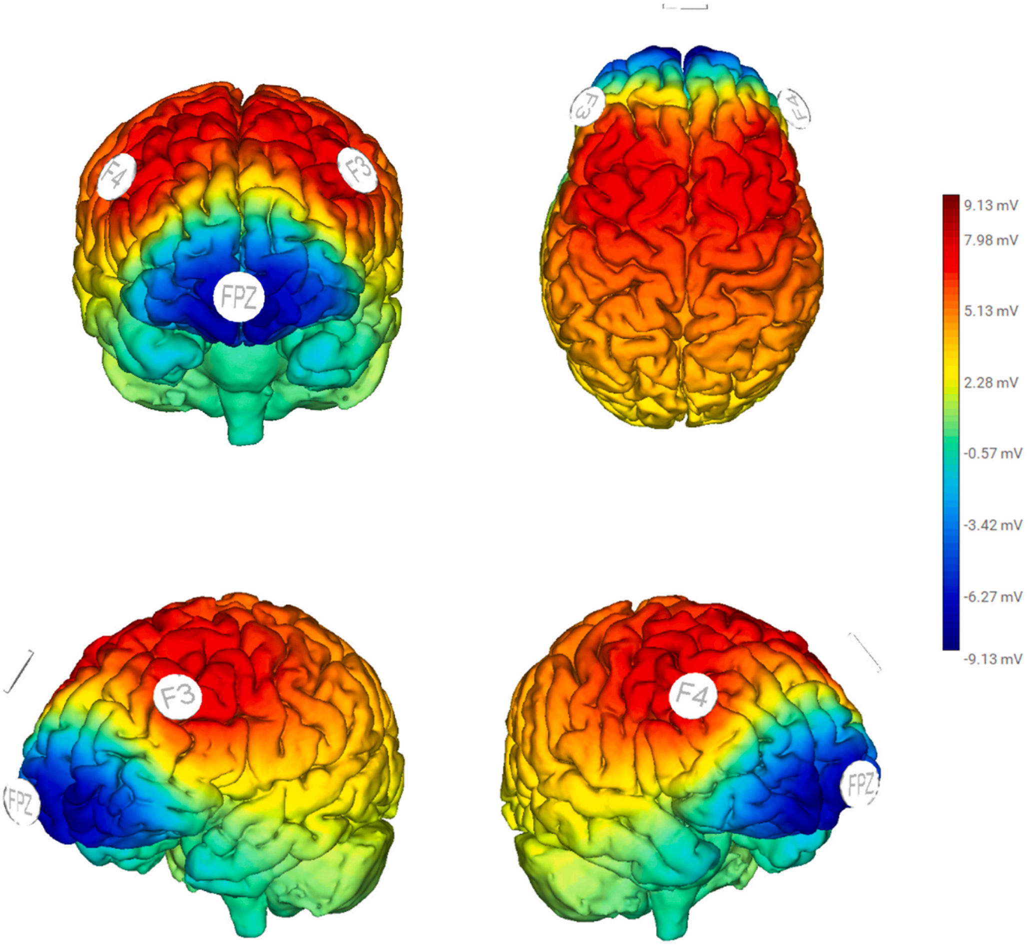


Fig. 1. so-tDCS (2 ×1 HD) montage and electric field simulation. Note. Magnitude of the total electric field due to so-tDCS displayed: red-yellow colours indicate high electric field increase near F3 and F4 anode electrodes and blue colour indicates lower intensity near the common FPz cathode electrode. The simulation of the electric field according to the Stim Weaver software (Neuroelectrics Inc., Barcelona, Spain) based on a realistic head model derived from the Finite Element Method (Salvi et al., 2020).

offset (tDCS) and 0.5 mA of alternating current (tACS) at 0.75 Hz at each anode (F3 and F4) electrode. The total peak current administered through the head was 2 mA with 1 mA applied at F3 and 1 mA at F4, returning through the Fpz electrode. The stimulation protocol lasted 30 min with additional ramp-up and -down phases of 30 s. For the sham condition, only a 30 s ramp up and immediate followed by a 30 s ramp down was applied. The impedance of the electrodes was checked before and during so-tDCS to ensure it was below 10kΩ. The stimulation protocol was previously created and monitored by the NIC2.0 software (www.neuroelectrics.com/products/software/nic2/). The double blind NIC2 setup was used to blind the experimenter to the session.

2.4. Behavioural assessment

2.4.1. The edinburgh handedness inventory

Participants completed the Edinburgh Handedness Inventory (Oldfield, 1971) to indicate their hand use preference for 10 daily activities. Scores range from −100 (perfectly right-handed) to 100 (perfectly left-handed).

2.4.2. The torrance test of creative thinking (TTCT)

The Torrance Test of Creative Thinking (TTCT) is the most internationally used test to evaluate divergent thinking (Torrance, 1966; Oliveira et al., 2009). The reliability coefficient of the TTCT is.71 based on the Guttman two-half procedure (Jiménez et al., 2007). From TTCT can be extracted two main dimensions of creativity: (a) fluency or number of relevant responses; and (b) originality, which implies considering novel, unfamiliar and unusual, but relevant responses (Almeida et al., 2008).

2.4.2.1. Unusual uses (UU). The UU subtest of the TTCT (Torrance, 1966) requires primarily verbal processing. The participants have 2 min to tell as many unusual uses for an everyday object (a cardboard box or a can). Fluency is obtained by considering the number of different unusual uses ones produced (1 point for each answer). Originality is based on infrequency statistics of each response. To do this, the criteria is based on the list of elements of the manual (Torrance, 1966).

2.4.2.2. Picture completion (PC). The PC (Torrance, 1966) is a visuospatial task that presents incomplete shapes and requires participants to complete them by adding a few strokes to form drawings or objects as creative and original as possible in 2 min. Fluency is obtained by adding one point for each completed figure that is interpretable and meaningful. Originality is based on the standards described in Correction Guide IV (Torrance, 1966) (for each original answer one point is obtained).

2.4.3. Questionnaire of adverse effects

Following each session, participants completed an 11-item survey to evaluate any observed adverse effects including: headaches, itching sensations, difficulty concentrating, phosphene experiences, redness of the skin, etc.

2.5. Design and procedure

A double-blind, sham-controlled, crossover study including two sessions (sham vs. so-tDCS) was conducted. The order of the sessions and the version of the protocol were randomly assigned to participants and counterbalanced based on a computer-generated randomization software (https://www.random.org/). During the stimulation, assessment and task correction the rater was blind to the stimulation condition.

The study procedure is featured in Fig. 2. In the first session, participants read, understood and signed the informed consent, and completed the questionnaire on contraindications for the use of non-invasive electrical stimulation, demographic information and the Edinburgh Handedness Inventory. The next steps were followed exactly the same in both sessions (so-tDCS/sham). First, a bespoke neoprene cap with eight EEG electrodes (Starstim 8, Neuroelectrics Inc., Barcelona, Spain) and ten fNIRS optodes (OctaMon, Artinis Medical Systems, Elst, The Netherlands) was set on the participant's head. When the participant was ready to begin, the EEG and fNIRS devices started to record during resting state. Participants were instructed to look at a black cross centred on a white background screen for two minutes. Then, real so-tDCS or sham started. During stimulation (online) participants performed Unusual Uses (UU), and Picture Completion (PC) tasks. Parallel versions of these two tests were included. After 30 min stimulation stopped. Then, participants were instructed to look at a black cross on the screen for two minutes in order to obtain resting-state EEG and fNIRS measures. Immediately afterwards, the participants had the cap removed, responded to a questionnaire on possible adverse effects and reported their perceived experimental condition (stimulation/no stimulation/do not know). In total, each session lasted approximately 45 min.

2.6. EEG-fNIRS multimodal imaging

In this study, to capture both electrical activity and neurovascular coupling dynamics simultaneously with transcranial stimulation, a novel, integrated, EEG-fNIRS multimodal imaging platform was utilized. Two lightweight battery-operated wireless portable devices were securely attached to the back of a neoprene cap: the Starstim 8 system (Neuroelectrics Inc., Barcelona, Spain) was used for EEG (500 Hz) registration, and the OctaMon 8 continuous-wave device (OctaMon, Artinis Medical Systems, Elst, The Netherlands) for fNIRS (10 Hz) measures. Critical for seamless timestamp data fusion, both signals were synchronized in real-time via Lab Streaming Layer (LSL). All data were uploaded and stored in a cloud environment for further offline pre-processing using MATLAB® R2023a (MATLAB, 2023) and its associated graphical and statistical toolboxes. The montage is illustrated in Fig. 3.

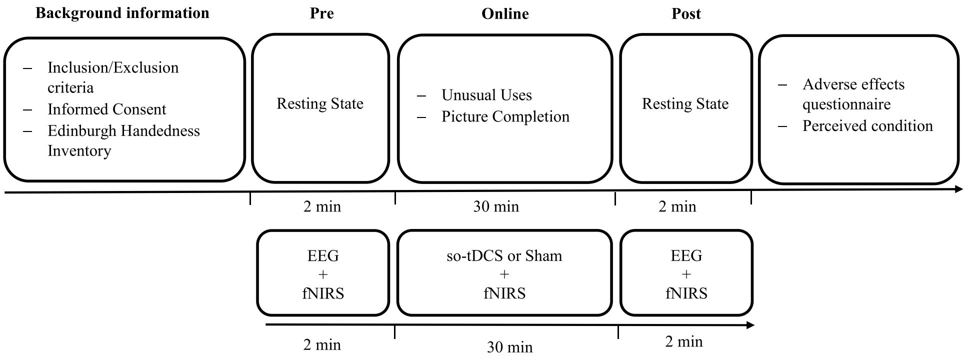


Fig. 2. Study procedure.

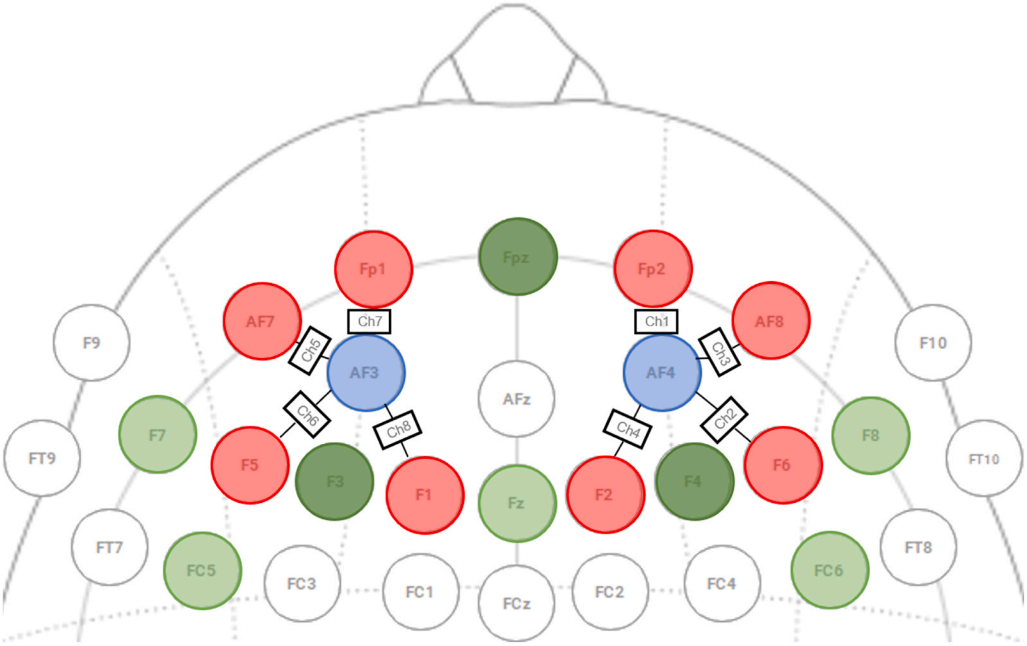


Fig. 3. so-tDCS and multimodal EEG-fNIRS montage. *Note.* Green circles correspond to EEG electrode locations for the resting state registration, and during so-tDCS, F3 and F4, and Fpz channels were stimulating electrodes (dark green). Red (transmitters, Tx) and blue (receivers, Rx) circles correspond to fNIRS montage for both resting and task registration, and squares are the channels derived from Tx-Rx combination.

2.6.1. *EEG acquisition and pre-processing*

Brain electrical activity was collected using eight AgCl electrodes placed at F3, F4, Fpz, Fz, F7, F8, FC5 and FC6 according to the 10–20 international system and considering Fpz as the reference point. The ground electrode was placed on the right ear lobe. The EEG protocol was previously created and monitored by the NIC2.0 software (https://www.neuroelectrics.com/products/software/nic2). The sampling rate was 500 Hz and the impedance of the electrodes was checked to ensure it was under 10kΩ.

As the current supplied during stimulation introduced substantial artefacts in the recorded EEG signals, the EEG measures were extracted from resting state blocks Pre and Post the application of so-tDCS/sham intervention. Pre-processing was performed with Brainstorm (Tadel et al., 2011) in MATLAB® R2023a (MATLAB, 2023), which is documented and freely available for download online under the GNU general public license (http://neuroimage.usc.edu/brainstorm). The artefactual segments were manually identified and rejected, and EEG signals were band-pass filtered between 0.1 and 45 Hz using a linear-phase FIR filter (Kaiser window, filter order = 18128, stopband attenuation = 60 dB) to ensure sharp frequency selectivity while preserving phase integrity.

The FC matrices were obtained from 0.1 to 1 Hz band pass filtered time-series data in order to capture slow frequency synchronization. Then, connectivity was calculated based on Pearson's correlation and non-windowed NxN matrices were extracted. Besides, the power spectral density (PSD) was estimated using the Welch method. The signal was segmented into four second windows with a 50% overlap, and Fast Fourier Transformation and Hanning window were applied to each segment. From the original 39 sample size, five EEG recordings were excluded due to bad quality of the signals and/or having less than 10 segments. Power values were extracted from the PSDs in two frequency bands: slow (0.1 – 1 Hz), delta (1 – 4 Hz) theta (4 – 8 Hz), alpha (8 – 12 Hz) and beta (13 – 30 Hz).

The mean values of channels F3, F7 and FC5, and F4, F8 and FC6 were calculated separately to determine the power for the left and right PFC, respectively. Additionally, the overall average across all channels was computed to derive the power for the total PFC.

2.6.2. *fNIRS acquisition and pre-processing*

To measure PFC haemodynamic responses, two sets of fNIRS probes were bilaterally placed over the PFC region (see Fig. 3). A total of eight transmitters (Tx) were placed on Fp2, F6, AF8, F2, AF7, F5, Fp1 and F1, and two receivers (Rx) were set on AF4 and AF3, resulting in a total of 8 channels (Ch) as displayed in Fig. 3. Distance between Tx and Rx was around 30 mm and the differential path-length factor (DPF) was established at six. Micromolar variations in oxygenated haemoglobin concentration changes (ΔHbO) and in deoxygenated haemoglobin concentration changes (ΔHHb) were measured using the optical densities obtained from two continuous light source wavelengths (757 and 852 nm) at a sampling rate of 10 Hz. Oxysoft v3.2.72 software (Oxysoft, Artinis Medical Systems, Elst, The Netherlands) was used to record fNIRS data, which received the raw fNIRS signals via Bluetooth.

2.6.2.1. Resting state fNIRS. Resting-state fNIRS signals were preprocessed and analysed using the NIRS-KIT (Hou et al., 2021) toolbox in MATLAB® R2023a (MATLAB, 2023). Channels with excessive noise were visually identified and manually excluded. Pre- and post-stimulation resting state data from two subjects were eliminated due to bad quality of the signal. For the remaining subjects, in the first step, the Temporal Derivative Distribution Repair (Fishburn et al., 2019) method was applied for motion artefact correction, and in the second step, bandpass filtering with an IIR filter between 0.01 and 0.08 Hz was applied to isolate spontaneous low-frequency fluctuations relevant for FC and minimise interference from systemic oscillations. No detrending filter was applied. The FC matrices were calculated by Pearson correlation method based on both ΔHbO and ΔHHb followed by Fisher z-transformation.

2.6.2.2. Task-related fNIRS. The haemodynamic response function (HRF) of ΔHbO and ΔHHb during the PC task was obtained using the HomER3 v1.87.0 toolbox (Huppert et al., 2009) in MATLAB® R2023a (MATLAB, 2023). In the first step, raw data were converted into optical density (OD) using the hmrR_Intensity2OD function. Next, the hmrR_MotionArtifactByChannel function was applied to detect motion artefacts on a channel-by-channel basis. The following parameters were set for all participants: tMotion = 0.5, tMask = 1.0, and AMPThresh = 50.0, except for the standard deviation threshold (SDEVThresh), which was set individually and corrected by spline interpolation function (hmrR_MotionCorrectSpline). The OD data were then converted into concentration changes (μM, micromoles) by the modified Beer–Lambert law (Duncan et al., 1996) assuming a DPF of 6. To minimise the influence of brain systemic physiological signals (cardiac, respiratory, and Mayer-wave oscillations), the ΔHbO and ΔHHb signals were passed through a low pass filter set at 0.1 Hz. No high band filter was applied. Time range was set from -10s to 150 s to obtain the HRF of the eight channels. To obtain the ΔHbO and ΔHHb HRF of the task block we used values from −5–120 s, as this window corresponds to the duration of the PC task and also allows to capture initial dip, as well as the return to baseline levels as neural activity subsides. The 120 s task block was divided into 10 s intervals (12 in total).

Additionally, the average values from channels Ch1 to Ch4 and Ch5 to Ch8 were independently calculated to obtain HRF for the left PFC and right PFC, respectively. The average across all channels was also calculated to obtain the total PFC HRF.

2.7. *Statistical analysis*

SPSS Statistics v28.0 (IBM Corp., 2021) was used to conduct behavioural, EEG resting-state power data and fNIRS task-related data statistical analysis. All continuous variables were subjected to normality analysis using Shapiro-Wilk test ($n < 50$) and categorical variables were analysed using the chi-squared (X^2) test. Group differences (so-tDCS vs. sham) were then assessed using a Student’s *t*-test (for normally distributed variables) or Wilcoxon test for continuous variables.

The FC matrices differences between pre- and post-stimulation, and between sessions (so-tDCS/sham) were assessed using a paired Wilcoxon signed-rank test with Monte-Carlo permutation testing (5000 permutations), depending on the assumptions of normality based on Shapiro-Wilk test. Multiple comparisons of signals were corrected through the false discovery rate (FDR) method ($p < .05$) over the signal dimension. All analyses were performed using Brainstorm software (Tadel et al., 2011).

For EEG power data, the pre- and post-stimulation mean power values for the four frequency bands (slow, delta, theta, alpha, and beta) were compared between the so-tDCS and sham sessions using the appropriate paired test (*t*-test or Wilcoxon) based on the normality assessment.

For PC task-related HRF, two factor (Session × Time) repeated measures ANOVA tests were conducted separately for each channel, as well as for the left PFC, right PFC, and total PFC. The time factor corresponded to the 12 × 10 s intervals of the 120 s PC task period. Subsequently, *post hoc* analyses were performed with Bonferroni correction applied.

In order to obtain FC differences between sessions (so-tDCS/sham), paired t-tests were run using the NIRS-KIT (Hou et al., 2021) toolbox with the FDR method applied ($p < .05$).

All statistical tests were two-tailed, and the significance level was set at.05. Hedges’ g was calculated to inform about effect sizes.

3. Results

3.1. *Blinding efficacy and side effects*

There were no differences between so-tDCS and sham conditions in the frequency distribution of responses regarding perceived condition [X^2 (4, N = 39) = 2.48, $p = .65$]. In addition, participants did not experience any severe adverse effects during or after the sessions (refer to Tables S1 and S2 in the Supplementary Material for further statistics).

3.2. *Effect of so-tDCS on creativity*

Wilcoxon test revealed a significant difference ($T = 10$, $z = 2.45$, $p = .014$) in the originality score of the PC task between so-tDCS and sham sessions. Originality was higher in so-tDCS than in sham indicating a moderate effect ($g = 0.40$) of the so-tDCS. In addition, originality of the UU task ($p = .082$, $g = 0.31$) and fluency of the PC task ($p = .073$, $g = 0.23$) showed a non-significant trend ($.05 < p < .10$), indicating higher scores in the so-tDCS session. See Table 1 for more information.

3.3. *Effect of so-tDCS on EEG*

3.3.1. *Resting state FC*

Fig. 4 shows the FC differences during post-stimulation resting-state period for the so-tDCS compared to sham (pre-post within-session differences are shown in Fig. S1 of the Supplementary Material). During the pre-stimulation resting state period, the statistical analysis did not reveal any significant differences ($p > .05$) in FC between the so-tDCS and sham sessions. Nonetheless, post-stimulation lower FC between F3, and Fpz, Fz, F7, FC5 and FC6, and between F4, and Fpz, Fz, FC5 and FC6 were observed during so-tDCS compared to sham ($p < .05$).

3.3.2. *EEG power*

The SWA power results are summarized in Fig. 5 (see Tables S3 and S4 in Supplementary Material for more details).

EEG power values obtained during the pre-stimulation resting period did not show statistical differences ($p > .05$) between so-tDCS and sham sessions in any of the analysed EEG bands. Statistical tests showed significant differences between so-tDCS and sham during the post-stimulation resting state period. Specifically, for the so-tDCS session SWA band power (0.1 – 1 Hz) was significantly lower in channels F3 ($p = .022$), F4 ($p = .020$), Fz ($p = .025$), FC5 ($p = .033$) and FC6 ($p = .011$), and in the left PFC ($p = .015$). Channels F7 ($p = .076$) and total PFC ($p = .054$) exhibited a non-significant trend suggesting a possible bilateral effect of the so-tDCS in the SWA power of the PFC.

Analysis of the delta (1 – 4 Hz), theta (4–8 Hz), alpha (8–12 Hz), and beta (13–30 Hz) bands revealed no significant differences between the so-tDCS and sham sessions (all $p > .05$). Refer to Tables S5 to S12 in Supplementary Material for more details.

3.4. *Effect of so-tDCS on fNIRS*

3.4.1. *Resting state FC*

Fig. 6 shows the FC analysis during the pre- and post-stimulation resting-state period for the so-tDCS compared to sham. During the pre-stimulation resting state period, the statistical analysis between the so-tDCS and sham session only revealed a significantly lower FC between Ch1 (right PFC) and Ch8 (left PFC) ($t(36) = -2.97$, $p = .005$) suggesting a minor baseline difference between conditions. However, during the post-stimulation resting state, a greater number of channels showed significant FC changes between the so-tDCS and sham session: higher intrahemispheric FC within the left PFC between Ch5 and Ch7 ($t(36) = 2.86$, $p = .007$) and with a trend between Ch5 and Ch6 ($t(36) = 1.75$, $p = .089$); lower intrahemispheric FC within the right PFC between channels Ch1 and Ch3 ($t(36) = -2.45$, $p = .019$) with a trend between Ch1 and Ch2 ($t(36) = -1.84$, $p = .074$); and, lower inter-hemispheric FC between Ch1 (right PFC) and Ch7 (left PFC) ($t(36) = -2.31$, $p = .027$).

In summary, these resting-state FC results show that compared to the sham session, the so-tDCS induces higher synchronization within the left PFC and lower synchronization within the right PFC, accompanied by a reduced interhemispheric synchronisation between left and right PFC (see Fig. 6).

Table 1
Creativity statistics in so-tDCS and sham sessions.

	Sham	**so-tDCS**				
	Mean ± SE	**Mean ± SE**	**Statistic**	***p***	**Hedges' *g***	**Statistical Power**
UU Fluency	10.80 ± 0.65	11.90 ± 0.90	$Z = 1.34$	.180		0.33
UU Originality	6.82 ± 0.58	8.26 ± 0.92	$Z = 1.74$	.082	$g = 0.31$	0.50
PC Fluency	5.00 ± 0.35	5.54 ± 0.34	$t\ (38) = 2.01$	.073	$g = 0.23$	0.30
PC Originality	2.51 ± 0.26	3.26 ± 0.30	$Z = 2.45$	**.014***	$g = 0.40$	

SE: Standard Error; UU: Unusual Uses Task; PC: Picture Completion Task. * $p < .05$

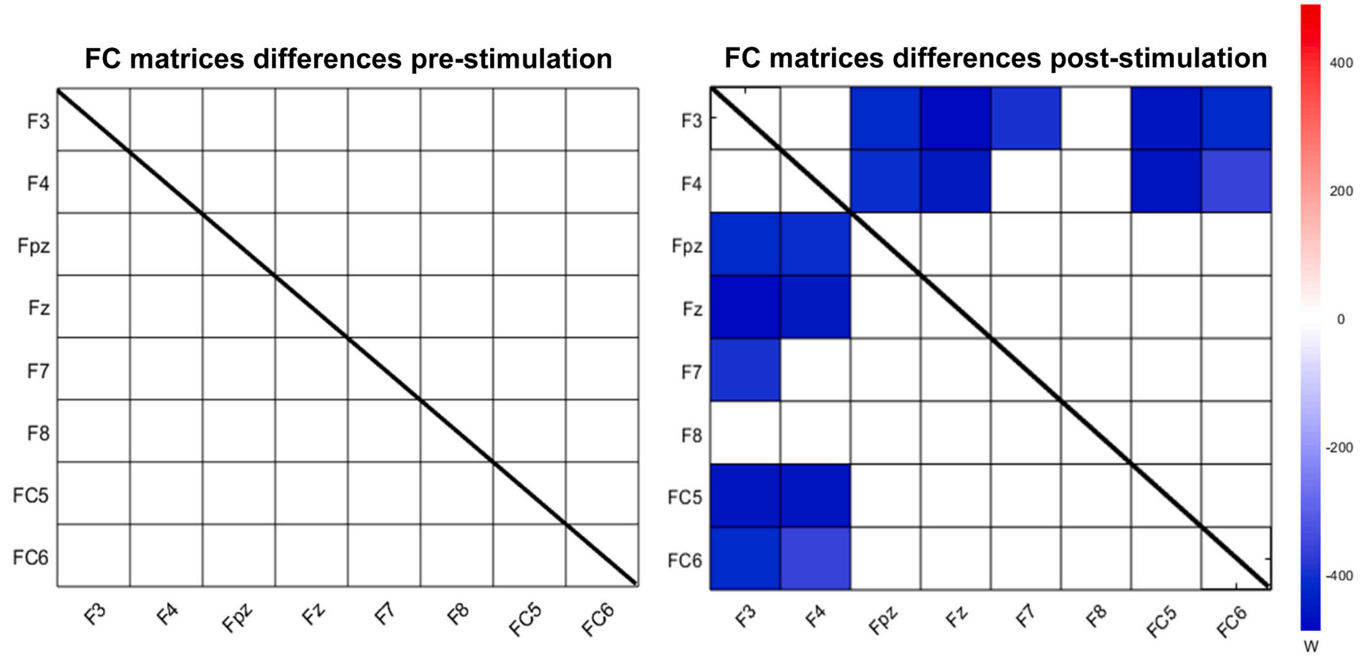


Fig. 4. Functional connectivity analysis between prefrontal cortex EEG signal for the so-tDCS compared to the sham session. *Note.* Functional connectivity matrices were extracted for the slow band (0.1 – 1 Hz), and the values represent the FDR-corrected W-statistics from Wilcoxon test (5000 permutations) for *p*-values < .05. Red colour indicates greater functional connectivity, while blue indicates lower functional connectivity. so-tDCS: slow oscillatory transcranial direct current stimulation; FC: functional connectivity; W: Wilcoxon statistic.

3.4.2. *Picture completion task-related HRF*

Fig. 7 shows the changes in PFC oxygenated (ΔHbO) and deoxygenated (ΔHHb) haemoglobin concentration during the PC task for the so-tDCS and sham session. As shown in Fig. 7 (and supplementary Fig. S3 for individual channels), at the onset of the PC task, the haemodynamic response begins with a small initial dip (seen as a brief downward deflection in the signal) reflecting the transient mismatch between oxygen consumption and supply. This is followed by a robust HRF characterised by a greater increase in blood flow to meet the heightened metabolic demands (i.e., neurovascular coupling). After the PC task, the haemodynamic signals gradually return to their respective baseline levels as neural activity subsides.

Significant Session × Time interaction effects were found for ΔHbO in the left PFC [$F(11, 418) = 6.14$, $p = .003$, $\varepsilon = .182$, $\eta_p^2 = 0.139$] and total PFC [$F(11, 407) = 5.46$, $p = .002$, $\varepsilon = .247$, $\eta_p^2 = 0.129$]. For ΔHHb, there was a significant Session × Time interaction in the left PFC [$F(11, 418) = 3.23$, $p = .039$, $\varepsilon = .192$, $\eta_p^2 = 0.078$]. Session × Time interactions were also shown at the individual channel level for the left PFC channels: Ch6 [$F(11, 418) = 5.18$, $p = .016$, $\varepsilon = .133$, $\eta_p^2 = 0.120$], Ch7 [$F(11, 407) = 2.93$, $p = .034$, $\varepsilon = .287$, $\eta_p^2 = 0.073$], and Ch8 [$F(11, 418) = 4.75$, $p = .017$, $\varepsilon = .151$, $\eta_p^2 = 0.111$].

Post hoc tests revealed that ΔHbO was significantly greater for the so-tDCS compared to sham in the left PFC after ~60 s into the PC task. The individual channels confirmed that left PFC ΔHbO was significantly greater for Ch6 and Ch8 after ~60 s into the PC task in so-tDCS session compared to sham. The total PFC ΔHbO also showed greater increases from ~80 s into the PC task, but these differences in total PFC may be attributed to a greater contribution from the left PFC, given that no significant differences were found in the right PFC individual channels.

In summary, these results indicate that ΔHbO was significantly greater, reflecting a more pronounced HRF, in the left PFC during the second half of the Picture Completion task in the so-tDCS session compared to sham. For detailed statistics refer to Supplementary Material.

4. Discussion

To the best of our knowledge, this is the first study exploring the potential effects of so-HD-tDCS at 0.75 Hz over the bilateral DLPFC and mPFC on creative cognition and PFC activity measured by multimodal EEG-fNIRS neuroimaging. The main results of the study indicated that so-tDCS at 0.75 Hz delivered for 30 min during creative task performance enhanced visual creativity, along with increased ΔHbO over the left PFC compared to the sham session. During resting state periods, EEG registration revealed lower FC in SWA between bilateral DLPFC, and central and medial regions of the PFC, and lower SWA power post-stimulation in the so-tDCS session. Moreover, haemodynamic measures indicated greater synchronization in the left PFC for so-tDCS, while right PFC intrahemispheric FC and mPFC interhemispheric FC were lower compared to sham during the post-stimulation resting period. However, the physiological data did not significantly correlate with creativity scores.

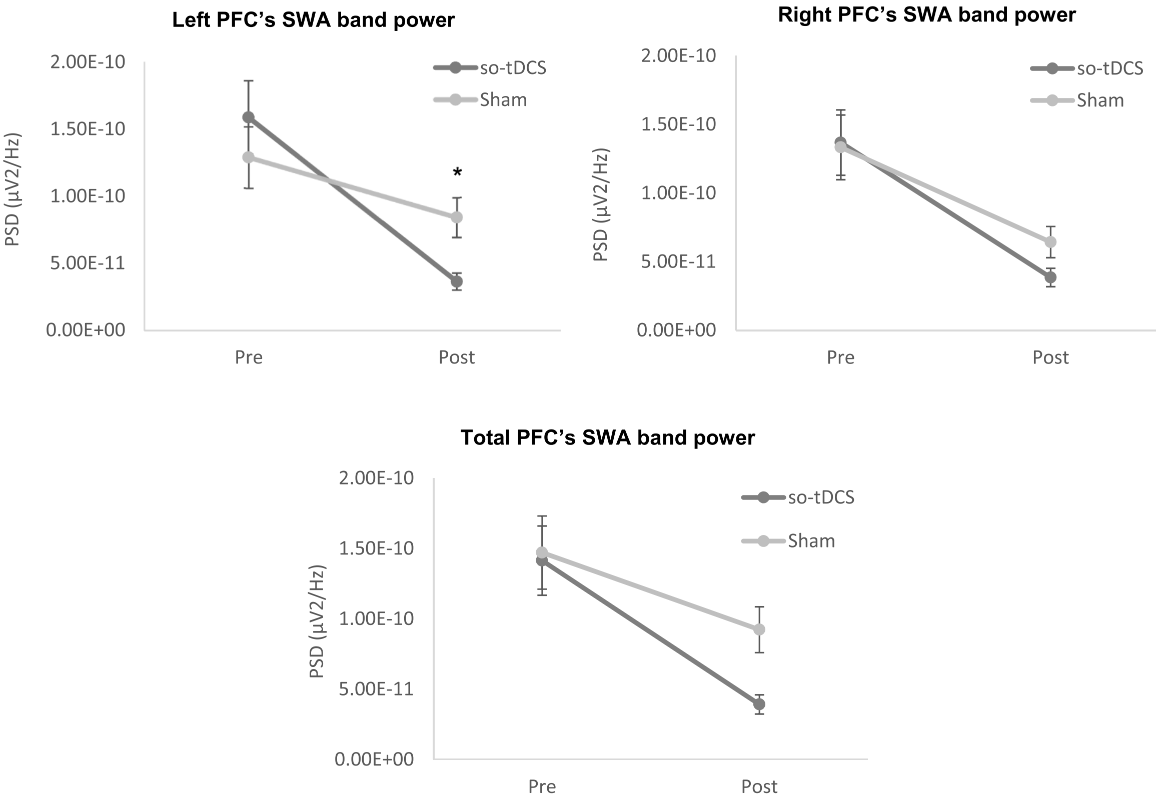


Fig. 5. Comparison of prefrontal cortex's power in the SWA band (0.1 – 1 Hz) between so-tDCS and sham sessions. *Note*. The plots represent power spectrum densities aggregated across PFC electrodes over the left (F3, F7, FC5), right (F4, F8, FC6) PFC, and total (F3, F4, Fpz, Fz, F7, F8, FC5, FC6) during the pre- and post-stimulation resting state periods. Note the significantly greater post-stimulation reduction in SWA power, particularly in the left PFC for the so-tDCS session compared to sham. SWA: slow wave activity; PFC: prefrontal cortex; so-tDCS: slow oscillatory transcranial direct current stimulation. *, $p < .05$.

4.1. *Effect of so-tDCS on creativity*

In line with our predictions, so-tDCS over the bilateral DLPFC and mPFC enhanced creative performance. The simultaneous stimulation of the bilateral DLPFC and the mPFC may have facilitated a more integrated engagement of both controlled and spontaneous modes of processing.

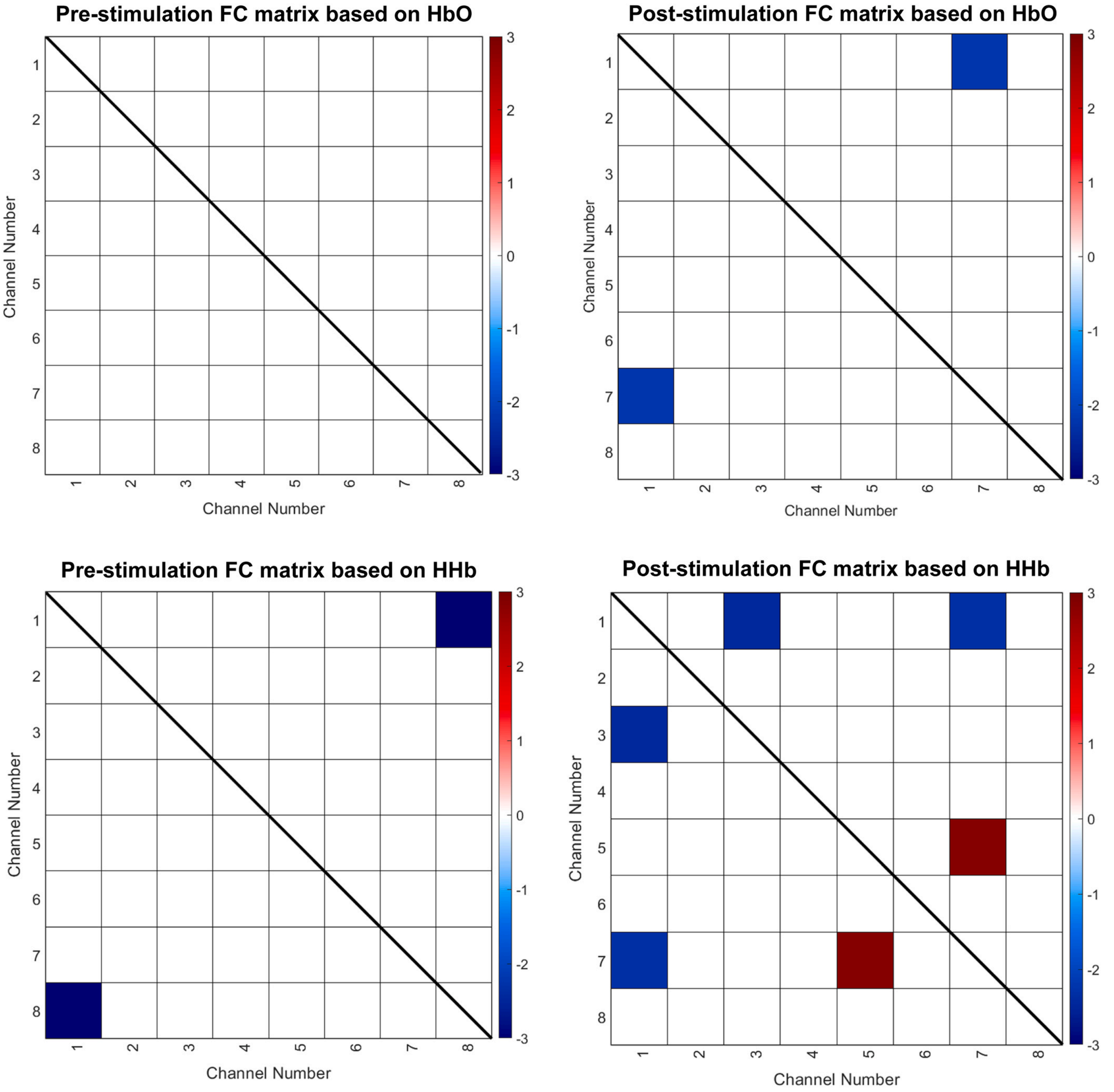
Recent literature highlights that the neuromodulatory effects of transcranial electrical stimulation are highly dependent on current directionality relative to cortical folding, rather than a strict anode/cathode binary (e.g., Hannah et al., 2019). Foundational so-tDCS studies (e.g., Marshall et al., 2006) utilized anode electrodes over the bilateral DLPFC and cathode electrodes over the bilateral mastoids to effectively drive and enhance slow-wave activity. By placing the anodes over the bilateral DLPFC and the return cathode over mPFC, our montage deliberately has directed this oscillating current from the bilateral DLPFC to the mPFC. This directionality effectively has created and driven a rhythmic 0.75 Hz wave between these specific cortical sites. Therefore, rather than suppressing the mPFC, driving the 0.75 Hz oscillation from the DLPFC to the mPFC has brought these hubs into a synchronized oscillatory state, promoting mPFC-DLPFC associative processing. In particular, entraining slow oscillations in the mPFC may have supported the generation of candidate remote associations through a more internally directed processing (Zabelina & Andrews-Hanna, 2016). Moreover, it was expected that the rhythmic entrainment of slow oscillations at 0.75 Hz over the bilateral DLPFC, which prior studies have shown to acutely increase SWA during the stimulation period (e.g. Kirov et al., 2009; Marshall et al., 2006; Ladenbauer et al., 2016), could have increased the capacity to sustain goal-directed attention, maintain focus, and inhibit distractions during the PC task performance, thereby facilitating the selection of the most appropriate responses (Beaty et al., 2015).

Although verbal creativity showed a trend toward higher scores, it did not reach statistical significance. Therefore, only originality in the visual creativity task was significantly greater in the so-tDCS session. Müri et al. (2023) found similar effects when comparing resting and nap interventions. Although both interventions enhanced divergent thinking, the nap specifically improved figural divergent thinking, with no significant effect on verbal creativity. This suggests a possible differential effect of sleep on figural versus verbal domains. Similarly, Ladenbauer et al. (2016) found increased visual but not verbal memory after so-tDCS during a nap. These authors (Ladenbauer et al., 2016) suggest that so-tDCS primarily may enhance slow oscillations and cortical synchronization typical of lighter non-REM sleep stages, which support the consolidation of visual or figural information, thereby improving figural creativity. In contrast, verbal creativity appears to rely on deeper sleep stages, where more complex semantic and linguistic processes are consolidated – stages that naps often do not reach. Despite the available evidence, the found trend toward a significant difference in verbal creativity, together with the limited statistical power of the analysis, prevent the authors from making a strong claim regarding a dissociation effect. Therefore, more research is needed specifically designed to disentangle how so-tDCS impacts different domains (i.e. verbal and figural) of creative cognition.

4.2. *Effect of so-tDCS on EEG*

4.2.1. *Resting state FC*

So-tDCS induced FC reduction in the SWA between the bilateral DLPFC and the rest of the PFC. These findings align with our predictions, as bilateral stimulation of the DLPFC was expected to elicit similar effects across both hemispheres of the PFC. The observed reduction in FC suggests a reorganization of the PFC toward a more local and functionally segregated configuration of the bilateral DLPFC following so-


Pre-stimulation FC matrix based on HbO

Post-stimulation FC matrix based on HbO

Pre-stimulation FC matrix based on HHb

Post-stimulation FC matrix based on HHb

Fig. 6. Functional connectivity analysis between prefrontal cortex fNIRS channels for the so-tDCS compared to the sham. *Note.* The values represent the FDR-corrected *t*-statistics from Student's *t*-tests for *p*-values < .05. Red colour indicates greater functional connectivity, while blue indicates lower functional connectivity. fNIRS: functional near infrared spectroscopy; so-tDCS: slow oscillatory transcranial direct current stimulation; FC: functional connectivity; HbO: Oxygenated haemoglobin concentration; HHb: Deoxygenated haemoglobin concentration; Δ: Change; μM: Micromoles.

tDCS. This shift toward reduced long-range coupling within the PFC may indicate a redistribution of functional interactions after so-tDCS, favouring more specialized processing within PFC.

This reorganization may reflect the brain's transition from a globally synchronized state induced by so-tDCS to a more specialized and differentiated pattern of cortical functioning. Such effects are consistent with the role of SWA in synaptic plasticity and support the synchronization and reorganization of brain dynamics (Ujma et al., 2018; Yoshida & Toyoizumi, 2022). Post-stimulation induced PFC connectivity is in line with the pattern of post-sleep activation which prioritizes brain functioning related to external attention and executive functions, including bilateral DLPFC, upon awakening (Stevner et al., 2019). Overall, so-tDCS could have reshaped PFC activity by promoting local, specialized functioning within the bilateral DLPFC while aligning with post-sleep brain dynamics.

4.2.2. *EEG power*

A greater reduction in SWA (0.1 – 1 Hz) was observed after so-tDCS in the left PFC compared to the sham condition. However, the observation that the right PFC showed a similar SWA decrease after both real and sham sessions suggests this response reflects a general task related effect. While anodal so-tDCS over bilateral DLPFC was applied, it was expected that SWA power would increase close to the stimulation areas, consistent with previous empirical studies (e.g. Kirov et al., 2009;

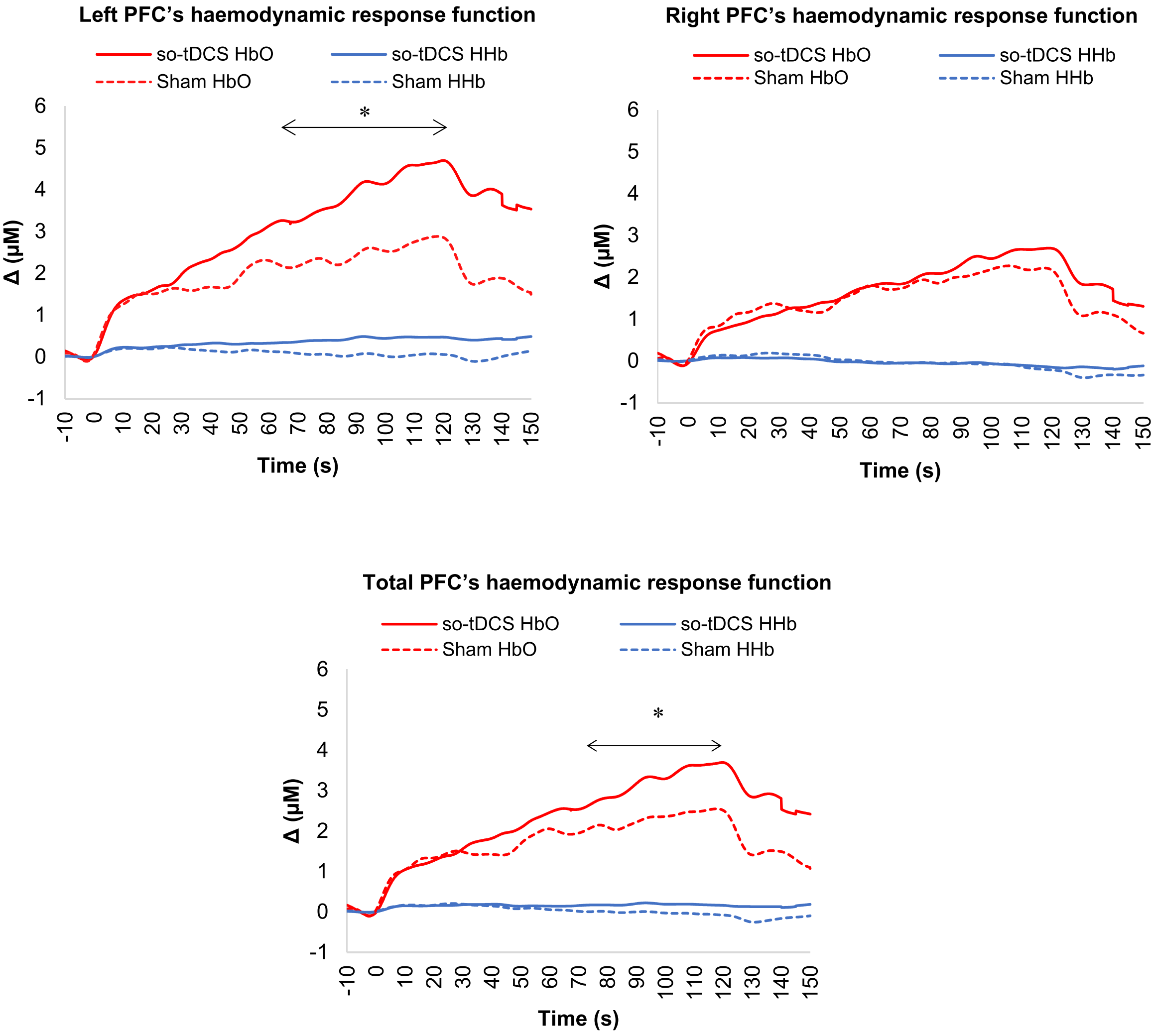


Fig. 7. Haemodynamic response function in so-tDCS and sham sessions during Picture Completion task. *Note.* so-tDCS: slow oscillatory transcranial direct current stimulation; PFC: Prefrontal cortex; HbO: Oxygenated haemoglobin concentration; HHb: Deoxygenated haemoglobin concentration; Δ: Change; μM: Micromoles; s: seconds. *, $p < .05$ between so-tDCS and sham.

Marshall et al., 2006; Ladenbauer et al., 2016) that reported an increase in SWA between stimulation blocks during sleep (Marshall et al., 2006; Ladenbauer et al., 2016), and quiet wakefulness (Kirov et al., 2009). Since our stimulation protocol was continuous, it was not planned to analyse the immediate EEG effects during the stimulation due to the large artefacts generated. Nevertheless, we could confirm these artefactual SWA oscillations in the five EEG channels surrounding the F3, F4, Fpz stimulating electrodes.

Our novel finding of reduced SWA in the period after the creative tasks and stimulation can be explained by a dynamic adjustment of left PFC resources. The lateralized effect whereby the so-tDCS preferentially modulated the left PFC because it was efficiently recruited during the creativity task –evidenced by the significant increase in ΔHbO during the task and higher originality scores– is key. This left PFC recruitment, such as that induced by NIBS, task, and combinations of NIBS and task, subsequently forced the hemisphere to trigger an immediate, stabilizing Long-Term Depression (LTD)-like down-regulation – the reduced SWA (Wilckens et al., 2018). This left PFC lateralised so-tDCS effect post-stimulation may reflect an efficient, localized down-scaling mechanism afterward. Specifically, computational models of so-tDCS predict that the increase in neuronal firing rates during stimulation causes accelerated synaptic downscaling (LTD-like effects) online, thereby leading to a reduced SWA power in the period following stimulation (Reato et al., 2013). Thus, a general reduction in SWA after the task may reflect LTD-like compensatory response, i.e. the lasting weakening of connections for pruning and stabilization (Ziemann & Siebner, 2008), indicating a dynamic adjustment of PFC resources to the high cognitive load-induced recruitment of the left PFC during the task.

The absence of an effect on alpha-band power suggests that so-tDCS over bilateral DLPFC and mPFC does not promote significant modulation on this band commonly associated to creative ideation (Fink & Benedek, 2014). To our knowledge, this is the first study causally linking SWA to creative cognition, and more specifically to enhanced figural creativity. Additionally, the lack of effect on alpha power may be explained by the high variability in the brain regions reported to show changes in this frequency (Agnoli et al., 2020; Benedek et al., 2011; Mazza et al., 2023). Moreover, most of the EEG studies about creativity are based on verbal tasks and compared band power with resting baseline levels rather than with a control task (Fink & Benedek, 2014). Since the effect of so-tDCS was observed in figural creativity but not in verbal creativity, it is reasonable that the electrophysiological changes found differed from those reported in previous studies. In addition, the placement of the return electrodes over the mastoids in previous studies (see Marshall et al., 2006 for details on the stimulation protocol) may have been relevant for effects on alpha activity (Koo-Poeggel et al., 2019).

According to the meta-analysis by Pidgeon et al. (2016), visual creative tasks are consistently associated with decreases in EEG power in the delta, theta, and both lower and upper alpha bands, and increases in beta band. These effects were broadly observed across bilateral frontal, central, and occipital electrode sites. However, several of the reviewed EEG studies found that visual creativity related effects on power were more robust over occipital compared to more anterior electrode sites (Pidgeon et al., 2016). Thus, our study's low-density EEG setup limited to the PFC may have missed relevant activity in more posterior regions. Moreover, in this study we compared post-task resting state electrical activity rather than the brain response during the figural task which makes it more difficult to link the brain electrical changes to increased originality observed in so-tDCS session.

Taken together, our findings suggest that applying so-tDCS during an active cognitive task, such as the creative tasks used in the study, may have partially engaged the left PFC recruitment in real time. By rhythmically entraining slow-oscillatory dynamics while participants remained awake, so-tDCS could have facilitated task-dependent PFC engagement. This interpretation aligns with the dynamic adjustment of resources framework proposing that high-demand cognitive task promotes higher PFC recruitment. In this sense, the reduced post-stimulation SWA observed in the left PFC may reflect an increased dynamic neural adjustment following a high cognitive load task resulting from the combined effects of task demands and stimulation-induced slow-wave entrainment.

4.3. Effect of so-tDCS on fNIRS

4.3.1. Resting State FC

So-tDCS induced greater intrahemispheric FC in the left PFC, and lower FC within the right PFC, particularly between anterior and dorsolateral frontal regions. While the increased FC in left PFC aligned with our hypothesis, the decreased FC observed in the right PFC was contrary to our predictions. Bilateral stimulation of the DLPFC was expected to induce similar effects in both hemispheres of the PFC. Hence, the observed mismatched effect between left and right PFC may be reflecting different implications of both hemispheres of the PFC on creative thinking, specifically on figural creativity. In addition, the reduced FC between left (Ch7) and right (Ch1) mPFC, may indicate a decreased communication between both sides.

The present findings revealed asymmetric effects of so-tDCS on PFC, characterized by increased intrahemispheric connectivity in the left PFC and decreased connectivity within the right PFC, as well as reduced interhemispheric connectivity within mPFC regions. Although bilateral stimulation of the DLPFC was expected to induce similar effects across hemispheres, such asymmetrical modulation is consistent with previous evidence indicating hemispheric specialization in creative cognition (Li et al., 2016; Shi et al., 2018). In particular, visual and figural creativity has been associated with FC changes involving both the DLPFC and mPFC regions, reflecting the critical role of PFC organization in creative processing (Li et al., 2016). Notably, altered functional connectivity patterns, including both increases and decreases across PFC regions, have been linked to creative performance, suggesting that creativity may rely on functional reconfiguration rather than uniform increases in connectivity. Therefore, the observed decrease in FC in the right PFC and in the mPFC regions may reflect a task-relevant reorganization of creative networks, potentially facilitating functional specialization and reducing redundant interhemispheric communication. This interpretation aligns with prior findings showing that creative cognition depends on dynamic interactions within and between PFC (Li et al., 2016; Shi et al., 2018), particularly involving the DLPFC and mPFC (Zhuang et al., 2023), which support cognitive control (Beaty et al., 2015) and internally directed cognition (Zabelina & Andrews-Hanna, 2016).

4.3.2. Task-related HRF

Under so-tDCS, greater increases in ΔHbO were found in the left PFC and the total PFC scores in so-tDCS session. This was confirmed by the greater increases in ΔHbO from the individual left PFC channels (Ch6 and Ch8) for the so-tDCS compared to the sham session, which are the closest channels to the anode placed over F3. Since no differences were observed in the right PFC, it is likely that the effect observed in the total PFC is primarily driven by the left PFC. Huang et al. (2013) reported similar results in healthy non-artists during figural creative task where the left PFC was more activated compared to brain response during visual non-creative thinking. They suggested a possible inhibitory mechanism of the left-over-right PFC, enabling a more efficient selection of the most original ideas. Similarly, Aziz-Zadeh et al. (2013) examined differences in PFC activation between a figural creative task and a control visuospatial task. Although both tasks recruited bilateral PFC processing, the creative task elicited stronger activation in the left PFC, whereas the non-creative control task relied more on the right PFC. It should also be noted that there is evidence pointing to a central role of the right PFC on visual creativity especially in experienced artists (Chen et al., 2019). However, many of these studies compared the brain response at baseline or resting-state period with the figural creative task instead of comparing to a control or low creativity demanding tasks (Pidgeon et al., 2016).

In summary, our results indicate that so-tDCS improves visual originality with a greater haemodynamic response from the left PFC. This does not mean that the right PFC does not contribute, but rather that the left PFC makes the critical difference when so-tDCS is applied during figural creative performance in non-artist individuals.

5. Limitations and future directions

One key limitation of the present study is the reliance solely on two single creativity behavioural measures to represent complex constructs such as verbal and figural creativity. Creativity is a multifaceted cognitive process, and these singular measures may not fully capture the breadth and depth of creative abilities. Therefore, given the trend showed in verbal originality, it is not possible to determine the extent to which there is a specific effect on spatial-executive processing. Future research endeavours would benefit from incorporating a broader array of tasks and assessments to more comprehensively evaluate creative performance across different domains.

Another important consideration stems from the concurrent application of tACS at 0.75 Hz and tDCS over the bilateral DLPFC and mPFC using a novel HD-montage. Given the novelty of this combined montage/protocol and the absence of prior studies employing it, the observed effects cannot be definitively attributed to slow oscillatory entrainment alone. Therefore, further research is needed to disentangle how so-tDCS modulates brain connectivity by entrainment (slow oscillations), excitatory/inhibitory (direct current) or both mechanisms. It is also essential to determine the extent to which these results are driven by the specific stimulation protocol (open and closed-loop so-tDCS), dose (greater current amplitude), and the targeted brain regions, or the interaction between these various factors.

Although the application of so-tDCS was intended to enhance communication between extended networks, stimulation in this study was confined to the central node or core hub of each network rather than encompassing the entire network. Furthermore, the relatively small number of channels used for neuroimaging restricted our ability to determine whether the effects of stimulation extended to other regions within the same network. Consequently, these findings should be interpreted with caution and future studies could employ hybrid neuroimaging techniques and higher-density montages (>30 channels) to more precisely investigate the effects of so-tDCS on the FPCN and DMN.

Finally, our study captured only an averaged snapshot of so-tDCS effects that could have explained the lack of correlation between physiological and originality changes. Given the multiple distinct cognitive and neural processes implicated in creative thinking, future work could involve more in-depth analyses to capture the dynamic changes induced by so-tDCS. Specifically, despite the results of the ANOVA analysis on the task-related HRF appear robust, it may violate the assumption of independence by aggregating temporally adjacent observations that are inherently autocorrelated, affecting the validity of statistical inferences. Future investigations should incorporate General Linear Model approaches to more accurately model and capture the temporal dynamics of the HRF relevant for behaviour response. Moreover, this study examined resting-state electrical activity after the task rather than neural responses occurring during the figural task itself, which limits the ability to directly relate the observed electrophysiological changes to the increased originality found in the so-tDCS condition. Further analysis including neural biomarkers at pre-intervention may contribute to understand how baseline brain state mediates and/or moderates the effect of NIBS on brain response and creative cognition, thus addressing the observed lack of linear correlation between physiological metrics and behavioural gains.

6. Conclusion

This study reveals for the first time distinct oscillatory and haemodynamic patterns associated with the so-tDCS brain state-induced enhancement of creative cognition, offering insights into the neurovascular dynamics underlying creative performance. The use of EEG-fNIRS multimodal imaging in research to mechanistically understand the effects of NIBS on creativity remains largely unexplored. However, this work provides promising evidence of its potential to shed new light on the brain mechanisms involved in the interaction between so-tDCS and creativity.

CRediT authorship contribution statement

Javier Peña: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Natalia Ojeda:** Writing – review & editing, Resources, Funding acquisition. **Makii Muthalib:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Agurne Sampedro:** Writing – review & editing, Resources, Funding acquisition. **Sarai Martinez-Martinez:** Writing – review & editing, Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Funding sources

This work was supported by 2018 Leonardo Grant for Researchers and Cultural Creators (BBVA Fundation); Department of Education and Science of the Basque Government [IT1545–22]; and University of Deusto.

Declaration of Generative AI and AI-assisted technologies in the writing process

The authors of the manuscript entitled *Effects of Slow Oscillatory HD-tDCS on Creative Cognition and Prefrontal Cortex Activity: A Multimodal EEG-fNIRS Study* declare that no generative AI or AI-assisted technologies were used in the preparation of this manuscript.

Declaration of Competing Interest

Makii Muthalib is a R&D Consultant at Silverline Research Ltd (UK). Silverline Research Ltd offers specialized R&D solutions and consulting services for the integration and application of non-invasive brain stimulation (NIBS) techniques (including tES) and multimodal neuroimaging (EEG-fNIRS).

Acknowledges

We want to sincerely thank all volunteers for their participation in this study.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.biopsycho.2026.109264.

Data availability

Data will be made available on request.

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