

Research Paper

Investigating the neural substrate variations between easy and challenging creative association tasks during product design within an fMRI scanner

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ABSTRACT

In practice, individuals strive to develop highly original and valuable creative products within specific limitations. However, previous functional Magnetic Resonance Imaging (fMRI) studies focused on divergent-thinking tasks without considering the "valuableness" of an idea. Additionally, different types of creative tasks (e.g., the easier association vs. the harder association task) may engage distinct cognitive processes. This study aimed to investigate the underlying neural mechanisms associated with different types of creative thinking, specifically focusing on the generation of the most original and valuable creative product within an fMRI scanner. Twenty-one college students participated in a block design study. During each trial, participants were instructed to draw the most original and valuable product inspired by a given figure. The findings revealed that, in comparison to the harder association task, the easier association task led to broader activation across multiple brain regions. However, this broader activation resulted in inefficient thinking and poorer creative performance. Notably, the orbitofrontal cortex exhibited activation across various creativity tasks and displayed connectivity with several seed brain regions, highlighting the importance of decision-making when only one original and valuable product design is allowed. Furthermore, the complex functional connectivity observed between different brain networks reflects the intricate nature of creative thinking. To conclude, widespread activation of brain regions does not necessarily indicate superior creativity. Instead, optimal creative performance within constraints is achieved through an efficient utilization of association for generating innovative ideas, inhibition for suppressing unoriginal ideas, and decision-making to select the most creative idea.

1. Introduction

Creativity is widely recognized as a crucial skill for future development, particularly in the era of artificial intelligence. It is a multifaceted process that involves the interconnectedness of dynamic episodes through concatenation, dynamic estimation, and exaptation mechanisms (Corazza et al., 2022). Over the past decade, numerous studies utilizing functional magnetic resonance imaging (fMRI) have explored the neural processes underlying creative thinking (Khalil et al., 2023; Kleinmintz et al., 2019; Madore et al., 2019; Palmiero et al., 2022; Ren et al., 2023; Sunavsky and Poppenk, 2020; Takeuchi et al., 2020; Zhuang et al., 2021). However, a limited number of studies have specifically instructed participants to express their thoughts through drawing during fMRI scans (Pidgeon et al., 2016; Saggari et al., 2015; Shah et al., 2013; Tam et al., 2011), primarily due to the absence of suitable devices.

Typically, participants are tasked with recalling and providing responses outside of the scanner. In this investigation, we employed an innovative device that enables participants to immediately draw creative products within the scanner, mirroring processes akin to those in daily life during creative endeavors.

Moreover, most fMRI studies on creativity have utilized divergent thinking tasks that measure originality without considering valuableness. However, both originality and valuableness (or usefulness and effectiveness) are acknowledged as pivotal factors for creative performance (Corazza et al., 2022; Ren et al., 2023; Yeh et al., 2019; Zhu et al., 2020). Creativity tasks emphasizing both indices involve a cyclical shift between the processes of idea generation and evaluation (Lin and Vartanian, 2018); the brain activations may differ from those emphasized in tasks focusing solely on originality. On the other hand, creativity can manifest in diverse patterns (Takeuchi et al., 2020), encompassing

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instances of high fluency but low originality, or low fluency but high originality. As per association theory (Liu et al., 2021), the former may arise from easy or near associations, facilitating the generation of readily available ideas, while the latter may stem from hard or distant associations, necessitating more effort in idea generation. Consequently, when requiring the selection of the most creative idea, decision-making becomes especially crucial when numerous ideas are generated. Moreover, creative thinking relies on a synergy of associative and controlled attention processes, with inhibitory control playing a pivotal role in facilitating a departure from functional fixedness and restraining habitual or prepotent responses (Chrysikou, 2019; Edl et al., 2014; Khalil et al., 2023; Palmiero et al., 2022; Zabelina et al., 2019). These processes may become particularly pronounced when only one "best" original and valuable answer is permitted, and when ideas are easier to associate with.

Accordingly, we aim to address the following inquiries within the constraints of considering both originality and valuableness while allowing only one optimal answer during the creation of a creative product inside the brain scanner: (1) Would the activation of brain regions associated with inhibition, controlled attention, and decision-making be more pronounced in easy-association stimuli compared to hard-association stimuli, as a means to suppress less original and valuable responses? (2) Would decision-making brain regions demonstrate activation across different types of creativity tasks? To our knowledge, no previous fMRI study has investigated these specific aspects, particularly when participants are instructed to produce an original and valuable product while inside the scanner. By addressing these questions, we aimed to advance our understanding of the cognitive processes involved in creativity and their associated neural mechanisms.

In behavioral studies, it was found that controlled attention allows an individual to properly organize information obtained from displaced senses, focalization, or irrelevant stimuli inhibition (Garrido et al., 2021). Inhibition, therefore, plays a central role in controlled attention processes and is critical in the creative process as it facilitates the rejection of non-original ideas, enabling individuals to reach more remote associations (Edl et al., 2014). The significance of inhibition during divergent thinking tasks has been supported by numerous studies (Khalil et al., 2023; Zabelina et al., 2019). However, it has been observed that exposure to high inhibition demands enhances fluency in divergent thinking tasks but not in convergent tasks such as the Remote Associate Task (Radel et al., 2015). This raises the question of whether inhibition would have a different impact on creativity tasks that emphasize both originality and valuableness. Furthermore, Yeh et al. (2019) suggested that, by employing product-based tasks that highlight both originality and valuableness, evaluation and decision-making emerge as crucial aspects during creative thinking. Therefore, it is reasonable to hypothesize that when only one answer is permitted in the design of a creative product, tasks that facilitate easier associations may also necessitate more pronounced inhibition processes to determine which product should be selected, as compared to tasks that involve more challenging association requirements.

In fMRI studies, it has been found that various forms of creative thinking involve intricate interactions among the executive control network (ECN), default mode network (DMN), and salience network (SN) (Beaty et al., 2018; Yeh et al., 2019). The DMN is widely acknowledged to play a role in idea generation and originality (Beaty and Kenett, 2023; Kleinmintz et al., 2019; Marron et al., 2018). Key brain regions within the DMN include the medial prefrontal gyrus (mPFC), posterior cingulate cortex (PCC), and right temporal-parietal junction (TPJ) (Kleinmintz et al., 2019). On the other hand, the ECN is involved in evaluating the value of ideas (Beaty et al., 2019; Kleinmintz et al., 2019; Kuang et al., 2022), working memory updating, inhibition (Zhao et al., 2021), and error detection (Kleinmintz et al., 2019; Perchtold et al., 2018; Vossel et al., 2014). It was also found that working memory is facilitated by the dorsolateral prefrontal cortex (dlPFC), attention involving the frontal eye fields (FEF), and TPJ

(Kleinmintz et al., 2019; Vossel et al., 2014). Lastly, the SN, which is associated with idea generation and selection, facilitates the transition between the DMN and ECN, with core brain regions including the anterior cingulate cortex (ACC) and insula (Yeh et al., 2019).

Notably, Extensive neural evidence supports the significant role of inhibition in creativity (Chrysikou, 2019; Khalil et al., 2023; Palmiero et al., 2022; Zabelina et al., 2019). Inhibition is a complicated function involving working memory, attention, and semantic decision, and it relates to IPL, the middle temporal gyrus, and the anterior cingulate gyrus (Shen et al., 2017). Research suggests that a synergistic interplay between frontotemporal and fronto-subcortical networks, functioning through mutual inhibition, can enhance the generation of innovative ideas (Flaherty, 2005).

On the other hand, recent studies have revealed the involvement of the orbital frontal cortex (OFC) in executive functions related to inhibiting salient responses (Brockett and Roesch, 2021), regulating response selection during the suppression of unwanted movements (Bryden and Roesch, 2015), and enacting automatic constraints that support the elaboration of highly valued sequences of thought (Zamani et al., 2022). Moreover, the OFC plays a role in the interplay between decision-making and cognitive impulse control (Ouellet et al., 2015). In the same vein, the medial prefrontal cortex has been found to contribute to adaptive decision-making processes and the integration of novel experiences into existing knowledge networks (Stawarczyk and D'Argembeau, 2015). Additionally, in a study focused on product-based creative thinking, the right middle temporal gyrus (MTG), left inferior frontal gyrus (IFG), lateral precuneus, lateral insula, left fusiform gyrus, and left ventrolateral prefrontal cortex (vlPFC) were associated with evaluation and decision-making (Yeh et al., 2019). In the same vein, recent studies (Ren et al., 2020; Ren et al., 2023) found that MTG and medial temporal lobe (MTL) play crucial roles in the processing of usefulness. These findings provide support for the significance of decision-making in assessing value while engaging in product-based creative tasks.

In a limited number of fMRI studies that focused on tasks emphasizing both originality and value, Yeh et al. (2019) introduced a three-stage model of the creative process, grounded in observed brain activations: exploration and association, incubation and insight, and evaluation and decision-making. They identified several critical brain regions, including the dlPFC, vlPFC, dmPFC, precuneus, inferior parietal lobule (IPL), PCC, ACC, and insula. Additionally, connectivity analyses suggest a trend that the DMN and the SN that relate to bottom-up thinking attenuate as time proceeds, whereas the vlPFC, which relates to top-down thinking, becomes stronger at later stages. These findings provide support for dual-process theories (Benedek and Jauk, 2018; Dygert and Jarosz, 2020; Kuang et al., 2022), suggesting that individuals employ both associative and controlled-attention processes to actively engage in creative thinking.

Recognizing the significance of encompassing both originality and valuableness, Yeh et al. (2013) developed a product-based creativity test utilizing three figures (C, □, and ×). In this assessment, participants were directed to generate as many products as possible based on each given figure within a five-minute timeframe for each figure. Based on a sample of 407 college students, the results indicated higher fluency scores in the C task compared to the □ and × tasks, although no significant differences were observed in terms of originality and valuableness scores. These findings suggest that the three creativity tasks (C, □, and ×) manifest distinct patterns of creative thinking, emphasizing that a greater quantity of ideas does not necessarily correlate with enhanced creativity. It has been proposed that creativity involves connecting relatively weak or distant semantic components and integrating them into original concepts (Liu et al., 2021), with the latter contributing to superior creativity performance. Consequently, it can be inferred that the C task represents an easier or near-association task, leading to the generation of more general but less original and valid ideas. In contrast, the □ and × tasks represent harder or remote-association tasks,

resulting in fewer ideas generated, each of which is more original and valid. In this study, we utilized the product-based tasks (i.e., the C, \square , and \times tasks) as stimuli to explore whether creativity tasks with varying levels of association difficulty would trigger distinct neural activations, particularly when considering only the most original and valuable product.

Based on the aforementioned literature, we hypothesized that an easier association stimulus (e.g., the C task) would activate stronger or more brain regions associated with inhibition, controlled attention, and decision-making to suppress less original and valuable responses compared to a harder association stimulus (e.g., the \square or the \times task). Additionally, considering the nature and constraints imposed during the creative thinking process, we expected that decision-making brain regions would be activated across different types of creativity tasks. In this study, we were particularly interested in brain regions of two ECNs (dlPFC and vlPFC), four DMNs (dmPFC, precuneus, IPL, and PCC), two SNs (ACC and insula), two attention networks (FEF and TPJ), and one decision-making network (OFC).

2. Materials and Method

2.1. Participants

Twenty-one college students (10 males and 11 females) in Taiwan, aged 20–29 (21.95 ± 1.82 years), participated in this study. All participants were right-handed, had normal or corrected-to-normal vision, and underwent a prescreening process to ensure the absence of any history of neurological or neuropsychological disorders. The study received approval from the Research Ethics Committee of the university where it was conducted, and written informed consent was obtained from all participants. A compensation of approximately US\$25 was provided as a reward for their participation.

2.2. Stimuli

The stimuli for this study were taken from the "Product-based Figural Creativity Test" (PB-FCT) (Yeh et al., 2013; Yeh et al., 2019). The original PB-FCT assesses both the originality and valuableness of creative ideas. It consists of three figural subtests (C, \square , and \times), where participants were encouraged to think creatively and generate as many original and valuable product designs as possible using the shapes of C, \square , and \times . The correlations between originality and valuableness for the C, \square , and \times subtests were 0.755, 0.822, and 0.785 respectively ($ps < 0.001$) (Yeh et al., 2019). In this study, participants were instructed to draw the most original and valuable product based on a given stimulus (C, \square , or \times). Building upon previous findings (Yeh et al., 2013) indicating that the C task exhibits higher fluency but lower originality compared to the \square and \times tasks, we posit that the C task reflects an easier association task, while the \square and \times tasks involve harder associations. In this study, the correlation between the two types of tasks is 0.457 ($p = 0.037$) for originality and 0.338 ($p = 0.134$) for valuableness.

Each designed product was evaluated based on two criteria: originality (scored from 0 to 3 points) and valuableness (scored from 0 to 3 points). Originality was determined by the rarity of a response according to predefined percentages (0 points: $\geq 5\%$; 1 point: $\geq 2\%$ and $< 5\%$; 2 points: $\geq 1\%$ and $< 2\%$; 3 points: $< 1\%$). Valuableness was assessed by the number of distinct functions exhibited by a response, with scoring rules as follows: 0 = not valid, 1 = single function, 2 = two different functions, and 3 = three or more different functions (Yeh et al., 2019).

2.3. Experimental design and procedures

The experiment consisted of two runs, with each run including three blocks of creativity stimuli (C, \square , or \times) that were randomly assigned. Each run comprised six trials, with each stimulus (C, \square , or \times) presented for 75 s on the screen twice. It was found that 60 s was an appropriate

amount of time to complete each creativity task without drawing inside the scanner (Yeh et al., 2019). Therefore, we allowed an additional 15 s to draw out the product. In each run, "ready" was presented on the screen, followed by a dummy scan. Then, jittered intertrial intervals of 2 s of fixation were shown. The participants were requested to draw one original and valuable product inspired by the given stimulus (see Fig. 1 for procedures and Fig. 2 for examples of creativity performances).

Scans were performed in a 3-tesla Siemens Magnetom Skyra fMRI scanner using a 32-channel head coil, and the in-scan drawing was performed through the use of a hand-drawing board which allows for visual inspection of the drawn figure (see Fig. 1). Visual stimuli were presented to the participants on a Hitachi CP-SX635 Projector. All participants reported having no difficulties in viewing the stimuli or instructions during the fMRI scan.

3. Data acquisition

BOLD echoplanar images (EPIs) were collected using T2*-weighted gradient-echo echoplanar imaging sequences (voxel size, $4 \times 4 \times 3$ mm). Each volume contained 34 transverse slices of 3 mm slice thickness that were oriented parallel to the anterior and posterior commissure (AC-PC) line covering the entire brain (TR = 2000 ms, TE = 24 ms, flip angle = 90° , FOV = 256 mm, 64×64 matrices, in-plane resolution = 4.0×4.0 mm). High-resolution T1-weighted structural images were acquired using the 3D MPRAGE pulse sequence: TR = 1560 ms, TE = 3.30 ms, flip angle = 15.0° , 256×256 voxel matrix, FOV = 256 mm, number of slices = 192, slice thickness = 1.0 mm, and in-plane resolution: 1.0×1.0 mm. This study included three runs and the initial three dummy scans were discarded to allow for the T1 equilibration effect. The structural scans facilitated the localization and co-registration of the functional data. Each run consisted of a series of 460 EPI scans.

3.1. Image analyses

Functional data were processed using SPM12. Preprocessing steps included a slice-time correction to align with the middle slice onset and spatial realignment to correct head motion. The high-resolution T1 images were then co-registered with the functional images, which were subsequently normalized to the standard Montreal Neurological Institute EPI template using a voxel size of $4 \times 4 \times 3$ mm. Additionally, statistical analyses were performed on spatially smoothed data using an 8-mm full-width-at-half-maximum Gaussian kernel and a high-pass filter (cutoff period: 128 s) to eliminate low-frequency artifacts.

fMRI data from 4 blocks for each condition were acquired throughout the entire scan. The onset time of each block was set at the beginning of each stimulus (C, \square , or \times) presented, and each block had a duration of 75 s. Head movement parameters were included as covariates of no interest, separately modeled for each task and run. The parameter estimates from the first-level analysis were entered into a second-level (random effects) analysis using one-sample t-tests to evaluate significant activations per condition. For each participant, two contrast images coding from the three conditions (C, \square , and \times) onset were constructed. Six contrasts were employed ($\square > C$, $\times > C$, $C > \square$, $C > \times$, $\square > \times$ and $\times > \square$). Corresponding contrast images of the parameter estimates were used in a second-level analysis. Each participant's contrast volumes were entered into a random-effects analysis, which created group average maps for all contrasts across the entire brain using a within-subject GLM. The resulting mask of creativity tasks was associated with 11 brain regions in the predefined ROIs.

ROI analysis was utilized to investigate the interaction between key brain regions of the DMN, ECN, and SN in creative thinking. A GLM was employed for first-level analysis. For each voxel, the regressors of three conditions (C, \square , and \times) were modeled by convolving a boxcar function representing the timing of stimulus events with the canonical hemodynamic response function in SPM. Anatomical ROI masks were generated

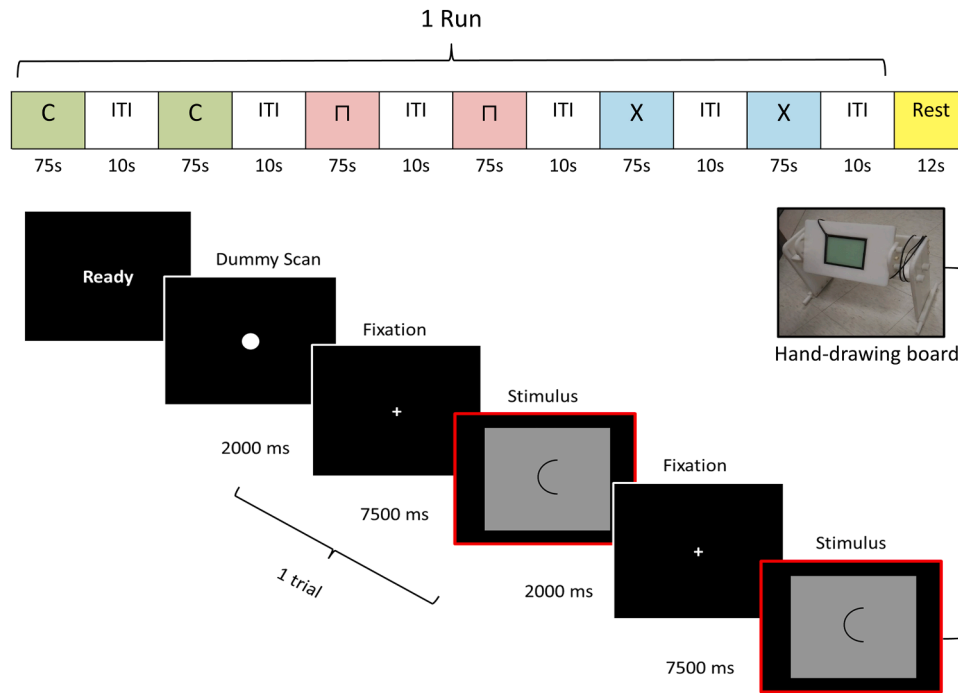


Fig. 1. The in-scan procedures: There were two runs in total, with each run including three blocks of creativity stimuli (C, □, or X) that were randomly assigned. Each stimulus was presented for 75 seconds on the screen. This figure only demonstrates the block of C. Note: ITI: Intertrial interval.

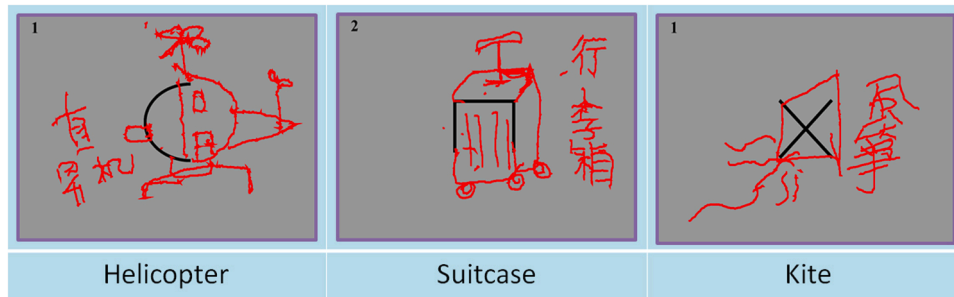


Fig. 2. Examples of the drawn products: The helicopter was created from stimulus C; the suitcase was created from stimulus □; and the kite was created from stimulus X.

using the WFU PickAtlas Tool software (Maldjian et al., 2003) for the ROI analyses. Furthermore, conjunction analysis was conducted to identify brain regions commonly active across the task of C, □, and X. The minimum t statistic in SPM was employed to test each contrast, and only voxels significant in three contributing SPM maps were retained (Bangert et al., 2006).

Additionally, psychophysiological interaction (PPI) analysis (Friston et al., 1997; Tomasi, 2007) was conducted to investigate potential interactions of functional connectivity between a psychological variable and the functional coupling among activated brain regions in the C > X, C > □, and □ > X comparisons. The BOLD signal time course corresponding to each activation region of interest (seed) was deconvolved to obtain the neuronal signal time course. Three regressors were created based on the neuronal signal time course for each condition (C, □, and X), which were then convolved with the canonical hemodynamic response function. These regressors, along with the effects of no interest (i.e., motion correction parameters), were entered into a first-level GLM for each functional run. Subsequently, PPI analyses were carried out using a second-level random effects group analysis, employing a one-sample t -test for group comparisons. Both subtraction and functional connectivity analyses were performed using an ROI approach (Beatty et al., 2015; Chen et al., 2023; Pinho et al., 2015).

ROI, Conjunction, and PPI analyses were conducted whole-brain clusterwise inference was performed using an uncorrected cluster-level threshold of $p < .001$ with a threshold of 10-mm voxels on each of the specified regions and using small volume correction (SVC) with a significance level of $p < 0.001$ for the magnitude of activation and extent threshold of the 8-mm sphere on each of the specified regions (Shah et al., 2013). Moreover, the significant activation level was set at a peak-level threshold of $p < 0.05$ family-wise error rate (FWE) with a threshold of 10-mm voxels on each of the specified regions.

4. Results

4.1. In-scan behavioral results

Repeated-measures analysis of variance revealed significant differences in participants' scores of originality across the three creativity tasks: Wilks' $\Lambda(1, 20) = 0.722, p = 0.045, \eta_p^2 = 0.278$. Similarly, participants' scores of valuableness differed significantly across the three tasks: Wilks' $\Lambda(1, 20) = 0.670, p = 0.022, \eta_p^2 = 0.330$. Further analyses revealed that the originality score of the X task was higher than that of the C task, $F(1, 20) = 5.565, p = 0.029, \eta_p^2 = 0.218$. The X task score was also marginally higher than the □ task score, $F(1, 20) = 3.445, p = 0.078$,

$\eta_p^2 = 0.147$. Furthermore, the participants' valuableness score for the \square task was higher than that of the C task, $F(1, 20) = 8.767, p = 0.008, \eta_p^2 = 0.305$. The score for the \times task was higher than that of the C task, $F(1, 20) = 5.426, p = 0.030, \eta_p^2 = 0.213$. However, the valuableness score for the \square task was not significantly higher than that of the \times task, although it was slightly higher ($M = 4.76$ vs. 4.52) (see Fig. 3).

4.2. fMRI results

4.2.1. ROI analyses

Based on the previous literature review, we utilized eleven regions of interest (ROIs) in the ROI analyses, including two Executive Control Networks (dlPFC and vlPFC), four Default Mode Networks (dmPFC, precuneus, IPL, and PCC), two Saliency Networks (ACC and insula), two Attention Networks (FEF and TPJ) and one Decision-Making Network (OFC). A second-level analysis involved six contrasts. Fig. 4 provides the seed voxel locations and the beta values of contrast estimation for brain activation in ROI analysis, while the GLM results for the C, \square , and \times contrasts are presented in Table 1.

The GLM analysis for the "C > \times " contrast revealed stronger activation in the right dlPFC, bilateral dmPFC, bilateral precuneus, bilateral IPL, left PCC, bilateral ACC, right insula, right OFC, and right FEF. Similarly, the "C > \square " contrast exhibited greater activation in the left dlPFC, right dmPFC, bilateral precuneus, bilateral IPL, bilateral ACC, bilateral insula, right OFC, and right FEF. Furthermore, the " \square > \times " contrast showed enhanced activation in the right dlPFC, right dmPFC, right precuneus, left IPL, right PCC, right ACC, right insula, right OFC, and right FEF. No significant brain activations were observed in the other contrasts.

4.2.2. Conjunction analysis

Based on the conjunction analysis results, increased activation was observed in the Orbitofrontal Cortex (OFC) during the tasks labeled as C, \square , and \times . Consequently, we analyzed the correlation between the beta values of contrast estimation activity and valuableness scores. The findings indicated a negative correlation between activity in the left OFC and valuableness scores in both the C condition and the \square condition, $r_s = -0.439$ and

-0.482 , respectively, $p_s < 0.05$. However, left OFC activity did not exhibit a significant correlation with valuableness scores in the \times condition (see Fig. 5 and Table 2).

4.2.3. PPI analysis

Given that the orbitofrontal cortex (OFC) constitutes the primary focus of our study, we utilized the activated brain regions identified through ROI analyses as seed regions in the PPI analysis. This approach allowed us to explore the functional connectivity between these key brain regions and the OFC. The significant functional connectivity between the seed brain regions and the OFC, as highlighted in Table 3 and Fig. 6, addresses our primary research focus.

In the "C > \times " analysis, we found that the right dlPFC showed

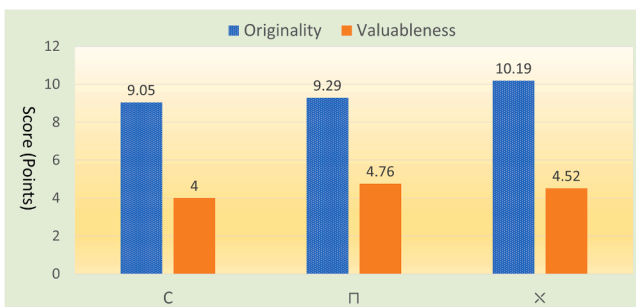


Fig. 3. In-scan behavioral results: The Ms and SDs of the three creativity tasks (C, \square , or \times) in originality and valuableness.

connectivity with the left OFC; the right precuneus demonstrated connectivity with the right dlPFC and left OFC; the right PCC showed connectivity with bilateral OFC; the right insula exhibited connectivity with the right dlPFC, left dmPFC, left OFC, right precuneus, and right FEF. In the "C > \square " analysis, we observed that the right precuneus showed connectivity with bilateral OFC; the right insula exhibited connectivity with left OFC, PCC, and FEF.

5. Discussion

This study aimed to explore the neural mechanisms underlying different patterns of creative thinking during the design of original and valuable products within an fMRI setting. Drawing on previous research (Yeh et al., 2019; Yeh et al., 2015), we compared the neural mechanisms involved in two types of creativity tasks: the easier association task and the harder association tasks. The behavioral and fMRI findings from this study provide support for our hypotheses and shed light on the underlying processes involved in these distinct creative thinking patterns. Specifically, our results demonstrate that association, inhibition, and decision-making processes exert diverse influences on different types of creative tasks that strive for optimal design.

Consistent with previous findings (Beaty et al., 2018; Beaty and Kenett, 2023; Shen et al., 2017; Yeh et al., 2019), this study provides support for the involvement of the executive control network (ECN), default mode network (DMN), salience network (SN), and cognitive inhibition. However, our findings suggest that, in comparison to the more challenging association tasks (i.e., the \square task and the \times task), the easier association task (i.e., the C task) induces heightened activations in the dlPFC, right dmPFC, bilateral precuneus, bilateral IPL, bilateral ACC, right insula, right OFC, and right FEF. Significantly, the easier association tasks trigger more robust and widespread activation across brain regions associated with association, inhibition, decision-making, and evaluation. While the easier association task may stimulate a multitude of ideas, the requirement for only one original and valuable product may provoke robust inhibition of unoriginal ideas, focused attention, and decisive decision-making, potentially resulting in decreased creativity performance. These results align with previous findings in divergent thinking research (Brockett and Roesch, 2021; Khalil et al., 2020; Kleinmintz et al., 2019; Yeh et al., 2019).

According to dual-process theories (Benedek and Jauk, 2018; Dygert and Jarosz, 2020), associative and controlled-attention processes are both important to creative thinking. The associative process is related to idea generation, which is closely related to the DMN network (Beaty and Kenett, 2023; Kleinmintz et al., 2019; Marron et al., 2018). However, our findings support the notion that broad activation of the DMN indicates that participants make many close associations that are neither original nor valuable (Beaty and Kenett, 2023; Takeuchi et al., 2020); moreover, deactivation of the DMN reflects the efficiency of attentional reallocation (De Garrido, 2022; Takeuchi et al., 2020) and originality was negatively related to the activation of the precuneus (Chen et al., 2015). Our findings also suggest that strong activation in the ECN and SN networks may hinder the remote association of novel ideas, which is in line with the finding that reduced inhibitory control leads to increased originality or creative production (Radel et al., 2015) and the less creative people were essentially fixed in a state of cognitive inhibition (Xuejun and Haijuan, 2018). To conclude, attenuating the activation of the DMN, SN, ECN, attention, and decision-making network during challenging association leads to enhanced creativity performance, particularly in situations with high constraints (e.g., allowing only one original and valuable product).

Remarkably, through conjunction analyses, it was discovered that all types of tasks stimulated a shared brain region in the left OFC. This discovery underscores the pivotal roles of decision-making and value assessment in fostering product-based creativity. This aligns with prior research linking the assessment of appropriateness to the orbitofrontal cortex (OFC) (Huang et al., 2018; Lin and Vartanian, 2018), where the

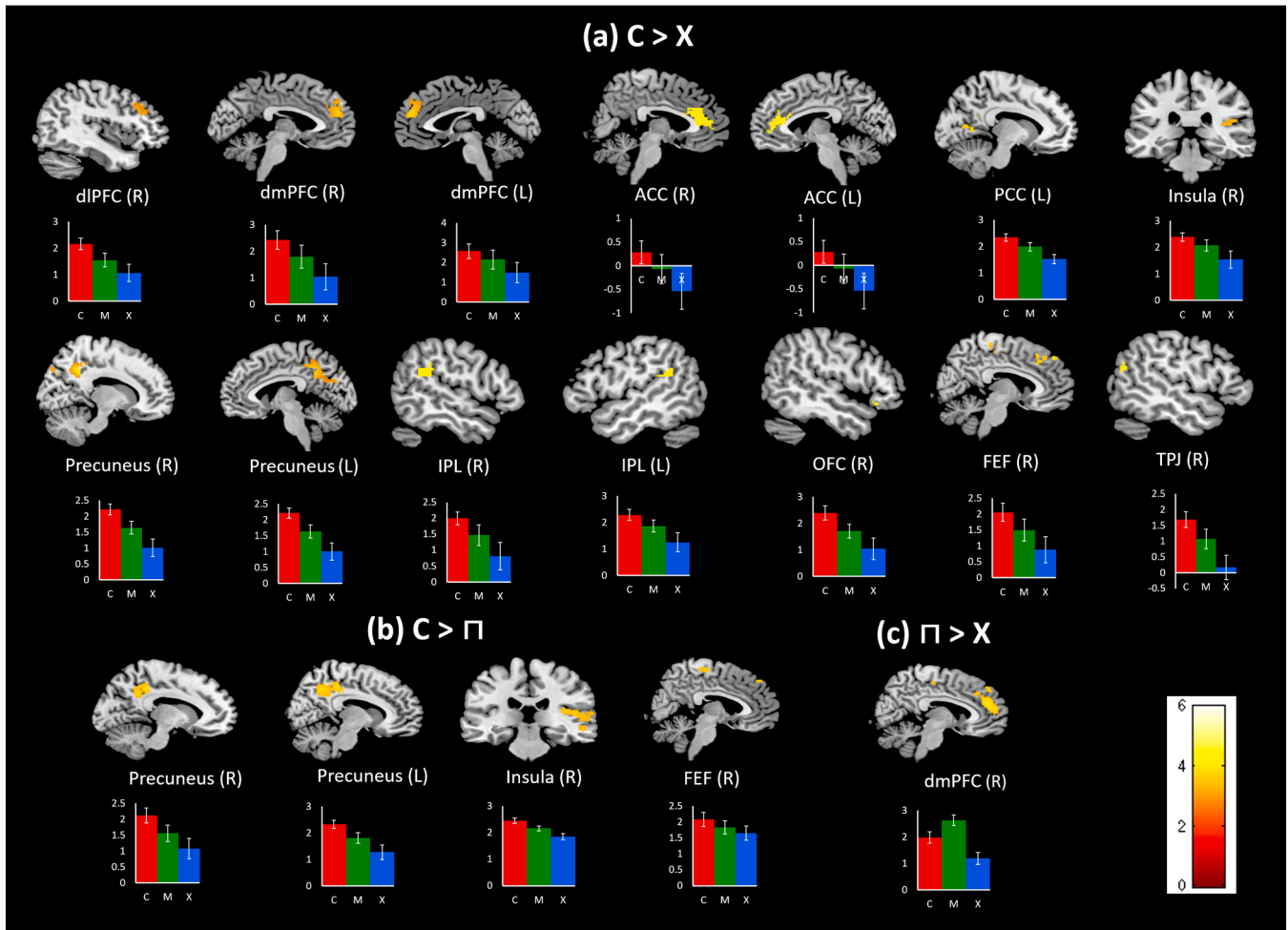


Fig. 4. Seed voxel locations and the beta values of contrast estimation for brain activation in ROI analysis. Note. (a) $C > X$; (b) $C > \Pi$; (c) $\Pi > X$. Y-axis is the beta values and X-axis is the three conditions. The bar charts represent the T values.

OFC facilitates the formation of thoughts based on considerations of value (Zamani et al., 2022). Additionally, our findings resonate with the observation that individuals demonstrating higher creative achievement scores tend to exhibit reduced cortical thickness in their left OFC. Notably, the activation of the OFC during the evaluation of appropriateness in creative drawing has been reported in previous studies (Ellamil et al., 2012; Kleinmuntz et al., 2019; Shah et al., 2013). Moreover, our results align with the concept that the OFC plays a role in making economic decisions within a neural circuit (Padoa-Schioppa and Conen, 2017). The consistency of these findings strengthens the understanding of how the OFC contributes to the intricate processes involved in decision-making, value assessment, and creativity in a product-based context. Notably, prior studies utilizing divergent thinking tasks rarely identified OFC activation. Therefore, the significance of the decision-making brain network identified in this study underscores the uniqueness and validity of the creative tasks employed.

In the PPI analysis, it was revealed that the easier association task exhibited intricate coupling compared to the more challenging association tasks. The main neural circuits identified are as follows: (1) the ECN-decision-making circuit, with dIPFC coupled with OFC; (2) the SN-ECN-DMN-attention-decision-making circuit, where insula exhibited coupling with dIPFC, dmPFC, precuneus, PCC, FEF, and OFC; and (3) the decision-making circuits, where the OFC demonstrated coupling with ECN (dIPFC), DMN (precuneus, PCC), and SN (insula). These complex functional connections between brain networks signify the dynamic interplay between large-scale networks during the process of creative thinking (Zhuang et al., 2021). Furthermore, the findings support

previous research indicating that the insula alternately collaborates with the DMN (Yeh et al., 2019) and that the precuneus plays a vital role in creativity (Orwig et al., 2021). Notably, a key distinction between this study and previous investigations on divergent thinking lies in the activation of the OFC, which supports the distinctive nature of our creative tasks. Additionally, our findings showed that the decision-making circuits were more likely to be present in the easier association task and that OFC activation was adversely connected with the valuableness scores. This section aligns with past research findings as well (Japardi et al., 2018; Liu et al., 2018).

6. Conclusions

There has been a consensus that creativity encompasses both originality and valuableness. However, previous fMRI studies predominantly utilized divergent-thinking tasks, which allowed for multiple answers but did not assess "valuableness." In reality, our goal is often to develop the most original and valuable creative product within specific constraints. Therefore, this study aimed to investigate the underlying neural mechanisms associated with different patterns of creative thinking while designing an original and valuable product within an fMRI scanner. Building upon prior research, we employed product-based creativity tasks that addressed this objective.

The results of the study confirmed our hypothesis, revealing two distinct patterns of creative thinking: easier association tasks exhibited lower creativity, whereas harder association tasks demonstrated higher levels of creativity. It is important to note that broad brain activation

Table 1
GLM results for the contrasts between C, □, and X.

Anatomical region	BA	Side	Voxels	MNI coordinates			Z score
				x	y	z	
C > X							
dIPFC	9	R	152	32	32	42	3.76
dmPFC	9	R	101	6	50	24	4.68
	9	L	50	-4	50	30	3.89
Precuneus	31	R	131	12	-50	38	4.47
	31	L	161	-8	-52	34	3.99
IPL	40	L	67	-58	-46	22	4.73
	40	R	100	56	-46	22	4.29
PCC	30	L	45	-6	-68	8	3.36
ACC	32	R	94	4	44	16	4.19
	24	L	55	-2	38	12	3.80
Insula	13	R	22	56	-40	18	3.92
OFC	47	R	10	48	24	-14	3.33
FEF	8	R	34	6	48	44	3.95
TPJ	39	L	26	-52	-62	24	4.12
□ > X							
dIPFC	9	L	6	-22	44	36	3.22
dmPFC	9	R	14	4	50	28	3.74
Precuneus	7	L	202	-4	-50	46	3.99
	7	R	44	8	-36	46	3.91
IPL	40	L	52	-52	-48	22	4.29
	40	R	60	58	-46	24	3.64
ACC	32	R	25	6	38	24	3.53
	32	L	29	-6	46	6	3.41
Insula	13	R	97	38	-30	14	4.24
	13	L	116	-42	-16	2	4.12
OFC	47	R	17	48	26	-12	3.93
FEF	6	R	20	8	-30	66	3.73
□ > C							
dIPFC	9	R	27	32	36	42	3.37
dmPFC	9	R	104	6	46	24	3.76
Precuneus	7	R	32	12	-82	38	4.03
IPL	40	L	55	-58	-46	24	4.82
PCC	30	R	38	14	-58	6	3.80
ACC	32	R	44	4	50	12	3.38
Insula	13	R	17	56	-40	20	3.97
FEF	8	R	15	6	48	44	3.45
TPJ	39	L	39	-52	-62	24	4.46
□ > C; X > C; X > □ n.s.							

Note. The whole-brain activation threshold was set to uncorrected cluster-level $p < .001$ and all clusters greater than or equal to 10 are presented. A small volume correction (SVC) was applied. MNI= Montreal Neurological Institute; BA = Brodmann's area; Voxels = number of voxels in a cluster.

Table 2
Conjunction analyses results.

Anatomical region	BA	Side	Voxels	MNI coordinates			Z score
				x	y	z	
C & □ & X							
OFC	47	L	23	-22	38	-6	3.51

Note. The whole-brain activation threshold was set to uncorrected cluster-level $p < .001$ and all clusters greater than or equal to 10 are presented. A small volume correction (SVC) was applied. MNI= Montreal Neurological Institute; BA = Brodmann's area; Voxels = number of voxels in a cluster.

Table 3
PPI analyses of functional connectivity.

Anatomical region	BA	Voxels	Side	MNI coordinates			Z score
				x	y	z	
C > X							
Seed: dIPFC (32, 32, 42)							
OFC	11	24	L	-38	34	-14	3.10
Seed: Precuneus (12, -50, 38)							
dIPFC	46	112	R	50	20	26	3.44
OFC	11	13	L	-18	54	-10	3.11
Seed: PCC (-6, -68, 8)							
OFC	47	10	L	-32	30	-8	3.17
	11	16	R	6	54	-12	3.45
Seed: Insula (56, -40, 18)							
dIPFC	46	70	R	54	30	26	3.05
dmPFC	9	89	L	-4	48	32	3.20
OFC	11	39	L	-40	58	-10	3.94
Precuneus	7	97	R	8	-64	32	3.63
FEF	8	8	R	4	22	52	2.93
C > □							
Seed: Precuneus (8, -36, 46)							
OFC	47	35	R	60	22	-2	3.78
	47	41	L	-54	26	0	3.15
Seed: Insula (38, -30, 14)							
OFC	11	18	L	-24	30	-12	3.07
PCC	30	39	L	-4	-62	10	3.06
FEF	6	48	L	-2	-22	66	3.58

Note. The whole-brain activation threshold was set to uncorrected cluster-level $p < .001$ and all clusters greater than or equal to 10 are presented. A small volume correction (SVC) was applied. MNI= Montreal Neurological Institute; BA = Brodmann's area; Voxels = number of voxels in a cluster.

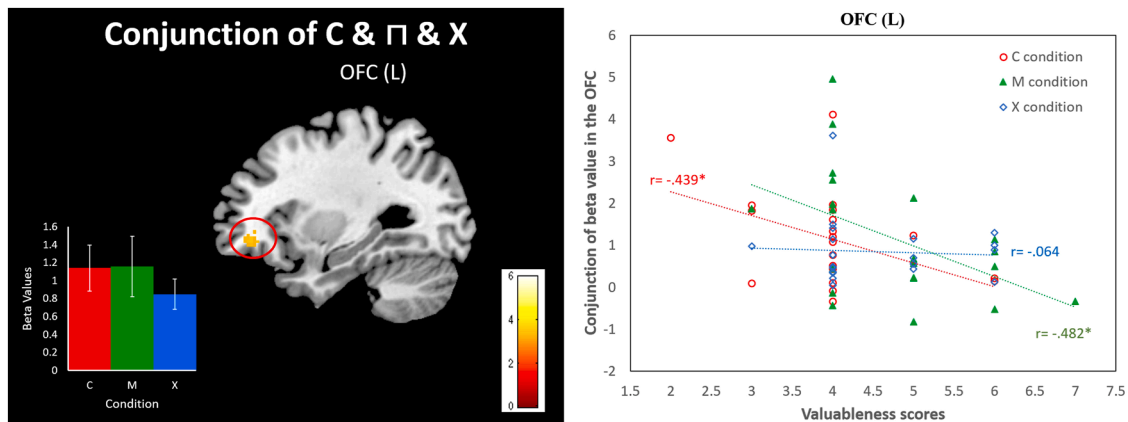


Fig. 5. Conjunction of seed voxel locations (top left) and beta values of contrast estimation for brain activation (bottom left). The bar graph shows the T-value. The beta values of contrast estimation activity correlate with valuableness scores (right). The red scatterplot illustrates the negative correlation between valuableness scores for the C condition and left OFC activation ($r = -0.439, p < 0.05$). The green scatterplot illustrates the negative correlation between valuableness scores for the □ condition and left OFC activation ($r = -0.482, p < 0.05$). The blue scatterplot illustrates the negative correlation between valuableness scores for the X condition and left OFC activation ($r = -0.064, p > 0.05$).

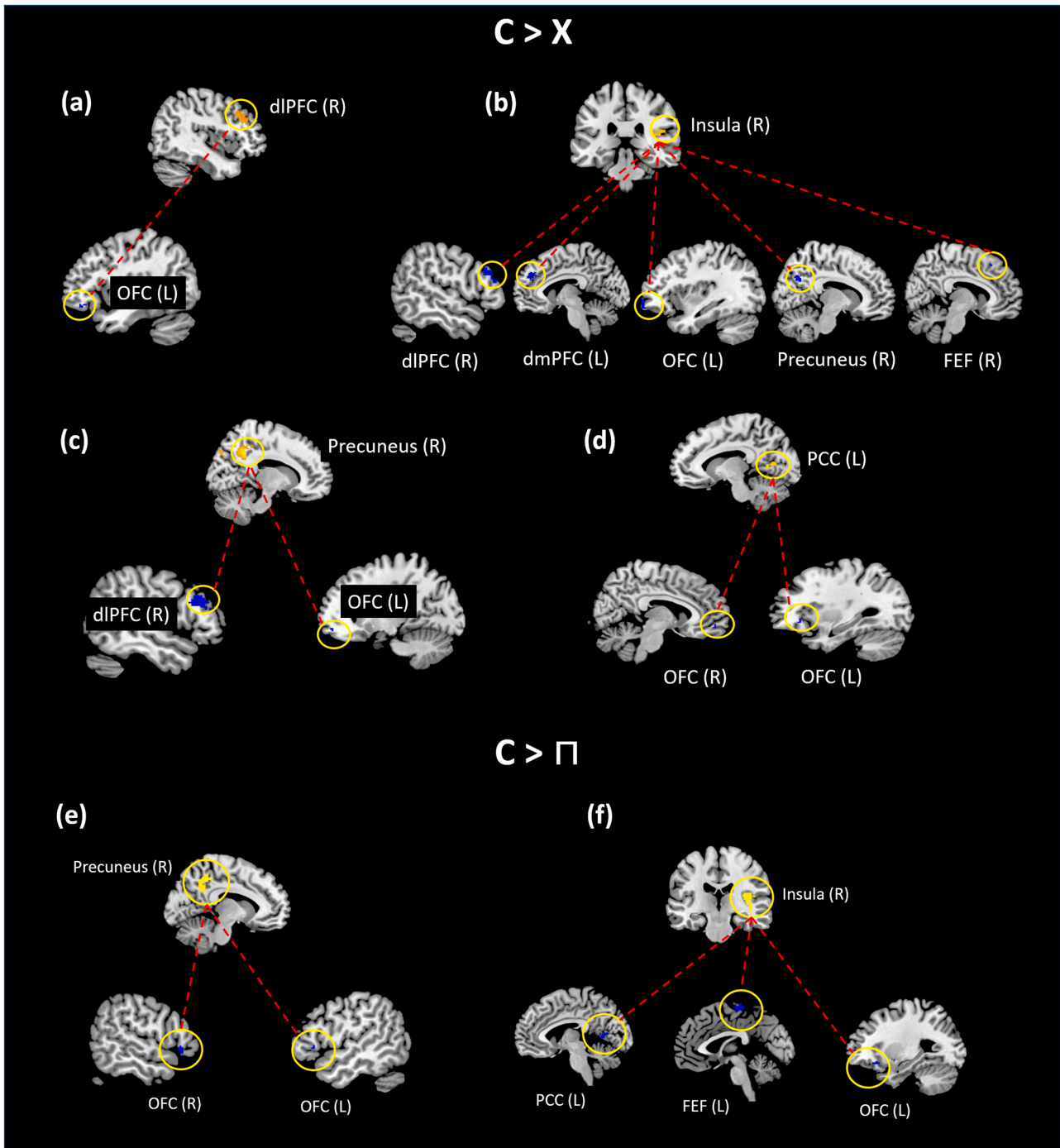


Fig. 6. PPI analysis of functional connectivity for the $C > X$ contrast and $C > \Pi$ contrast. Note. Seed voxel location (yellow) exhibited positive functional connectivity with the voxel locations (blue). Seed nodes: (a) dIPFC (32, 32, 42); (b) insula (56, -40, 18); (c) precuneus (12, -50, 38); (d) PCC (-6, -68, 8) for the $C > X$ contrast. Seed nodes: (e) precuneus (8, -36, 46); (f) insula (38, -30, 14) for the $C > \Pi$ contrast.

does not necessarily indicate superior creativity. Instead, efficient utilization of association to generate creative ideas, inhibition to suppress unoriginal ideas, and decision-making to select the best ideas were associated with optimal creativity performance under high constraints. Furthermore, the involvement of the OFC emerged as crucial in the decision-making processes during the generation of an original and valuable product. Additionally, the intricate functional connectivity observed between various brain regions reflects the complex nature of creative thinking and the dynamic interplay between large-scale networks during product-based creative endeavors.

Limitations and implications

In real-life scenarios, the ability to design a product or solve a problem effectively within specific constraints is often crucial. This study aimed to replicate such situations and discovered that remote association, along with appropriate utilization of inhibition and decision-making, plays a critical role in generating an original and valuable product. While this study did not differentiate between specific thinking stages within different types of creative thinking, its findings carry significant implications for the teaching and training of creativity.

The results suggest that imposing constraints and actively guiding

learners to engage in challenging association tasks may enhance thinking efficiency and facilitate the generation of original and valuable ideas. The tasks employed in this study emphasized both originality and valuableness, setting them apart from traditional divergent thinking tasks discussed in the existing literature. While different brain activations were observed in comparison to previous studies, we did not explicitly incorporate such comparisons into our research design. Future studies could explore and compare the neural mechanisms involved in these two distinct types of creativity tasks using fMRI methodologies.

Declaration of Competing Interest

There is no conflict of Interest and the study is in compliance with ethical standards

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