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Teaching-induced changes in neural networks: Toward a model of the creative universe

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ABSTRACT

According to the standard definition, a creative act requires originality and effectiveness. Creativity is widely considered an exclusively human characteristic, linked to the activity of brain networks such as the Default Mode Network (DMN), the Fronto-Parietal Network (FPN), and, to a lesser extent, the Salience Network (SN). A significant body of literature explores the viability of teaching creativity, often reporting positive results. However, little attention has been paid to the neural network modifications induced by creativity training.

This study investigates changes of creativity-related brain networks over time in the resting state (participants without specific cognitive activities). The stages considered were before and after a learning process focused on visual aesthetic creation tasks (Gabarron Method). High-density electroencephalography (EEG) was used to record brain activity. 51 female volunteers participated in the research.

The results show a significant increase in the activation of the DMN and FPN, with a more limited effect in the SN. The DMN and FPN are neural networks commonly activated during artistic creation and aesthetic perception tasks. This finding supports the existence of what could be called a 'creative universe,' encompassing capacities such as creation, perception, and divergent thinking.

1. Introduction

1.1. *Creativity as a human characteristic*

Since Kant, and even Plato's time, creativity has been widely recognized as a distinctly human characteristic (Hausman, 1979). A creative act is generally understood to be original and unique (Anderson, 1960). Over time, the criterion of "effectiveness" was added, culminating in what Mark Runco and Garrett Jaeger (2012) define as the "Standard Definition": Creativity consists of both originality and effectiveness. This definition remains widely accepted today.

Creativity is also considered a significant factor in the adaptive success of our species. As Liane Gabora and Scott B. Kaufman observed: "Many species engage in acts that could be called creative […]. However, human creativity is unique in that it has completely transformed the planet we live on" (Gabora and Kaufman, 2010, p. 279).

Sequencing chimpanzee and Neanderthal genomes has identified more than 200 genes unique to humans "over-expressed in brain regions involved in human self-awareness and creativity, including late-myelinating and phylogenetically recent regions of the neocortex for autobiographical memory in frontal, parietal, and temporal regions" (Zwir et al., 2022, p. 354).

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1.2. Neural networks of creativity: functional connectivity and domain specificity

Human cognition is not localized in any single brain area. Cognitive processes arise from synchronized activation patterns across distant regions of the brain. These regions form neural networks through functional connectivity (Sporns et al., 2004). Functional connectivity is observed when two distant areas activate and deactivate in synchrony, even if their physical connections remain unknown. Consequently, the analysis of creativity begins with identifying the neural networks associated with creative acts.

In terms of specific creative acts, in the 1930s, Catharine Parker's work on poets and artists introduced the question of domain specificity (Patrick, 1935, 1937). For example, visual creativity (as seen in artists) and verbal creativity (as seen in poets) are distinct phenomena with their own characteristics. Nevertheless, many studies disregard domain specificity, often examining creativity through divergent thinking or problem-solving tasks (Hamid et al., 2023).

Domain specificity seems to have limited relevance to the relationship between neural networks and creativity. Studies adopting a general perspective suggest that creative processes commonly involve the joint activation of two networks: the Default Mode Network (DMN) and the Fronto-Parietal Network (FPN, also referred to as the Executive Network, EN) (Chrysikou et al., 2020; Shi et al., 2018). The DMN includes regions in the medial prefrontal cortex, lateral and medial parietal cortex, and medial temporal lobes, while the FPN involves the dorsolateral prefrontal cortex and posterior parietal cortex. Some studies also include the Salience Network (SN), comprising regions in the anterior insula and dorsal anterior cingulate cortex (Beaty et al., 2018a,b; Cao et al., 2016).

When focusing on visual creativity, evidence also indicates coordinated activation of the DMN and FPN (De Pisapia et al., 2016). Furthermore, research shows that for both visual and verbal creativity, "strength of connectivity between the DMN and FPN was positively related to both creative domains" (Zhu et al., 2017, p. 2094). This suggests that activation of the DMN and FPN neural networks (often alongside the SN) is a consistent feature of creative acts, regardless of the domain. This activation is so robust that it often appears in the resting state, when individuals are not engaged in specific cognitive tasks.

Many studies have found a correlation between creativity and neural activity in the resting state. High creative abilities are most frequently linked to increased DMN activity (Lotze et al., 2014; Takeuchi et al., 2012), often in combination with other networks, Sensorimotor network (Jiao et al., 2017), Fronto-parietal network (Shi et al., 2018), Attention/Sensorimotor network (Sun et al., 2019), and Attentional network (Deshayes et al., 2021).

1.3. Neural network identification techniques

Functional connectivity resting state data have been mainly associated with the DMN. In the past, DMN had been associated with different cognitive functions, but modern network theory considers its main role in the representation of episodic memory (Ferguson et al., 2019) and as an interplay between salience and executive network (Menon, 2022). In previous research by our group, using electrophysiological data, we found that the DMN, in the beta frequency band, was associated with subsequent aesthetic decisions, most probably due to the activation of episodic representations about beauty. Those prior results led us to think that a similar brain network could be modulated by the effects of creativity training.

Electroencephalography (EEG) has a temporal resolution that allows the identification of the frequencies (alpha, beta, gamma and theta) in which neural networks operate. As Carl E. Stevens Jr and Darya L. Zabelina (2019) suggest: "Electroencephalographic (EEG) methodology in creativity research has been remarkably fruitful, establishing the potential of EEG to illuminate complex and transient creativity-related neural processes. [ ] There is a general consensus that alpha-band activity plays a key role in the creative process, though other frequency bands, such as theta and gamma also serve critical functions."

To estimate cortical source activity, source reconstruction techniques (LCMV beamforming) and a standard anatomical template were used. However, due to the inherent limitations of EEG (see below), no reliable localization of deep sources such as the hippocampus, basal ganglia, or thalamus could be identified. Consequently, while our connectivity analysis included regions such as the hippocampus and precuneus (as parcellated by the AAL atlas), these findings should be cautiously interpreted as potential measures of deep brain activity.

The study's focus was on the Default Mode Network (DMN), Fronto-Parietal Network (FPN), and Salience Network (SN), which are known to be both accessible to surface-level EEG analyses and strongly implicated in creative cognition.

In previous research using electrophysiological data, we found that the DMN, in the beta frequency band, was associated with the subsequent aesthetic decision, most probably due to the activation of episodic representations about beauty (Cela-Conde et al., 2013). Those results led us to think that a similar brain network should be modulated by the effects of creativity training.

However, EEG has limitations. The main neural networks related to creativity, DMN and SN encompass deep brain regions whose neural activity cannot be detected by EEG. It is true that DMN is mainly related to cortical regions. As Marcus Raichle indicates: "The brain's default mode network consists of discrete, bilateral and symmetrical cortical areas, in the medial and lateral parietal, medial prefrontal, and medial and lateral temporal cortices of the human, nonhuman primate, cat, and rodent brains" (Raichle, 2015). However, Li et al. (2021), for instance, postulate that "central lateral nucleus of the thalamus and ventral tegmental area of the midbrain are strongly correlated with that of the DMN. In an exploratory analysis, additional subcortical sites in the median and dorsal raphe, lateral hypothalamus, and caudate nuclei were correlated with the cortical DMN". Despite this, there are many studies that analyze both DMN and SN by EEG. But because of the fact that strictly EEG only identifies cortical activity, some researchers refer to "EEG-DMN" (Chen et al., 2008).

The most efficient technique for obtaining recordings of brain activity is the multimodal approach, combining fMRI and EEG. Using a multimodal approach, Fink et al. (2009) have measured brain activity during creative problem solving and have obtained very satisfactory results in terms of spatial and temporal resolution. However, we are not aware of any multimodal approach to ascertain increases in functional connectivity after creativity training periods.

1.4. The power of teaching creativity

An interesting feature of creative ability is its capacity for development through teaching. Traditional teaching methods generally require the physical presence of participants. As a result, it remains unclear whether creativity can be effectively taught through online training. This type of training, increasingly in demand, offers the advantage of reaching people in diverse locations worldwide. Consequently, it is important to investigate whether online teaching can improve creativity and whether such improvement leads to changes in brain activity.

Most studies evaluating the effectiveness of educational methods for fostering creativity focus on children and adolescents (see Scott et al., 2004 Review). However, some research has explored creativity training for adults, reporting positive results (see Clapham, 2003; Tsai, 2012 Reviews). Despite these findings, analyses of neural network activity in adults participating in creativity development programs remain limited.

Few studies consistently report increased functional connectivity in the resting state following creativity training periods (Guidotti et al., 2015; Schlaffke et al., 2017; Sun et al., 2020). However, these studies rely only on Functional Magnetic Resonance Imaging (fMRI), and do not provide information on the specific frequencies at which neural networks operate.

Our study aimed to achieve a deeper understanding of the functional dynamics of activated networks. The novelty of our research is that, for the first time, the frequency bands in which the functional connectivity of neural networks increased following creativity training have been identified.

These results allow us to go beyond the question of creativity. As we will see later, the networks with increased activity through creativity training also intervene in other aesthetic capacities. This finding supports the notion that the human capacity for visual aesthetics consists of a robust set of perception, creation and evaluation.

1.5. Visual creativity training and neural changes

Our experiment aims to ascertain whether visual creativity teaching (i) improves participants' creative levels and (ii) increases functional connectivity within brain networks associated with creative processes in the resting state. To test these hypotheses a specific method for teaching artistic creativity to adults, the Gabarron Method (GM; see Methods), was applied through online classes over a short duration (less than two months). Only the experimental group (G1) participated in the GM, while a control group (G2) received no GM teaching (see Methods).

The creative levels of G1 and G2 participants were measured using the Torrance Test of Creative Thinking (see Methods), administered at two points: before and after the GM training for G1 (respectively, Pre-GM and Post-GM). Brain activity for both groups was recorded using electroencephalography (EEG) at the same two points. Neural networks activated in the resting state were identified for each time point (see Methods).

Our hypotheses were as follows.

H1a. Participants in groups G1 and G2 will exhibit similar levels of creativity at Pre-GM.

H1b. Participants in group G1 will demonstrate a higher level of creativity at Post-GM compared to Pre-GM. In contrast, participants in group G2 will show no significant change in creativity between Pre-GM and Post-GM.

H2a. In the resting state, G1 participants will exhibit a significant increase in functional connectivity within creativity-related brain networks at Post-GM compared to Pre-GM.

H2b. G2 participants will show no significant increase in the functional connectivity of creativity-related brain networks at Post-GM compared to Pre-GM.

2. Methods

2.1. Groups

The sample consisted of 51 healthy female volunteer students from Comillas University (Madrid, Spain) and Complutense University (Madrid, Spain). All participants were right-handed native Spanish speakers. No compensation was provided for participation. Participants were randomly assigned to two groups: G1 (experimental group), 25 women (mean age 20.36 years) which followed the Gabarron Method (GM, see below), and G2 (control group), 26 women (mean age 20.34 years) which received no training.

Initially, our work included an experimental group of 33 men. However, 27 men did not correctly complete behavioral tests and EEG recordings. For this reason, only women were included in the study. Therefore, our results apply exclusively to women.

The study was approved by the local Ethics Committee and adhered to the Declaration of Helsinki. All participants signed informed consent forms before EEG recordings, which included an explanation of the study's technical and ethical considerations.

2.2. Creativity assessment

The Torrance Test of Creative Thinking (TTCT; Torrance, 1974) was used as a behavioral measure of creativity.

The TTCT is the most widely used standardized test for evaluating creative production (Kim, 2006; Vally et al., 2019). Some criticisms about the difficulties of application and correction of the Torrance Test of Creative Thinking exist (Snyder et al., 2019). Also, doubts on its ability to measure creativity in a broad way have been expressed (Almeida et al., 2008; Baer, 2011). However, no other test has reached TTCT level of use.

To assess creativity levels, all participants completed the TTCT twice: once before and once after G1 participants completed the Gabarron Method. Although repeating the same test can lead to habituation effects, this approach has proven useful in previous studies (Dere, 2019).

The version used was the Abbreviated Torrance Test for Adults (Spanish Edition), which includes Verbal and Figural Responses. Two independent evaluators scored the tests, and the average of their scores was used for analysis.

2.3. Creativity Program

G1 participants engaged in the Gabarron Method (GM) as their Creativity Program (see a general explanation of the Method in https://gabarron.org/Method1). The GM program, adapted for online participation, consisted of 78 challenges completed over 13 sessions spanning six to seven weeks. Each challenge presented participants with a distinct element or system of elements, accompanied by specific stimuli and objectives. The conceptual planes guiding these challenges are as follows, depending on the context of the stimuli and the contents:

Apparent plane. Participants focused on aspects of an element such as shape, color, material, volume, and spatial position. Goals were defined for the entire element or its components to stimulate idea generation by breaking elements into their basic parts.

Practical plane. Participants analyzed the element's function from an objective (e.g., utility) or subjective (e.g., emotional impact) perspective. This approach encouraged flexible thinking by exploring challenges through diverse perspectives.

Metaphorical plane. Participants performed aesthetic analyses by altering an element's context or drawing analogies between its parts. This exercise fostered unique ideas by integrating rhetorical tools such as analogies and comparisons.

Symbolic plane. Participants proposed interpretations of the element using their imagination. By favoring intuition over logic, this plane promoted originality through abstract, surreal, or fantastical elements.

A schematic representation of these conceptual planes is provided in Table 6.

2.4. EEG recordings

High-density EEG data were recorded to measure participants' brain activity at two moments (Pre- and Post-GM).

Recordings were conducted during 5-min task-free (resting state) conditions. Participants were instructed to relax, avoid falling asleep, minimize body movements, and refrain from engaging in specific thoughts or mind wandering.

EEG data acquisition utilized a 64-channel eego mylab amplifier and eego64 software (eemagine Medical Imaging Solutions GmbH) with a 500 Hz sampling rate. Electrode placement followed the extended 10–20 system, using a medium-sized 64-channel cap (waveguard original cap, model CA-208, ANT Neuro) with gel-based Ag/AgCl pin electrodes. Electrode impedance was maintained below 10 kΩ. Reference and ground electrodes were positioned at CPz.

Recordings were conducted during 5-min resting-state sessions, with participants instructed to relax, avoid falling asleep, minimize movement, and abstain from engaging in specific thoughts (e.g., avoid mind wandering).

2.5. Signal processing

Automated artifact detection was performed using the FieldTrip package (Oostenveld et al., 2011) to identify ocular, muscle, and jump artifacts. The detections were validated through visual inspection by two EEG experts. Channels with poor signal quality were manually excluded. Post-artifact removal, the data were segmented into non-overlapping 4-s epochs. Only recordings with a minimum of 30 artifact-free segments (≥120 s of brain activity) were included for analysis.

Analyses covered standard frequency bands: delta (2–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), beta (12–30 Hz), and gamma (30–45 Hz).

2.6. Source reconstruction

Source reconstruction employed a regular volumetric grid with 10 mm spacing based on the Montreal Neurological Institute (MNI) template (Mazziotta et al., 2001), yielding 2459 homogeneously distributed sources. Linearly Constrained Minimum Variance beamformer techniques (Van Veen et al., 1997) reconstructed source time series. The cortex surface was segmented into 90 regions of interest (ROIs) following the AAL atlas. These ROIs were categorized into three networks: Default Mode Network (DMN), Fronto-Parietal Network (FPN), and Salience Network (SN).

2.7. Functional connectivity analysis

EEG data were used to estimate functional connectivity (FC) between all pairs of regions within the three networks (DMN, FPN, SN) for each frequency band: delta (2–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), beta (12–30 Hz), and gamma (30–45 Hz).

The Phase Locking Value (PLV) was used to estimate functional connectivity (FC) between all pairs of regions for the three networks in each frequency band. The PLV is a phase synchronization measure that estimates the connectivity between two time series while reducing the volume. Thus, the PLV between the time series *x(k)* and *y(k)* from two brain regions is defined as:

$$PLV_{xy} = \frac{1}{N}\sum_{k=1}^{N} \left| e^{i\left(\phi_x(k) - \phi_y(k)\right)} \right|$$

where N is the length of the time series, and ϕ_x *(k)* (resp. ϕ_y *(k))* is the phase of *x(k)* (resp. *y(k)*). Finally, the PLV in each frequency band (delta, theta …) was obtained by averaging the corresponding PLVs. in the given frequency range.

2.8. Statistical analysis

Creativity score differences between groups MG and CG were assessed using an unpaired *t*-test using Prism 8 software (GraphPad version 8.0.0 https://www.graphpad.com/, San Diego, CA, USA).

Connectivity values were compared between the MG and CG group of each time point (pre and post) using an analysis of variance (ANOVA) using MATLAB 2022b to assess the effects of group (MG vs. CG), time point (pre vs. post), and their interaction effect. Additionally, to correct for multiple comparisons and to assess between-group differences in pre and post-measures, post hoc tests were conducted using Tukey's multiple comparison test.

2.9. Functional connectivity changes in the DMN and FPN in each group post-intervention

Our study assessed changes in DMN (Default Mode Network), FPN (Fronto Parietal Network) and FN (Functional Connectivity) of both groups.

By comparing mean values before and after the intervention, we found a significant increase in the DMN and FPN FC after the Mg training only in G1 (experimental group). The results, summarized in Figs. 1 and 2 and Table 3, show that statistical significance was reached in the into-group differences of the following FC changes in each band included. In the theta band, the differences appear in (0,497 vs. 0,488; p = 0,02), lSMG and rSMG (0,479 vs. 0,470; p = 0,02), lHip and lAng (0,471 vs. 0,460; p = 0,02), rHip and lAng (0,501 vs. 0,493; p = 0,03), lAng and lPrecu (0,435 vs. 0,424; p = 0,01), lRectus and rPrecu (0,379 vs. 0,372; p = 0,02), lSMG and rPrecu (0,411 vs. 0,400; p = 0,01), rSMG and rPrecu (0,353 vs. 0,342; p = 0,01), lPrecu and rPrecu (0,482 vs. 0,470; p = 0,01), In alpha band: lRectus and rSMG (0,565 vs. 0,554; p = 0,02), lHip and rSMG (0,398 vs. 0,394; p = 0,04), lHip and lAng (0,489 vs. 0,477; p = 0,04); and finally, in beta band: lRectus and rSMG (0,503 vs. 0,501; p = 0,01), rParahip and rSMG (0,347 vs. 0,338; p = 0,03), rIPG and rSMG (0,445 vs. 0,443; p = 0,04), lPCC and lAng (0,274 vs. 0,261; p = 0,04). This suggests a positive effect of GM training on neural activity in functional connectivity across the brain.

Abbreviation names for AAL (Automatic Anatomical Labeling) atlas regions can be found in Table 5.

2.10. A cautionary note about the relationship between creative training and changes in the neural networks

Establishing the correlation between creative training and changes in the DMN and FPN networks during the resting state is a problem that affects any research on this topic. We concur with Schlaffke et al. (2016) when they cautioned: "Overall it needs to be acknowledged that in the current literature studies investigating the reorganization of resting state activity and connectivity within a learning process are far from being conclusive. This can be attributed to the different types of learning (motor vs perceptual vs lexical/semantic), but also other factors such as differences in learning protocols (duration/intensity of training, period between resting state scans, etc.) likely play a role. Apart from multimodal approaches, an important step to further explore the adaptation of resting state networks in future studies will be to investigate more closely the dynamics of these changes."

Cognizant of the fact that the activity of the DMN and the FPN are known to fluctuate depending on the subjects' resting and cognitive states (Schlaffke et al., 2016), the duration and intensity of training was the same for all subjects, and those who did not conform to the procedure were excluded. The period between records of resting state activity was similar for all participants. Further, the collection of data from the EEG recordings was rigorously controlled.

3. Results

3.1. Creativity levels

Table 1 shows the creativity levels, expressed as the creativity index, obtained by G1 and G2 participants during the Torrance Test. Complete creativity index changes between Pre-GM and Post-GM in G1 and G2 for all participants can be found in Table 2.

In Pre-GM, the creativity index values are very similar for both G1 and G2, as expected due to the random distribution of participants. These results support hypothesis H1a.

Both groups show an increase in the creativity index at Post-GM compared to Pre-GM. This result is expected, as the recall effect of taking the same test twice in a short time frame can enhance scores. However, the increase in the control group (G2) is smaller and not statistically significant. In contrast, G1 significantly increases the creativity index at Post-GM. These findings support hypothesis H1b.

Following the suggestion of one of the reviewers we computed individual change scores (ΔTTCT = Post-GM minus Pre-GM) and conducted independent samples t-tests between the groups. The difference was not statistically significant. The contrast between the significant

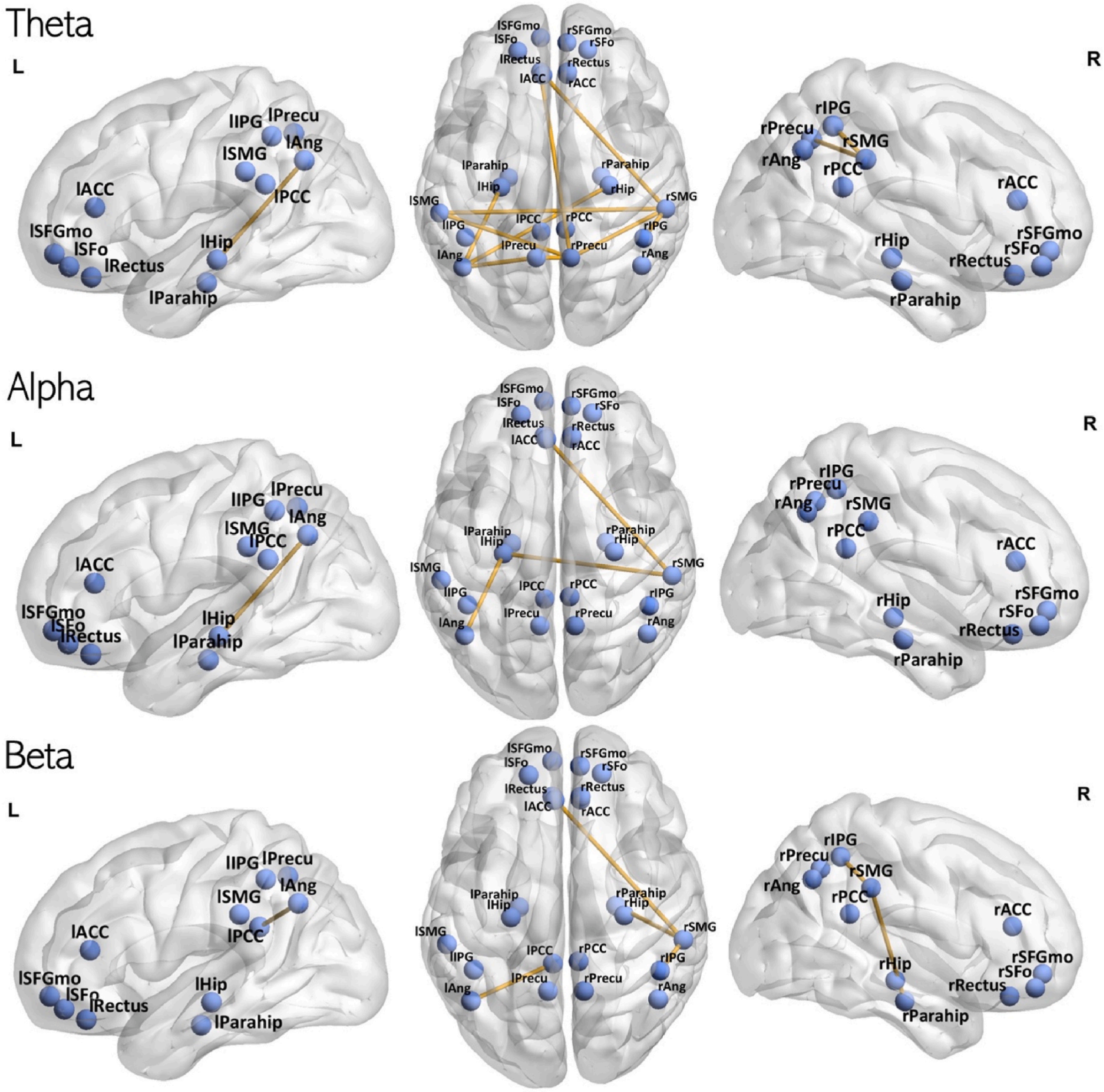

Fig. 1. G1 Default Mode Network Functional Connectivity: Statistically significant links for post-GM minus pre-GM.
Note: Table 3 presents the mean values of each statistically significant link identified in the ANOVA analysis for G1 and G2, across all frequency bands and conditions.

within-group results in the intervention group (G1) and the lack of significant differences in the between-group analysis is probably related to high individual variability in small groups. Further work with larger samples of participants are needed to confirm the TTCT intergroup tendency results shown here.

3.2. *Brain networks activated in the resting state*

Using EEG recordings, we analyzed the functional connectivity of brain networks activated in each group (G1 and G2) and at each time point (Pre-GM and Post-GM) according to the procedures detailed in Methods.

Functional connectivity was examined in creativity-related networks, as discussed earlier: the Default Mode Network (DMN), the Fronto-Parietal Network (FPN), and the Salience Network (SN). For a detailed definition of the active links in each network and a complete description of their features, refer to Methods.

Significant differences in functional connectivity between Pre-GM and Post-GM were observed in the links corresponding to Bands and Regions of Interest (RoI) within the DMN, FPN, and SN. See Figs. 1 and 2 and Table 3.

Figs. 1 and 2 and Table 3 indicate significant increases in the functional connectivity of creativity-related networks in the experimental group (G1) following the GM training. These results support hypothesis H2a.

In contrast, the control group (G2), which did not participate in GM, only showed increases in Post-GM functional connectivity in the beta band (see Table 3). This partially supports hypothesis H2b. The increase in functional connectivity in G2, specifically in the beta band at Post-GM, will be further interpreted in the Discussion.

4. Discussion

4.1. *Neural networks and the impact of training on creativity*

4.1.1. *The effect of the Gabarron Method (GM) on the creativity index*

The results presented in Table 1 indicate that participants in the experimental group (G1), who followed the GM, experienced a significant increase in the creativity index compared to their baseline (Pre-GM). Considering that the Gabarron Method was delivered online over

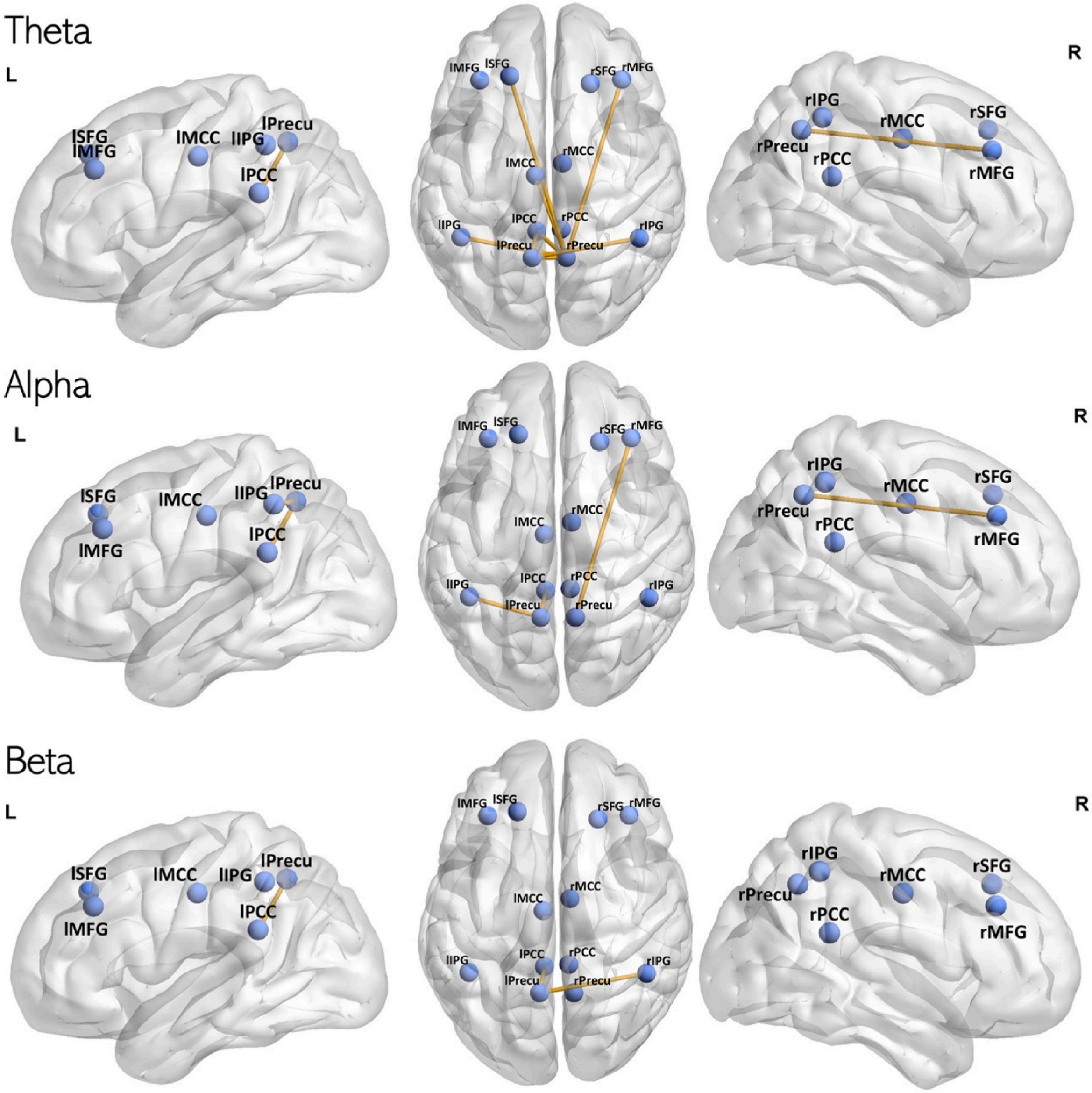

Fig. 2. G1 Frontoparietal Network Functional Connectivity: Statistically significant links for post-GM minus pre-GM.
Note: Table 3 presents the mean values of each statistically significant link identified in the ANOVA analysis for G1 and G2, across all frequency bands and conditions.

Table 1
Creativity Index (TTCT) intra-group values for G1 (experimental) and G2 (control) during Pre- and Post-Gabarron Method tests.

Group	Test	Creativity Index	% differences	*p*
G1	Pre	64.08		
G2	Pre	65.42		
G1	Post	68.28		
G2	Post	67.65		
G1 difference Post-GM minus Pre-GM		4.2	6.6 %	0.0027
G2 difference Post-GM minus Pre-GM		2.23	3.4 %	0.1265

less than two months, these results underscore its effectiveness in enhancing participants' creativity.

4.1.2. The effect of the Gabarron Method on functional connectivity

Participants in the experimental group (G1) experienced an increase in functional connectivity within neural networks during the resting state at Post-GM (see Table 3). These increases occurred in the Default Mode Network (DMN—Fig. 1 and Table 3), the Executive Network (FPN—Fig. 2 and Table 3), and a single link in the Salience Network (SN, see Table 3). Functional connectivity in DMN and FPN primarily increased in the theta band, with some increases also observed in the alpha band. The dominance of the theta band aligns with its well-established relationship with episodic memory and mental representation systems (Stevens Jr and Zabelina, 2019).

Regarding the beta band, increases were observed in both the experimental group (G1) and the control group (G2) for DMN and FPN, though the activated links differed between the groups. The beta-band increase in G2 is puzzling, as this group did not receive creativity training and showed no significant increase in the creativity index (Table 1). Therefore, this increase cannot be attributed to creative processes. In G2, the activated beta-band DMN and FPN links primarily involved the precuneus region (Table 3). Resting-state connectivity between the precuneus and other DMN areas has been linked to behavioral engagement with external tasks (Zhang and Li, 2011). Thus, merely

Table 2
Creativity index (TTCT) changes between Pre-GM and Post-GM in G1 and G2 for all participants.

G1 GROUP—PRE. MEAN VALUES

Participant	Group	Test	Scale[a]	Verbal	CREATIVITY INDEX
1	G1	pre	51	6	57
2	G1	pre	53	8	61
3	G1	pre	59	10	69
4	G1	pre	60	3	63
5	G1	pre	45	1	46
6	G1	pre	64	5	69
7	G1	pre	50	2	52
8	G1	pre	53	6	59
9	G1	pre	68	10	78
10	G1	pre	61	13	74
11	G1	pre	65	4	69
12	G1	pre	68	6	74
13	G1	pre	54	4	58
14	G1	pre	57	8	65
15	G1	pre	58	5	63
16	G1	pre	53	5	58
17	G1	pre	54	2	56
18	G1	pre	60	13	73
19	G1	pre	64	5	69
20	G1	pre	57	10	67
21	G1	pre	52	6	58
22	G1	pre	58	7	65
23	G1	pre	61	7	68
24	G1	pre	53	6	59
25	G1	pre	62	10	72
MEAN			**57.6**	**6.5**	**64.08**
STANDARD DEVIATION	**5.82**	**3.2**	**7.7**		

G1 GROUP—POST. MEAN VALUES

Participant	Group	Test	Scale[a]	Verbal	CREATIVITY INDEX
1	G1	post	61	9	70
2	G1	post	68	9	77
3	G1	post	56	6	62
4	G1	post	59	8	67
5	G1	post	51	2	53
6	G1	post	64	9	73
7	G1	post	61	5	66
8	G1	post	58	8	66
9	G1	post	61	11	72
10	G1	post	59	14	73
11	G1	post	70	6	76
12	G1	post	62	9	71
13	G1	post	65	6	71
14	G1	post	62	10	72
15	G1	post	62	6	68
16	G1	post	56	3	59
17	G1	post	57	4	61
18	G1	post	61	11	72
19	G1	post	62	6	68
20	G1	post	61	13	74
21	G1	post	59	10	69
22	G1	post	59	7	66
23	G1	post	60	7	67
24	G1	post	59	6	65
25	G1	post	60	9	69
MEAN			**60.52**	**7.76**	**68.28**
STANDARD DEVIATION			**3.82**	**2.91**	**5.46**

G2 GROUP—PRE. MEAN VALUES

Participant	Group	Test	Scale[a]	Verbal	CREATIVITY INDEX
26	G2	pre	58	10	68
27	G2	pre	54	7	61
28	G2	pre	60	13	73
29	G2	pre	54	5	59
30	G2	pre	59	5	64
31	G2	pre	59	5	64
32	G2	pre	50	1	51
33	G2	pre	66	12	78
34	G2	pre	64	7	71
35	G2	pre	59	6	65
36	G2	pre	56	6	62
37	G2	pre	56	5	61

(*continued on next page*)

Table 2 (*continued*)

G2 GROUP—PRE. MEAN VALUES

Participant	Group	Test	Scale[a]	Verbal	CREATIVITY INDEX
38	G2	pre	59	9	68
39	G2	pre	59	15	74
40	G2	pre	60	10	70
41	G2	pre	60	5	65
42	G2	pre	59	6	65
43	G2	pre	52	5	57
44	G2	pre	57	6	63
45	G2	pre	69	11	80
46	G2	pre	63	4	67
47	G2	pre	53	6	59
48	G2	pre	62	11	73
49	G2	pre	62	5	67
50	G2	pre	53	7	60
51	G2	pre	52	4	56
MEAN			**58.27**	**7.15**	**65.42**
STANDARD DEVIATION			**4.57**	**3.26**	**6.84**

G2 GROUP— POST. MEAN VALUES

Participant	Group	Test	Scale[a]	Verbal	CREATIVITY INDEX
26	G2	post	64	9	73
27	G2	post	55	6	61
28	G2	post	60	12	72
29	G2	post	56	7	63
30	G2	post	66	9	75
31	G2	post	60	9	69
32	G2	post	60	7	67
33	G2	post	66	12	78
34	G2	post	59	8	67
35	G2	post	66	2	68
36	G2	post	51	8	59
37	G2	post	62	9	71
38	G2	post	58	6	64
39	G2	post	59	10	69
40	G2	post	54	8	62
41	G2	post	55	4	59
42	G2	post	55	8	63
43	G2	post	55	10	65
44	G2	post	56	6	62
45	G2	post	64	8	72
46	G2	post	64	4	68
47	G2	post	65	9	74
48	G2	post	65	13	78
49	G2	post	65	6	71
50	G2	post	65	12	77
51	G2	post	**49**	**3**	**52**
MEAN			**59.77**	**7.88**	**67.65**
STANDARD DEVIATION			**5.04**	**2.80**	**6.50**

[a] Scale = Fluency + Originality + Elaboration + Flexibility (Torrance Test).

participating in the study may have enhanced attentional abilities in G2, as the beta band is often associated with increased attention.

As expected, G1 participants also showed beta-band increases, albeit with different neural topographies than G2. In the FPN, G1 also exhibited increased precuneus activation, similar to G2 (Table 3). Notably, there were no statistical differences in precuneus connectivity between G1 and G2 at Post-GM (see Table 4). However, in the DMN, G1 participants exhibited increased connectivity involving the right superior frontal gyrus (Table 3), possibly reflecting greater cognitive control demands during attentional processes due to the training.

The results align with most studies on creativity in the resting state, which associate high creative abilities with DMN and FPN activity. However, one of the most detailed studies on creativity-related neural network activity (Beaty et al., 2018a,b) also highlights SN activation, which was weakly observed in our case. Only one SN link was activated in the alpha band (Left Inferior Frontal Gyrus, Opercular - Left Anterior Cingulate Gyrus connectivity). To explain this discrepancy, refining the understanding of collaboration among creativity-related networks is essential.

The contributions of DMN, FPN, and SN networks to creativity are emphasized in the recent brain dynamics model proposed by Roger E. Beaty and collaborators (Beaty et al., 2018). According to this model, "the default network contributes to the generation of ideas via flexible and spontaneous combinatory mechanisms involved in memory retrieval and mental simulation. The salience network, in turn, functions to identify candidate ideas—potentially useful information generated via the default network—and forward such information to frontoparietal executive systems for high-order processing (e.g., idea evaluation, elaboration, or revision)." (Beaty et al., 2018, p. 1090)

This model posits a serial DMN, SN, and FPN network intervention. However, the authors also note that "executive systems may interact with ongoing generative processes within the default network by imposing constraints on performance and maintaining higher order goals" (Beaty et al., 2018, p. 1090). In such cases, the serial activation of networks may be altered, with FPN interacting directly with DMN in generative processes, potentially minimizing SN activation.

Our results indicate a robust relationship between creativity and activation of DMN, FPN, and SN networks in the resting state, even when the increase in creativity occurred under atypical conditions (short-term online teaching). This finding underscores an important adaptive and

Table 3

Statistically significant differences between G1 and G2 in pre- and post-conditions for DMN, FPN, and SAL networks. Values are presented as mean ± standard deviation. Connectivity values at each time point (pre and post) were compared between MG and CG groups using ANOVA in MATLAB 2022b, analyzing group, time point, and interaction effects. P-values correspond to Tukey's multiple comparison post hoc test for between-group differences. Abbreviations for AAL atlas regions are detailed in Table 5.

			G1			G2		
			PreGM	PostGM	Post-GM vs Pre-GM Δ p	PreGM	PostGM	Post-GM vs Pre-GM Δ p
DMN	Theta	lRectus-rSMG	0.544 ± 0.060	0.552 ± 0.090	0.016	0.525 ± 0.020	0.530 ± 0.023	0.457
		rIPG-rSMG	0.488 ± 0.064	0.497 ± 0.098	0.024	0.476 ± 0.024	0.478 ± 0.021	0.511
		lSMG-rSMG	0.470 ± 0.062	0.479 ± 0.102	0.027	0.454 ± 0.022	0.454 ± 0.020	0.417
		lHip-lAng	0.460 ± 0.059	0.471 ± 0.109	0.027	0.447 ± 0.025	0.446 ± 0.021	0.387
		rHip-lAng	0.493 ± 0.059	0.501 ± 0.102	0.034	0.477 ± 0.021	0.479 ± 0.027	0.358
		lAng-lPrecu	0.424 ± 0.077	0.435 ± 0.110	0.018	0.408 ± 0.019	0.407 ± 0.022	0.585
		lRectus-rPrecu	0.372 ± 0.093	0.379 ± 0.118	0.029	0.355 ± 0.026	0.356 ± 0.025	0.458
		lSMG-rPrecu	0.400 ± 0.082	0.411 ± 0.113	0.012	0.380 ± 0.022	0.382 ± 0.026	0.714
		rSMG-rPrecu	0.342 ± 0.091	0.353 ± 0.125	0.011	0.322 ± 0.027	0.322 ± 0.024	0.605
		lPrecu-rPrecu	0.470 ± 0.048	0.482 ± 0.103	0.019	0.456 ± 0.018	0.457 ± 0.017	0.505
	Alpha	lRectus-rSMG	0.554 ± 0.030	0.565 ± 0.080	0.024	0.544 ± 0.022	0.542 ± 0.027	0.229
		lHip-rSMG	0.394 ± 0.067	0.398 ± 0.092	0.049	0.385 ± 0.032	0.381 ± 0.025	0.219
		lHip-lAng	0.477 ± 0.022	0.488 ± 0.098	0.042	0.470 ± 0.023	0.463 ± 0.022	0.283
	Beta	lRectus-rSMG	0.501 ± 0.026	0.503 ± 0.031	0.019	0.493 ± 0.018	0.494 ± 0.027	0.089
		rParahip-rSMG	0.338 ± 0.029	0.347 ± 0.050	0.033	0.326 ± 0.029	0.324 ± 0.031	0.334
		rIPG-rSMG	0.443 ± 0.018	0.445 ± 0.040	0.041	0.439 ± 0.024	0.439 ± 0.022	0.107
		lPCC-lAng	0.261 ± 0.033	0.274 ± 0.051	0.049	0.255 ± 0.032	0.255 ± 0.028	0.095
		lSMG-rSMG	0.416 ± 0.020	0.418 ± 0.040	0.112	0.409 ± 0.022	0.408 ± 0.023	0.046
		lHip-lAng	0.405 ± 0.021	0.407 ± 0.035	0.080	0.401 ± 0.025	0.400 ± 0.024	0.038
		rHip-lAng	0.449 ± 0.018	0.444 ± 0.027	0.144	0.438 ± 0.020	0.441 ± 0.029	0.014
		lIPG-lPrecu	0.449 ± 0.013	0.459 ± 0.026	0.337	0.451 ± 0.023	0.455 ± 0.019	0.014
FPN	Theta	lPCC-lPrecu	0.544 ± 0.060	0.552 ± 0.090	0.016	0.525 ± 0.020	0.530 ± 0.023	0.457
		rIPG-lPrecu	0.488 ± 0.064	0.497 ± 0.098	0.024	0.476 ± 0.024	0.478 ± 0.021	0.511
		lSFG-rPrecu	0.470 ± 0.062	0.479 ± 0.102	0.027	0.454 ± 0.022	0.454 ± 0.020	0.417
		rMFG-rPrecu	0.460 ± 0.059	0.471 ± 0.109	0.027	0.447 ± 0.025	0.446 ± 0.021	0.387
		lMCC-rPrecu	0.493 ± 0.059	0.501 ± 0.102	0.034	0.477 ± 0.021	0.479 ± 0.027	0.358
		lPCC-rPrecu	0.424 ± 0.077	0.435 ± 0.110	0.018	0.408 ± 0.019	0.407 ± 0.022	0.585
		lIPG-rPrecu	0.372 ± 0.093	0.379 ± 0.118	0.029	0.355 ± 0.026	0.356 ± 0.025	0.458
		lPrecu-rPrecu	0.470 ± 0.048	0.482 ± 0.103	0.019	0.456 ± 0.018	0.457 ± 0.017	0.505
	Alpha	lPCC-lPrecu	0.554 ± 0.030	0.565 ± 0.080	0.024	0.544 ± 0.022	0.542 ± 0.027	0.229
		lIPG-lPrecu	0.394 ± 0.067	0.398 ± 0.092	0.049	0.385 ± 0.032	0.381 ± 0.025	0.219
		rMFG-rPrecu	0.477 ± 0.022	0.488 ± 0.098	0.042	0.470 ± 0.023	0.463 ± 0.022	0.283
	Beta	lPCC-lPrecu	0.501 ± 0.026	0.503 ± 0.031	0.019	0.493 ± 0.018	0.494 ± 0.027	0.089
		rIPG-lPrecu	0.443 ± 0.018	0.445 ± 0.040	0.041	0.439 ± 0.024	0.439 ± 0.022	0.107
		lSFG-rPrecu	0.416 ± 0.020	0.418 ± 0.040	0.112	0.409 ± 0.022	0.408 ± 0.023	0.046
		rMFG-rPrecu	0.405 ± 0.021	0.407 ± 0.035	0.080	0.401 ± 0.025	0.400 ± 0.024	0.038
		lMCC-rPrecu	0.449 ± 0.018	0.444 ± 0.027	0.144	0.438 ± 0.020	0.441 ± 0.029	0.014
SN	Alpha	IlFGo-IACC	0.421 ± 0.078	0.448 ± 0.114	0.049	0.417 ± 0.032	0.437 ± 0.029	0.372

Table 4

Differences in precuneus links for beta band in DMN between G1 and G2. Abbreviations for AAL atlas regions are detailed in Table 5.

DMN links	Post MG		
	G1(experimental)	G2(control)	p-values
lIPG-lPrecu	0.4598 ± 0.0260	0.4552 ± 0.0198	0.1338
rSMG-rPrecu	0.2720 ± 0.0542	0.2562 ± 0.0294	0.3488
lPrecu-rPrecu	0.4226 ± 0.0381	0.4226 ± 0.0381	0.5631

evolutionary aspect of creativity: it can enhance significantly through brief teaching processes. This is particularly relevant given the primary role of teaching in human cultural adaptation (Tomasello, 2010). As Michael Tomasello observes, "Teaching and conformity are main contributors to the stability of cultural practices in a group and — precisely because of this stability — to the unique ways in which human cultural practices ratchet up in complexity over historical time. The result is human artifacts and symbol systems with 'histories,' so-called cumulative cultural evolution […]." (Tomasello, 2010, p. 6)

4.1.3. Neural stability and the study design

The increases in neural network activity observed in this longitudinal design, with or without intervention, cannot be attributed to rapid intrinsic participant changes or instability in the metrics used. Previous electrophysiological studies have shown that functional connectivity remains stable over relatively short periods, with intra-class correlations above 0.8 across different sessions (Garcés et al., 2016). Furthermore, the participants in this study are not within age ranges associated with abrupt physiological changes, meaning their functional networks are likely to remain relatively stable over time.

The high temporal resolution of the EEG is a drawback for detecting brain activity related to a certain cognitive task. For example, to study the neural networks activated when performing an aesthetic judgment, it is essential to precisely synchronize the cognitive task (performing the aesthetic judgment) with the instant of the acquisition of EEG recordings. However, this difficulty is not presented in this work. It is known that the increase in creativity of a subject leaves its mark on the resting state. Greater creativity implies greater activation of the neural networks related to creativity. Such greater activation is, so to speak, characteristic of the resting state. Thus, the problem of synchronization is of much less importance.

4.2. Evolutionary origins of the creative universe

The human capacity for aesthetics—the ability to create works of art and to appreciate them as 'beautiful objects'—can be understood in

Table 5
Abbreviation names for AAL (Automatic Anatomical Labeling) atlas regions.

Abbreviation	Brain Area Name
’lPreCG’	’Left Precentral gyrus’
’rPreCG’	’Right Precentral gyrus’
’lSFG’	’Left Superior Frontal gyrus’
’rSFG’	’Right Superior Frontal gyrus’
’lSFo’	’Left Superior Frontal gyrus, Orbital’
’rSFo’	’Right Superior Frontal gyrus, Orbital’
’lMFG’	’Left Middle Frontal gyrus’
’rMFG’	’Right Middle Frontal gyrus’
’lMFGo’	’Left Middle Frontal gyrus, Orbital’
’rMFGo’	’Right Middle Frontal gyrus, Orbital’
’lIFGo’	’Left Inferior Frontal gyrus, Opercular’
’rIFGor’	’Right Inferior Frontal gyrus, Opercular’
’lIFGt’	’Left Inferior Frontal gyrus, Triangular’
’rIFGt’	’Right Inferior Frontal gyrus, Triangular’
’lIFGo’	’Left Inferior Frontal gyrus, Orbital’
’rIFGo’	’Right Inferior Frontal gyrus, Orbital’
’lRO’	’Left Rolandic operculum’
’rRO’	’Right Rolandic operculum’
’lMotor’	’Left Supplementary Motor area’
’rMotor’	’Right Supplementary Motor area’
’lSFGm’	’Left Superior Frontal gyrus, Medial’
’rSFGm’	’Right Superior Frontal gyrus, Medial’
’lSFGmo’	’Left Superior Frontal gyrus, Medial Orbital’
’rSFGmo’	’Right Superior Frontal gyrus, Medial Orbital’
’lRectus’	’Left Gyrus Rectus’
’rRectus’	’Right Gyrus Rectus’
’lInsula’	’Left Insula’
’rInsula’	’Right Insula’
’lACC’	’Left Cingulate gyrus, Anterior part’
’rACC’	’Right Cingulate gyrus, Anterior part’
’lMCC’	’Left Cingulate gyrus, Middle part’
’rMCC’	’Right Cingulate gyrus, Middle part’
’lPCC’	’Left Cingulate gyrus, Posterior part’
’rPCC’	’Right Cingulate gyrus, Posterior part’
’lHip’	’Left Hippocampus’
’rHip’	’Right Hippocampus’
’lParahip’	’Left Parahippocampus’
’rParahip’	’Right Parahippocampus’
’lAmyg’	’Left Amygdala’
’rAmyg’	’Right Amygdala’
’lCalc’	’Left Calcarine fissure and surrounding cortex’
’rCalc’	’Right Calcarine fissure and surrounding cortex’
’lCu’	’Left Cuneus’
’rCu’	’Right Cuneus’
’lLingual’	’Left Lingual gyrus’
’rLingual’	’Right Lingual gyrus’
’lSOccL’	’Left Superior Occipital lobe’
’rSOccL’	’Right Superior Occipital lobe’
’lMOccL’	’Left Middle Occipital lobe’
’rMOccL’	’Right Middle Occipital lobe’
’lIOccL’	’Left Inferior Occipital lobe’
’rIOccl’	’Right Inferior Occipital lobe’
’lFusiG’	’Left Fusiform gyrus’
’rFusiG’	’Right Fusiform gyrus’
’lPreG’	’Left Postcentral gyrus’
’rPreG’	’Right Postcentral gyrus’
’lSPG’	’Left Superior Parietal gyrus’
’rSPG’	’Right Superior Parietal gyrus’
’lIPG’	’Left Inferior Parietal gyrus’
’rIPG’	’Right Inferior Parietal gyrus’
’lSMG’	’Left Supramarginal gyrus’
’rSMG’	’Right Supramarginal gyrus’
’lAng’	’Left Angular gyrus’
’rAng’	’Right Angular gyrus’
’lPrecu’	’Left Precuneus’
’rPrecu’	’Right Precuneus’
’lParaL’	’Left Paracentral lobule’
’rParaL’	’Right Paracentral lobule’
’lSTG’	’Left Superior Temporal gyrus’
’rSTG’	’Right Superior Temporal gyrus’
’lTPsup’	’Left Temporal pole, Superior Temporal gyrus’
’rTPsup’	’Right Temporal pole, Superior Temporal gyrus’
’lMTG’	’Left Middle temporal gyrus’
’rMTG’	’Right Middle temporal gyrus’
’lTPmid’	’Left Temporal pole, Middle temporal gyrus’
’rTPmid’	’Right Temporal pole, Middle temporal gyrus’
’lITG’	’Left Inferior Temporal gyrus’
’rITG’	’Right Inferior Temporal gyrus’

Table 6
Content of conceptual planes in the Gabarron Method.

CONTEXT	Apparent	Practical	Metaphorical	Symbolic
Impact on	visual	function	emotion	fantasy
Analysis	visual (aspect)	functional	mood	allegorical
Approach	identification & fragmentation	approaches & perspectives	analogies, comparisons & setting	provocation & abstraction
Suggestion/ stimulus	objective	internal subjective	internal subjective	external subjective
Response from	observation	appreciation	perception	interpretation
Purpose	fluency	flexibility	singularity	originality

evolutionary terms as an exaptation, a trait initially shaped by natural selection for one function that later evolved to serve another (Furnari, 2009; Kaplan, 1987; Zaidel, 2019). Naturally, the sparse evidence the fossil and archaeological records provide limits our ability to explore this concept in depth. However, examining the neural networks underlying this capacity offers a promising perspective for evolutionary explanations.

Artistic creation and aesthetic perception have typically been studied separately when analyzing their neural correlates (e.g., Cela-Conde et al., 2013 for the perception of beauty and De Pisapia et al., 2016 for artistic creation). However, some studies have examined the neural networks underlying both traits—artistic creation and aesthetic perception—simultaneously. This joint examination has been carried out either directly (Bolwerk et al., 2014) or through meta-analyses of experiments addressing creation and perception separately (Sacheli et al., 2022). Both Cela-Conde et al. (2013) and De Pisapia et al. (2016) identified activation of the DMN and FPN. Anne Bolwerk et al. (2014) observed DMN activation during artistic creation and aesthetic perception, while the meta-analysis by Sacheli et al. (2022) added FPN activation to the DMN in tasks involving both creation and perception.

Thus, the same neural networks are activated during aesthetics’ creative and perceptive aspects. Furthermore, as shown in this study, visual artistic creativity—exploring alternative solutions or uses for visual symbols—has identical neural correlates. This convergence suggests the existence of what could be called a ’creative universe,’ encompassing capacities such as creation, perception, and divergent thinking. These fundamental aspects of the human mind share a common neural substrate.

It is worth emphasizing the importance of specific teaching methods in enhancing the creative universe. Such methods can yield significant results within a short time, even in adulthood. Creativity appears to be a uniquely human trait and one that can be relatively ’easily’ taught through organized instruction or simple imitation. This adaptability would have been a crucial factor in the evolution of the aesthetic capacities.

CRediT authorship contribution statement

Camilo J. Cela-Conde: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Sara Lumbreras:** Writing – original draft, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **Sandra Pusil:** Writing – original draft, Software, Methodology, Investigation,

Formal analysis, Data curation. **Brenda Chino:** Writing – original draft, Software, Methodology, Formal analysis, Data curation. **José M. Caamaño:** Project administration, Funding acquisition, Conceptualization. **Laura Gismera:** Investigation, Conceptualization. **Fernando Maestú:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Luis Rojas-Marcos:** Writing – original draft, Validation, Conceptualization.

Declaration of competing interest

All authors declare that they have no competing interests with regard to this work.

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Data availability

No data was used for the research described in the article.

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