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The Dynamic Relationship of Brain Networks Across Time Windows During Product-Based Creative Thinking[*]

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Consensus of creativity research suggests that the measurement of both originality and valuableness is necessary when designing creativity tasks. However, few studies have emphasized valuableness when exploring underlying neural substrates of creative thinking. The present study employs product-based creativity tasks that measure both originality and valuableness in an exploration of the dynamic relationship between the default mode (DMN), executive control (ECN), and salience (SN) networks through time windows. This methodology highlights relevance, or valuableness, in creativity evaluation as opposed to divergent thinking tasks solely measuring originality. The researchers identified seven brain regions belonging to the ECN, DMN, and SN as regions of interest (ROIs), as well as four representative seeds to analyze functional connectivity in 25 college student participants. Results showed that all of the identified ROIs were involved during the creative task. The insula, precuneus, and ventrolateral prefrontal cortex (vlPFC) remained active across all stages of product-based creative thinking. Moreover, the connectivity analyses revealed varied interaction patterns of DMN, ECN, and SN at different thinking stages. The integrated findings of the whole brain, ROI, and connectivity analyses suggest a trend that the DMN and SN (which relate to bottom-up thinking) attenuate as time proceeds, whereas the vlPFC (which relates to top-down thinking) gets stronger at later stages; these findings reflect the nature of our creativity tasks and decision-making of valuableness in later stages. Based on brain region activation throughout execution of the task, we propose that product-based creative process may include three stages: exploration and association, incubation and insight, and finally, evaluation and decision making. This model provides a thinking frame for further research and classroom instruction.

Keywords: default mode network, dynamic connectivity, executive control network, product-based creativity, salience network, time window

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Introduction

Creativity involves the development of a novel product or problem solution that is valuable to the individual and/or the larger social group; such product-based creativity requires the measurement of both originality (novelty) and valuableness (usefulness) (Hennessey & Amabile, 2010; Yeh, 2004; 2017). To date, most neuroimaging studies of creativity employ divergent thinking tasks (e.g., alternative use tasks) that measure originality or novelty only. However, the consensus regarding creativity is that both originality and valuableness should be measured (Diedrich, Benedek, Jauk, & Neubauer, 2015; Hennessey & Amabile, 2010; Mayer, 1999; Runco & Jaeger, 2012; Yeh, 2017; Yeh, Lai, Lin, Lin, & Sun, 2015).

Moreover, the complex neurological processes of creativity demand cognitive functions to operate independently, in collaboration, or in synchrony over the course of a task (Beaty, Benedek, Kaufman, & Silvia, 2015). A body of research has found that the executive control network (ECN), as well as the default mode network (DMN), play an important role during divergent thinking tasks (Beaty et al., 2015; Beaty, Benedek, Silvia, & Schacter, 2016; Ellamil, Dobson, Beeman, & Christoff, 2012). The ECN is commonly associated with controlled memory retrieval, executive processes, and idea evaluation, whereas the DMN relates to internally-directed attention, spontaneous cognition, and idea generation (Andrews-Hanna, 2012; Aron, 2007; Beaty et al., 2018; Di Domenico & Ryan, 2017). Researchers (e.g., Beaty et al., 2015) have also suggested that the salience network (SN), which helps distinguish relevant stimuli in order to guide behavior, is critical to divergent thinking tasks. The SN is thought to guide cognitive processes transitioning between the DMN and the ECN by identifying ideas generated in the DMN and advancing those thoughts to the ECN for higher level processing (Beaty et al., 2018).

Most of the neuro-creativity research thus far has focused on identifying discrete brain regions and confirmed that creative thinking involves both hemispheres. Although connectivity between the ECN, DMN, or SN has been observed in several recent studies (Beaty et al., 2018; Beaty, Christensen, Benedek, Silvia, & Schacter, 2017; Beaty, Benedek, Silvia, & Schacter, 2016; Beaty et al., 2014; Beaty et al., 2015), neuroimaging research identifying this dynamic relationship between the ECN, DMN, and SN with product-based creativity tasks through time windows, has yet to be conducted. A recent related study (Beaty et al., 2015) only examined the dynamic interactions between the DMN and ECN during a divergent thinking task with four time windows (each included 2 s). To explore the stages of product-based creative thinking which requires much more thinking time than the commonly used divergent thinking tasks, we conducted this exploratory study to analyze neural substrates across six time windows (each included 10 s). Briefly speaking, the goals of the study were to (a) explore activation of specific brain regions during different stages of product-based creative thinking; (b) highlight important DMN, ECN, and SN brain regions during the thinking process; (c) examine dynamic relationships between the identified core hubs of the DMN, ECN, and SN during creativity tasks; and (d) propose a tentative stage model of product-based creativity based on the integrated results.

The Cognitive Processes of Creativity

Several stage models of product-oriented creativity have been accepted by the scientific community. The Geneplore model considers creativity to be a product or outcome of two phases: a generative phase, where an individual constructs mental representations called preinventive structures; and an exploratory phase, in which a person searches for meaningful interpretations of preinventive structures to then generate creative ideas, while considering product constraints (Ward, Smith, & Finke, 1999). The Componential Model of Creativity comprises five stages of the creative process. The first two stages are problem or task identification and preparation. The third stage is response generation, the fourth stage is response validation and communication, and the fifth stage involves an appropriate decision (Amabile, 1996). In addition, the Ecological Systems Model of Creativity Development consists of four stages: preparation, incubation, insight, and evaluation (Yeh, 2017). Another perspective based on creative cognition emphasizes two processes, namely, the generation and evaluation of ideas (Lin & Vartanian, 2017). These stage theories of creativity suggest that creativity involves both divergent thinking emphasizing the originality of ideas, and convergent thinking emphasizing the valuableness of products or solutions.

Product-based creative processes involve information retrieval, association, integration, as well as executive selection and decision-making functions for evaluation. Researchers have observed these processes to be greatly influenced by working memory and emotion (Yeh, Lai, & Lin, 2016; Yeh et al., 2015; Yeh, Tsai, Hsu, & Lin, 2014). Working memory is thought to influence creativity through direct attention on task-related information and persistence, whereas emotion has been found to be an important mediator or moderator during creative thinking (Yeh et al., 2016). Positive emotion may broaden attention and thinking, enables higher-level connections, generates a wider range of ideas, and thereby leads to creative thought (Fredrickson, Cohn, Coffey, Pek, & Finkel, 2008). Moreover, positive mood states may stimulate greater motivation, higher levels of dopamine and noradrenaline, and enhanced working memory (WM) capacity; these processes should facilitate cognitive flexibility, abstract thinking, processing speed, and access to long-term memory (Baas, Dreu, & Nijstad, 2008; Dietrich, 2004).

In summary, the complex processes of creativity involve the interactions of divergent thinking and convergent thinking when producing original and valuable ideas. It is important to note that working memory and emotion have been found to play important roles during this process. Accordingly, investigating the underlying neural substrates or circuits of these functions is crucial in the exploration of creative cognition.

Neural Networks for Creativity

Neural Substrates of Varied Creativity Tasks

Over the years of creativity research, there have been some differences observed with regards to the types of creativity tasks implemented by researchers, which has led to inconsistencies among activation of specific corresponding brain areas (Fink & Benedek, 2014). Notably, most of the previously conducted research investigating creativity utilized verbal divergent thinking tasks (Beaty et al., 2018; Dietrich & Kanso, 2010; Fink & Benedek, 2014). These types of studies suggest that the involved brain regions include the superior frontal gyrus, posterior parietal cortex, premotor cortex, inferior frontal gyrus (IFG), dorsolateral prefrontal cortex (dlPFC), and the medial prefrontal cortex (PFC) (Fink & Benedek, 2014). With studies utilizing visual creativity tasks, there is strong activation of the premotor cortex, posterior parietal cortex, medial PFC, dlPFC, and right IFG, which might be involved in sustained attention, cognitive flexibility, working memory, and goal-directed planning (Dixon & Christoff, 2014; Zhu, Chen, Tang, Cao, Hou, & Qiu, 2016).

To date, only a few studies have employed product-based tasks in examining neural substrates of creativity. Product-oriented creativity tasks involve the process of thinking about originality and valuableness (Yeh, 2017). During product-based decisions, the PFC and the posterior cingulate cortex (PCC) may play important roles. Ellamil et al. (2012) found that while generating and evaluating ideas for the design of a book cover, functional magnetic resonance imaging (fMRI) results showed greater activation during evaluation in the medial frontal gyrus (MPFC) and PCC of the DMN. In addition, Hao, Ku, Liu, Hu, Grabner, and Fink (2016) suggested that evaluation might involve eliciting internal attention or top-down activity that facilitates efficient retrieval and integration of internal memory representations.

The Dynamic Interactions of the DMN, ECN, and SN During Creative Thinking

The ECN, which relates to top-down control of attention and cognition, such as working memory, relational integration, response inhibition, and task-set switching, is important to creative thinking (Aron, 2007; Di Domenico & Ryan, 2017). Two important regions of the ECN that are closely related to creative thinking are the dlPFC and the ventrolateral prefrontal cortex (vlPFC). It has been suggested that the lateral PFC moderates working memory functions and serves as an interface between sensory and motor areas in the brain. Working memory is accessed by the vlPFC and spatial functions are reached through the dlPFC (Dixon & Christoff, 2014). Moreover, the vlPFC is a key region for evaluating the emotional significance of external stimuli, short term information, and functions as an important substrate for cognitive influences on emotional states (Gilbert & Burgess, 2008). These findings suggest that the dlPFC and the vlPFC may moderate working memory function and emotion assessment which are critical to creative performance (Fredrickson et al., 2008, Yeh et al., 2016).

The DMN is associated with the spontaneous generation and evaluation of creative ideas that root from long term memory (Beaty et al., 2016). The core hubs of divergent thinking of creativity are the precuneus (Fransson & Marrelec, 2008), dorsomedial prefrontal cortex (dmPFC) (Bashwiner, Wertz, Flores, & Jung, 2016), and the posterior cingulate cortex (PCC) (Utevsky, Smith, & Huettel, 2014). Anatomical structures within the DMN serve slightly different functions. Autobiographical memories and self-reflection occur in the PCC; episodic and autobiographical memory is processed by the medial temporal lobes. The ventromedial prefrontal cortex (vmPFC) has been observed to activate during reflection of both the state of others and the self, emotional reasoning, and aesthetic judgement (Beaty et al., 2014); moreover, the left anterior dmPFC and the right middle temporal gyrus (MTG) may facilitate the generation of creative ideas, emotion expression, metaphor comprehension, and episodic future thought (Beaty et al., 2014; Vartanian & Goel, 2004; Vartanian, Jobidon, Bouak, Nakashima, Smith, Lam, & Cheung, 2013).

The SN assists targeted brain regions in the generation of appropriate behavioral responses to salient stimuli (Menon & Uddin, 2010). The insula and the anterior cingulate cortex (ACC) are two regions that couple and form the core regions of the SN (Di Domenico & Ryan, 2017). Salience judgements can be affected by the insula because of the close connection with all the sensory and association cortices (Perlovsky & Levine, 2012). The insula may also selectively amplify neural signals of important events for the effective deployment of cognitive resources; while participating in creative tasks, the salience system and insula regulate emotion during the formation of higher level abstract thoughts (Di Domenico & Ryan, 2017). On the other hand, the ACC mediates conflicting or ambiguous information about choices or rules between options, and this ACC activation may then activate the dlPFC which tends to selectively highlight desirable attributes that are relevant to the task performance (Perlovsky & Levine, 2012).

With regard to the interactions among the brain networks, SN has been observed to activate and deactivate with the ECN, which demonstrates that the SN and ECN facilitate disparate cognitive operations. The ECN nodes activate during cognitively challenging tasks involving working memory or judgment of goal directed behavior, whereas the SN distinguishes relevant stimuli in order to guide behavior (Menon & Uddin, 2010). Research findings also suggest that the right vlPFC and ACC regulate emotional modulation, as demonstrated in studies investigating the appraisal and evaluation of stimuli or self-regulation of emotional responses (Downar & Daskalakis, 2013; Pavuluri, Herbener, & Sweeney, 2005). Moreover, ECN nodes that show strong intrinsic functional coupling also show strong coactivation with the DMN during cognitively challenging tasks (Beaty et al., 2016). During working memory tasks, the DMN deactivates and the ECN typically show increased activation. The ECN and the DMN, though seemingly opposite, collaborate when producing complex cognitive processes, especially goal oriented, self-generated, creative thought. Accordingly, DMN, ECN, and SN may dynamically interact with each other during the complex thinking process of product-based creativity tasks.

The Present Study

Contrary to most creativity fMRI studies that used divergent thinking tasks, this study employed product-based creativity tasks that emphasize both originality and valuableness. Based on creativity product-oriented theories and the aforementioned fMRI study findings, we postulate that product-based creative thinking involves dynamic interactions of top-down and bottom-up thinking processes that are closely related to the DMN, ECN, and SN. Accordingly, the DMN, ECN, and SN may cooperate dynamically to perform a creativity task that requires both originality and valuableness.

It has been suggested that, to better understand the insight process of creativity, it is essential to break down the cognitive mechanisms involved in creativity tasks when investigating the neuropsychological regions that are involved in these processes (Kowatari, Lee, Yamamura, Nagamori, Levy, Yamane, & Yamamoto, 2009). To provide clarity about these mechanisms, the present exploratory fMRI study of creativity examined brain processes as they occurred over time. This provided a clearer picture of what and how neural substrates and circuits were interacting during product-based creative thinking. The scanned thinking processes were evenly divided into six, ten second time windows, which identified the whole-brain network associated with creativity performance, and additionally explored other potential connections between regions identified in the literature review, as well as in our study. The duration of the creativity task and the time window were decided based on the results of a behavioral study which used product-based creativity tasks (Yeh, Kao, & Peng, 2013) and a fRMI study which used two-second time windows in a 12-second thinking period for a divergent thinking task (Beaty et al., 2015).

The following hypotheses were proposed as possible outcomes during the product-based creativity task: (a) Both brain hemispheres would be involved and interact during the creative thinking processes; while bottom-up thinking would propel the whole creative process, top-down thinking may actuate the later stages of product-based decision making; (b) the dlPFC and vlPFC in the ECN would play an important role; (c) the precuneus, dmPFC, and PCC in the DMN would be essential during creative thinking; (d) the ACC and insula in the SN would be integral to the process; and (e) there would be dynamic coupling of the identified core hubs of the ECN, DMN, and SN.

Methods

Participants

Twenty-five college students (12 males and 13 females), age 20-29 (24.08 ± 3.98 years) participated in this study. They were right-handed with normal or corrected-to-normal vision. They were also pre-screened for a history of previous neurological or neuropsychological disorders. The study was approved by the Research Ethics Committee of the university where the study was conducted, and written informed consent was obtained from all participants. Approximately $25 USD was rewarded for participation.

Stimuli of Creative Thinking

"The Product-Based Figural Creativity Test" (PB-FCT) (Yeh et al., 2013) was adapted in this study to measure the participants' creative thinking processes. The original PB-FCT included three, five minute subtests in which participants were requested to design and draw as many original and valuable products as possible, based on three given figures: C, ㄇ, and ×. C is an English alphabet, ㄇ is a Chinese alphabet, and × is a commonly seen symbol across cultures. The three figures are designed to test whether the participants' thinking can escape from the restrictions of alphabets or stereotyped thinking and inspire creatively designed products. The scoring norm for the PB-FCT was established based on a sample of 407 college students, in which a total of 1,074 varied responses were obtained (Yeh et al., 2013). Two indices were measured in the PB-FCT: originality and valuableness. Based on a sample of 115 college students, the correlations between originality and valuableness for C, ㄇ, and × were 0.755, 0.822, and 0.785, *p*s < 0.001 (Yehet al., 2013). The originality and the valuableness of the PB-FCT were also correlated with fluency (0.675 and 0.736, *p*s < 0.001, *N* = 23) and the originality (0.565 and 0.711, *p*s < 0.001, *N* = 23) in the New Creative Thinking Test (Wu, 1998) which is a divergent thinking test.

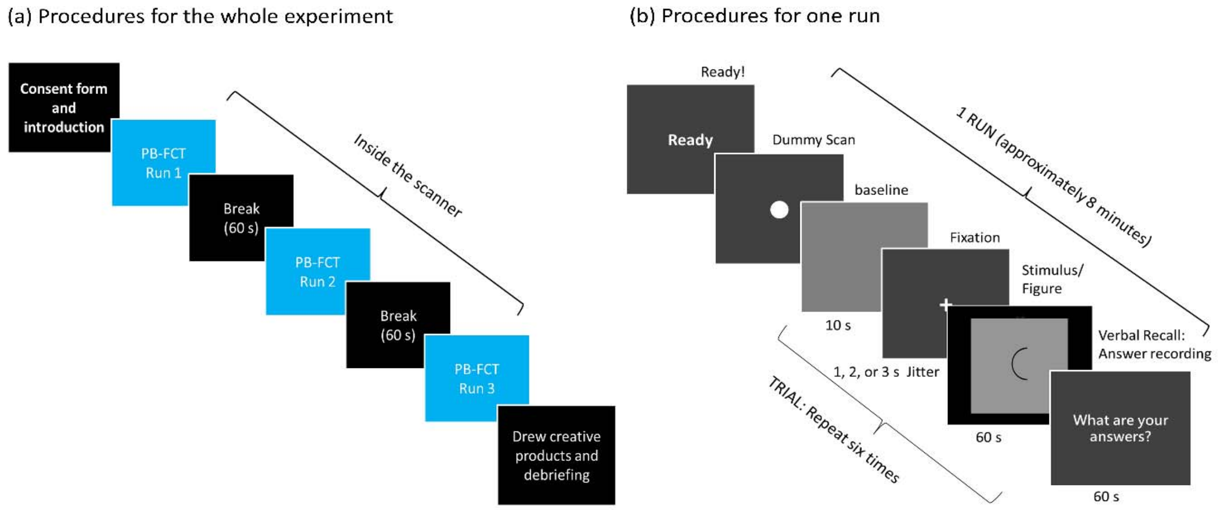
In the present fMRI study, during each trial the stimulus of C, ㄇ, or × was presented for 60 seconds, which was discovered to be an appropriate amount of time to complete the task (Yeh et al., 2013). Yeh et al. (2013) found that the average number of responses over 15 minutes was 13.15 (*SD* = 4.26, *N* = 407). The participants in this study were requested to think about "one" original and multi-functional product inspired by the given stimulus within one minute.

Experimental Design and Procedures

After filling out the consent form and required personal information, the participants received a brief introduction with a practice session of the in-scan tasks, and were instructed to think about "one" original and multi-functional product for each given stimulus. The within-subject block-design fMRI experiment requested participants to complete the PB-FCT, which contained three runs that lasted approximately eight minutes per run, totaling about 24 minutes of scanning time per participant.

At the start of each run, "ready" was presented on the screen, followed by a dummy scan, and a 10 second grey screen that functioned as baseline. Then, randomly jittered inter-trial intervals of one, two, or three seconds of fixation was shown. At this point in the run, the first stimulus was presented for 60 seconds. Within each run, there were six trials where the same figure, or stimulus, was presented six times, either C, ㄇ, or × and the order was randomly assigned per participant. The stimulus of C, ㄇ, and × was not randomly presented within a run because it might have caused confusion during the 60 second verbal recall answer recording stage at the end of each run; moreover, such design corresponds to the format of how typical divergent thinking tests are administered.

During the verbal recall answer recording stage, participants were instructed to speak through the MRI-compatible microphone that was placed by their mouths to record the name, and functions of the creative product they mentally designed during the stimulus presentation trials. The researcher then recorded their answers on a paper-and-pencil version of the creativity test. To prevent exhaustion, there was a 60-second rest or break period between runs. Following the fMRI scans, the participants drew the creative products they designed. The in-scan processes are depicted in Figure 1. All participants reported no difficulties in viewing stimuli or hearing instructions during the fMRI scan.


(a) Procedures for the whole experiment

(b) Procedures for one run

Figure 1. The experiment procedures and the PB-FCT in-scan procedures.

Data Acquisition and Image Analyses

The fMRI data were acquired on a 3T Siemens with a 32-channel head coil. The visual stimuli were displayed through a Hitachi CP-SX635 projector. Functional images were obtained with a T2*-weighted gradient echo-planar imaging sequence (voxel size, 4 × 4 × 3 mm^3). Each volume contained 34 transverse slices of 3 mm thickness that were oriented parallel to the anterior and posterior commissure (AC-PC) line and covered the whole brain (TR = 2,000 ms, TE = 24 ms, flip angle = 90°, FOV = 256 mm, 64 × 64 matrix, and in-plane resolution = 4.0 × 4.0 mm^2). Moreover, high-resolution T1-weighted structural images were acquired using a 3D MPRAGE pulse sequence: TR = 1,560 ms, TE = 3.30 ms, flip angle = 15.0°, 256 × 256 voxel matrix, FOV = 256 mm, 192 contiguous axial slices, thickness = 1.0 mm, and in-plane resolution = 1.0 × 1.0 mm^2. In this study, the first two TRs in each functional run were discarded to avoid T1 equilibrium effects. Each functional run acquired 216 volumes.

Data analysis was performed using SPM8. At the single-participant level, a general linear model was applied to the fMRI time series, where stimulus onset was convolved with SPM8's canonical hemodynamic response function. In order to understand specific stages of product-based creative thinking which requires more thinking time than the commonly used divergent thinking tasks (e.g., alternative uses), we analyzed the brain activation of six time windows (T1 to T6; each included 10 s) during the 60-second creative thinking. In addition, with this thinking period, a time-window of 10 seconds is proportionally similar to Beaty et al.'s (2015) design in which two-second time windows was used in a 12-second thinking period. Individual statistical maps (fixed effect) of the six main time windows and baseline control conditions were evaluated for each participant using the general linear model (GLM). In a first level analysis (single subject analyses), the six different time-windows event types (T1-baseline, T2-baseline, T3-baseline, T4-baseline, T5-baseline, and T6-baseline) were defined and parameter estimates for each regressor were calculated for each voxel. Task covariates were boxcar wave-forms convolved with an estimate of the blood oxygenation level-dependent (BOLD) hemodynamic transfer function. To remove motion-related artifacts, we included six motion parameters as regressors/nuisance covariates of no interest in the first level general linear model. Group analysis was done by obtaining contrast images using a second-level random-effects model. For the whole brain analyses, a significance level in which a voxel-wise threshold of $p < 0.005$ and a cluster threshold of $p < 0.05$ for family wise error rate (FWE corrected) were employed.

Two ECN (dlPFC and vlPFC), three DMN (precuneus, dmPFC, and PCC), and two SN (ACC and insula) brain regions were predefined as regions of interest (ROIs) in this study based on literature review. To examine the activation of these ROIs during the creativity tasks, ROI analyses were performed. In this ROI analysis, anatomical ROI maps were generated using WFU Pick Atlas Tool software that generates seven ROIs masks (Maldjian, Laurienti, Kraft, & Burdette, 2003). The resulting mask of creativity task was associated with brain regions in the predefined ROIs. The study also included a region in the ROIs for each contrast. ROI analyses were conducted using small volume correction (SVC) with a significance level of $p < 0.005$ for magnitude of activation and extent threshold of 10-mm sphere on each of the specified regions (Shah, Erhard, Ortheil, Kaza, Kessler, & Lotze, 2013). The significant activation level was set at a peak-level threshold of $p < 0.05$ FWE (family-wise error rate).

Finally, the present study conducted psychophysiological interaction (PPI) analyses to investigate functional connectivity among the ECN, DMN, and SN system. PPI analyses are regression-based connectivity analyses that examine changes in the contribution of activation in one brain region (i.e., seed region) to another based on changes in the psychological context. For each participant and seed region, the first eigenvariate time course of the seed volume of interest was extracted from a 10-mm radius sphere around the center of the predetermined coordinates as implemented in SPM8 in the first level. The significant activation level was set at a voxel-wise threshold of $p < 0.005$ and a cluster threshold of $p < 0.05$ for family wise error rate (FWE corrected) which were employed.

Results

Preliminary Analyses

The employed creativity test includes three types of stimuli: C, ⊓, and ×, in which participants were requested to design original and functional products. The score of each designed product was calculated by originality (0 to 4 points) × valuableness (0 to 3 points). Originality is the sum of “rareness” of a response (0 points: $\geq 5\%$; 1 point: $\geq 2\%$ and $< 5\%$; 2 point: $\geq 1\%$ and $< 2\%$; 3 points: $< 1\%$) and the specialty of the designed product (0 or 1 points). “Valuableness” was scored by the number of different functions of a response when it was valid (appropriate or useful). When a response was not a designed product (e.g., a fresh apple), it was regarded as invalid. The specific scoring rules were: 0 = not valid; 1 = has only one function; 2 = has two different functions; and 3 = has three or more different functions. The total score of creativity is the sum of scores of the designed products. The score of originality was calculated based on a validated scoring norm (Yeh et al., 2013); the score of product specialty and valuableness was rated based on the consensus of two trained research assistants. With six trials for each type of stimuli, the possible score for each stimuli was 0 to 72 points (originality × valuableness × 6 trials).

Analyses of behavioral data through Repeated Measures Analysis of Variance revealed that the participants’ creativity performances were not significantly different across the three tasks of creativity, Wilks’

Λ (2, 23) = 0.971, $p = 0.715$, $\eta^2_p = 0.029$. The mean (*M*) and standard deviation (*SD*) were as follows: C tasks: M = 12.40 (*SD* = 2.48); ⊓ tasks: *M* = 11.60 (*SD* = 4.20); and × tasks: *M* = 11.92 (*SD* = 3.80). Examples of the participants' creative performances are shown in Figure 2.

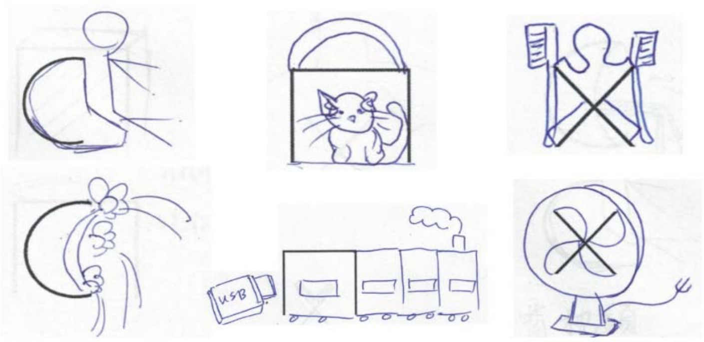


Figure 2. Examples of the participants' creative performances.

The Whole-Brain Analysis Results

The scanned data were first divided into six time periods (T1 to T6; 10 seconds in each session), by which the contrasts between different time periods and baseline (a grey picture) were first analyzed. The activated brain regions are depicted in Figure 3.

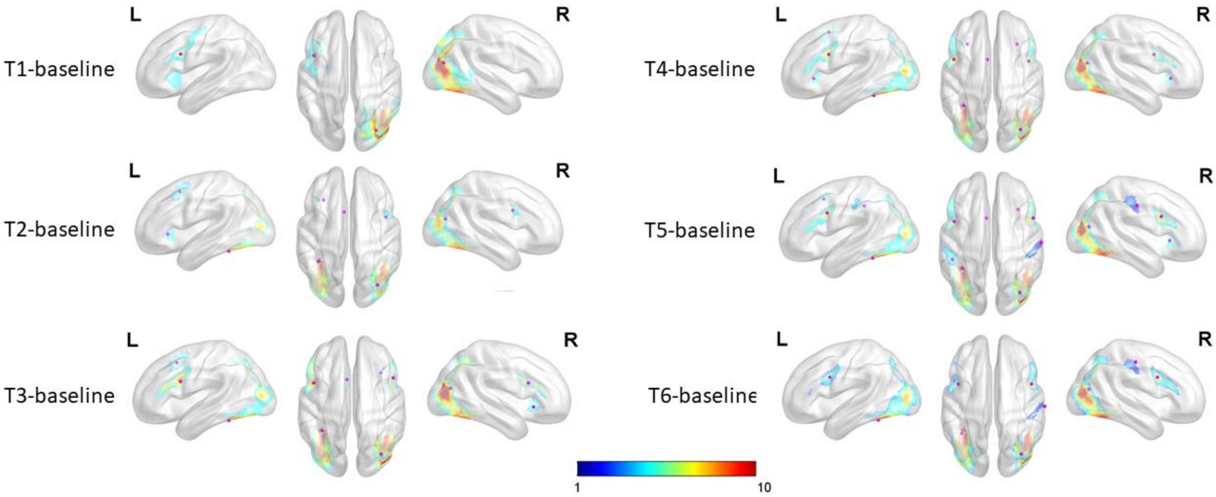


Figure 3. Activated brain regions of whole-brain analyses for T1-baseline to T6-baseline. Note: For the whole brain analyses, significant peak nodes with a voxel-wise threshold of $p < 0.005$ and a cluster threshold of $p < 0.05$ for family wise error rate (FWE corrected) were employed. Brain activations are overlaid in color on axial slices of the MNI template brain. The location of all spherical ROIs used as nodes in the whole brain GLM analysis are visualized with the BrainNet Viewer (http://www.nitrc.org/projects/bnv/).

The main results were: (1) T1-baseline to T6-baseline all involved both the right and the left brain activities as compared to the baseline. (2) The right precuneus (BA 31) and left middle frontal gyrus (BA 9) were first activated in T1 contrast. Then, three common brain regions were activated in T2 to T6 contrasts: left fusiform gyrus (BA 37), right IFG (BA 9), and right middle temporal gyrus (BA 39). (3) The left IFG was activated in T3 through T6 contrasts (BA 9). (4) The insula (BA 13) was activated in T2, T4, and T5 contrasts.

(5) The right precentral gyrus (BA 6) was activated in T5 and T6 contrasts. (6) The left dmPFC was activated in T2 and T3 contrast. In addition, the left ACC was activated in T5 contrast.

When looking at the brain activation from the viewpoints of ECN, DMN, and SN, the results reveal that the DMN (right precuneus, left dmPFC, or left IPL) was activated from T1 to T3 and T5, whereas the ECN (left middle frontal gyrus or right IFG) was activated in T1 and T3. Finally, the SN (left ACC or bilateral insula) was activated at T2, T4, and T5.

Analyses of ROI

In this study, two ECN (dlPFC, vlPFC), three DMN (dmPFC, Precuneus, and PCC) and two SN (ACC and Insula) were predefined as regions of interest (ROIs). The results revealed that the insula and precuneus were activated across time windows, whereas the right PCC and bilateral dmPFC were only activated in T1. For the ECN, the bilateral vlPFC was activated in T1 to T5, right vlPFC was activated in T6; ACC was only activated in T1; and the right dlPFC was activated in T1 and T2 (see Figure 4).

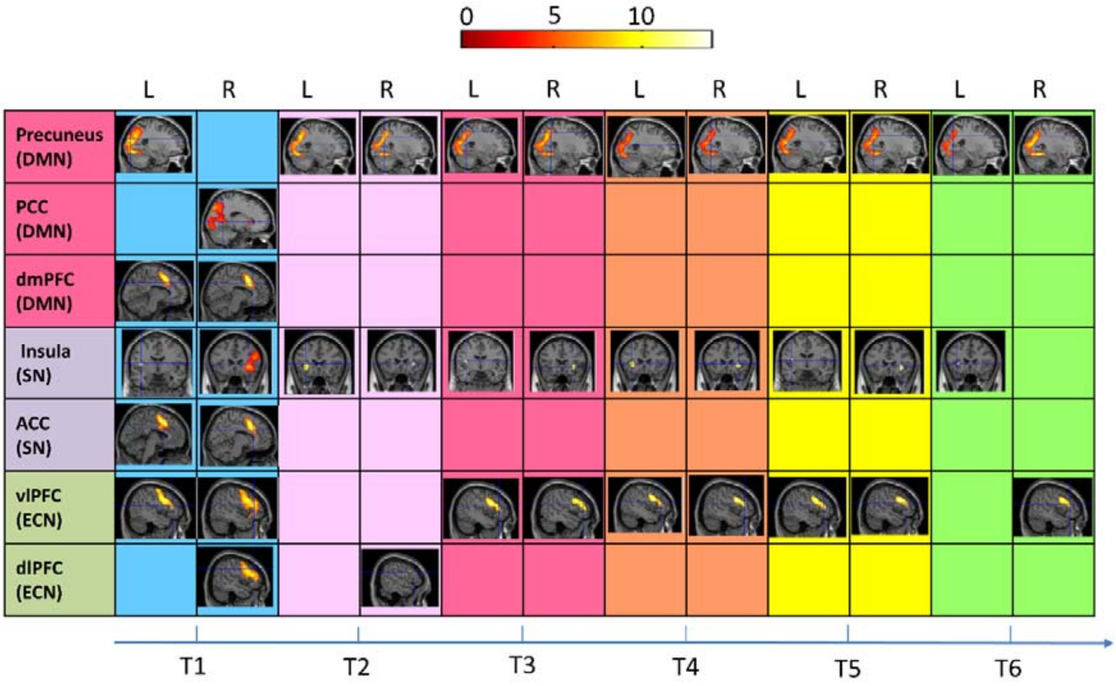
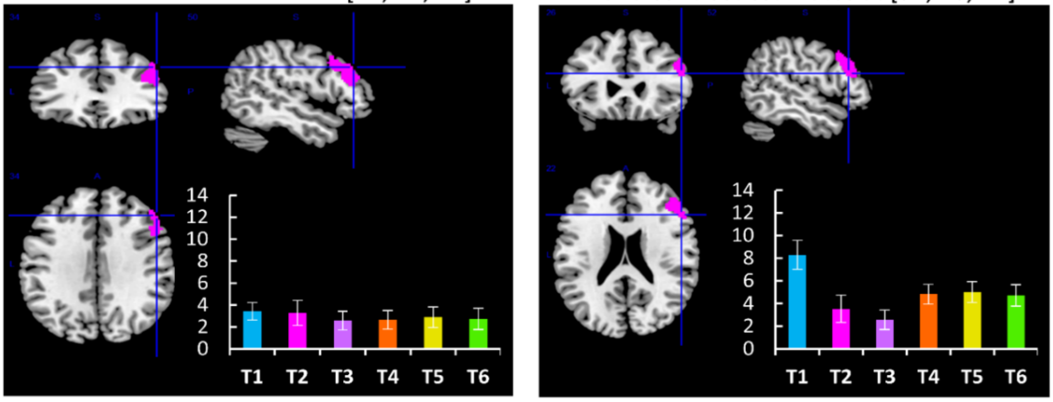


Figure 4. Activated brain regions of ROI analyses for T1-baseline to T6-baseline. Note: Brain regions show activation for contrasts of T1-baseline to T6-baseline. ROI analyses were conducted using small volume correction (SVC) with a significance level of $p < 0.005$ for magnitude of activation and extent threshold of 10-mm sphere on each of the specified regions. Significant activations at a $p < 0.05$ FWE-corrected level.

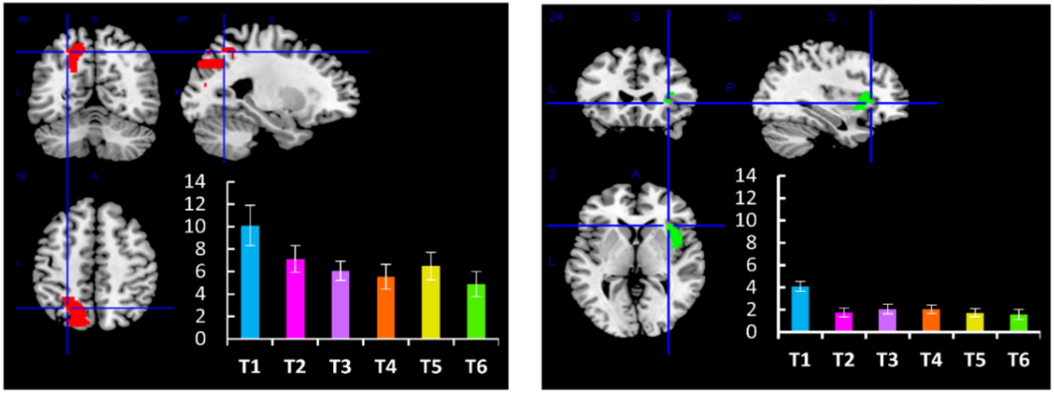
Analyses of Dynamic Connectivity

Based on our ROI results and our interest in this study, we used the right dlPFC, right vlPFC, left precuneus, and right insula as the seed to conduct functional connectivity analyses in time windows through the PPI technique. In these analyses, Marsbar (version 0.44) was employed to extract the mean contrast estimate values (beta value) of the four seed significant activation clusters for each time window that were contrasted against baseline [(T1-baseline) to (T6-baseline)]. These values represent the parameter estimates averaged over all voxels within the functional activation cluster and are only presented as descriptive statistics. The seed voxel locations and contrast estimates for each functional connectivity analysis are illustrated in Figure 5, and the activated brain regions of functional connectivity for T1-baseline to T6-baseline are displayed in Figure 6.



(a)Seed voxel localization on right dlPFC and contrast estimates at [50, 34, 34]

(b) Seed voxel localization on right vlPFC and contrast estimates at [52, 26, 22]



(c) Seed voxel localization on left Precuneus and contrast estimates at [-26, -60, 50]

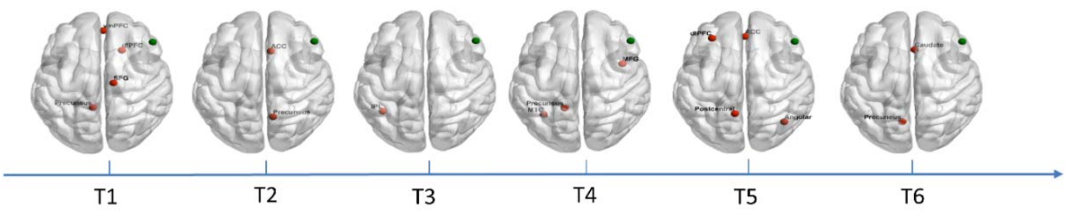
(d) Seed voxel localization on right Insula and contrast estimates at [34, 24, 2]

Figure 5. Seed voxel locations and mean contrast estimates (beta value). Note: Y-axis is the mean contrast estimate (beta value), and X-axis is the contrast of six time windows. ROI analyses were conducted using small volume correction (SVC) with a significance level of $p < 0.005$ for magnitude of activation and extent threshold of 10-mm sphere on each of the specified regions. Significant activations at a $p < 0.05$ FWE-corrected level. Bar-charts show the mean contrast estimate values (beta value) for regions of interests (ROIs) in six time-windows.

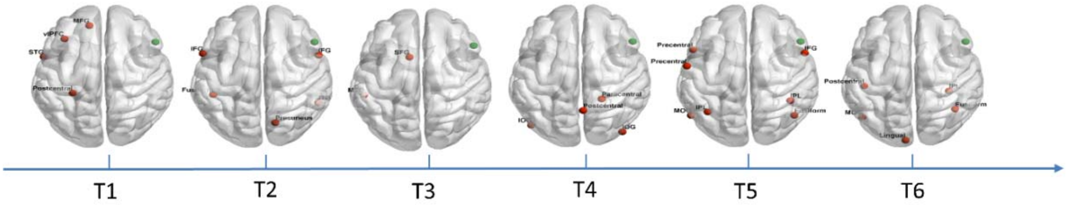
The analyses of the right dlPFC seed and the right vlPFC seed revealed that these two ECN regions had coupling activation with the DMN and SN at different thinking stages. The right dlPFC coupled with the left dlPFC in the ECN at T5, the DMN (left precuneus, right precuneus, right vmPFC, or left IPL) from T1 to T4 and T6, and the SN (right ACC) at T2 and T5. The right vlPFC coupled with the left vlPFC in the ECN at T1, the decision-making network in the ECN (left superior frontal gyrus, left precentral gyrus, or left postcentral gyrus) at T3 and T5, and the DMN (right precuneus, right IPL, or left IPL) at T2, T5, and T6.

The seed analyses of the left precuneus revealed coupling with the DMN (right precuneus or lateral IPL) from T1 to T6, and the ECN (left dlPFC or left RLFPC) from T1 to T3. Finally, the seed analyses of the insula revealed activated coupling with the SN (left ACC or right ACC) from T1 to T3, the ECN (right OFC) in T2, and the DMN (left dmPFC or left IPL) in T1 and T2.

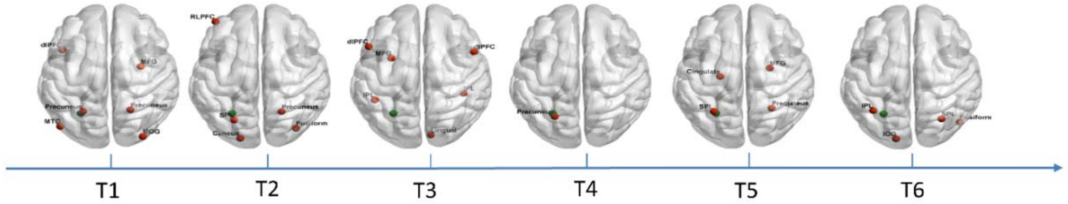
(a) Seed: right dlPFC (50, 34, 34)



(b) Seed: right vlPFC (52, 26, 22)



(c) Seed: left Precuneus (-26,-60, 50)



(d) Seed: right Insula (34, 24, 2)

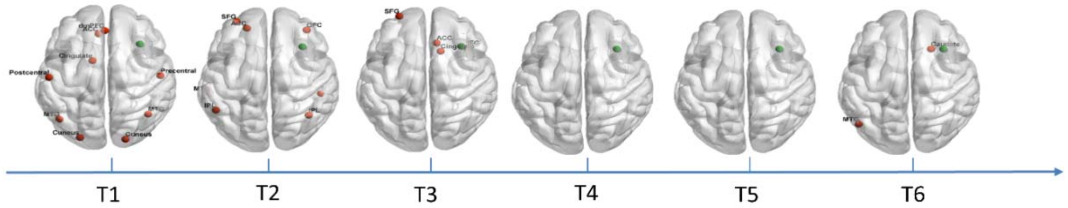


Figure 6. Activated brain regions of functional connectivity for T1-baseline to T6-baseline. Note: For PPI analyses, the seed nodes (green peak) were conducted using small volume correction (SVC) with a significance level of $p < 0.005$ for magnitude of activation and extent threshold of 10-mm sphere on each of the specified regions. Significant activations at a $p < 0.05$ FWE-corrected level. The red nodes were the activated regions resulting from the functional connectivity of the seeds through PPI analyses. The locations of all spherical ROIs used as nodes in the GLM analysis are visualized with the BrainNet Viewer (http://www.nitrc.org/projects/bnv/).

Discussion

The present study exploring dynamic relationships among the ECN, DMN, and SN applied three brain scanning runs, which had a series of 60 second trials that presented figural stimuli. Each stimuli presentation was evenly divided into 6, 10 second time windows to identify the important brain regions and networks associated with the product-based creativity tasks. The whole brain analyses revealed that T1 to T6 all involved both right and left brain activities as compared to baseline. Notably, the right MTG (BA 39), left fusiform gyrus (BA 37), lateral IFG (BA 9), and lateral insula (BA 13) were fundamental to the entire thinking process. Moreover, while the precuneus and left dmPFC seem to play important roles in earlier stages, the left IFG (BA

9) seems to play a crucial role in later stages. When focused on brain regions of the ECN, DMN, and SN, we found that the DMN (right precuneus, left dmPFC, or left inferior parietal lobule) is fundamental to the entire process of creative thinking, whereas the ECN (left middle frontal gyrus or right IFG) and the SN (left ACC or bilateral insula) take turns collaborating with the DMN.

To further confirm whether the seven identified hubs of the concerned neural networks play critical roles during the creative thinking, we conducted ROI analyses. The continued activation of the precuneus, or dmPFC, throughout the process confirmed the fundamental role of the DMN during creative thinking. Interestingly, the insula was activated across all of the time windows; moreover, the activation of vlPFC and the dlPFC illustrated the importance of the ECN during creativity. The other concerned ROIs were activated at the beginning of creative thinking. These results imply a great possibility of functional connectivity among the ECN, DMN, and SN. Based on the ROI results, we chose the right dlPFC, right vlPFC, left precuneus, and right insula as seeds to conduct functional connectivity analyses. After cross-checking with the results of whole brain and ROI analyses, we found that the ECN, DMN, and SN were all involved in the product-based creative thinking across the time windows, and the ECN (the right dlPFC or the right vlPFC) was coupling with the DMN and SN at different stages.

Overall, the findings in this study support the hypotheses we proposed. The interactions of the DMN, ECN, and SN support the argument that creativity networks consist of several frontal, temporal, and parietal regions (Jung, Mead, Carrasco, & Flores, 2013), in addition to creativity involving several core hubs of the DMN and the ECN brain regions, which are linked to cognitive control and spontaneous imaginative processes (Beaty et al., 2015). In this study, the participants were requested to think about "one" original and multi-functional product inspired by the given stimulus within one minute. Seed analyses revealed a trend that bottom-up thinking which is related to DMN and the SN attenuates as time proceeds during the creativity task. Top-down thinking which is related to vlPFC gets stronger at the later stages, suggesting that top-down thinking is critical to product-based decision making at a later stage. This trend reflects the nature of our employed creativity tasks which emphasizes both originality and valuableness. Briefly speaking, this trend operates within the assumption that both top-down and bottom-up thinking remain active throughout the creative task, although their degree of activation varies dynamically. These observations can be seen in Figures 3 and 4.

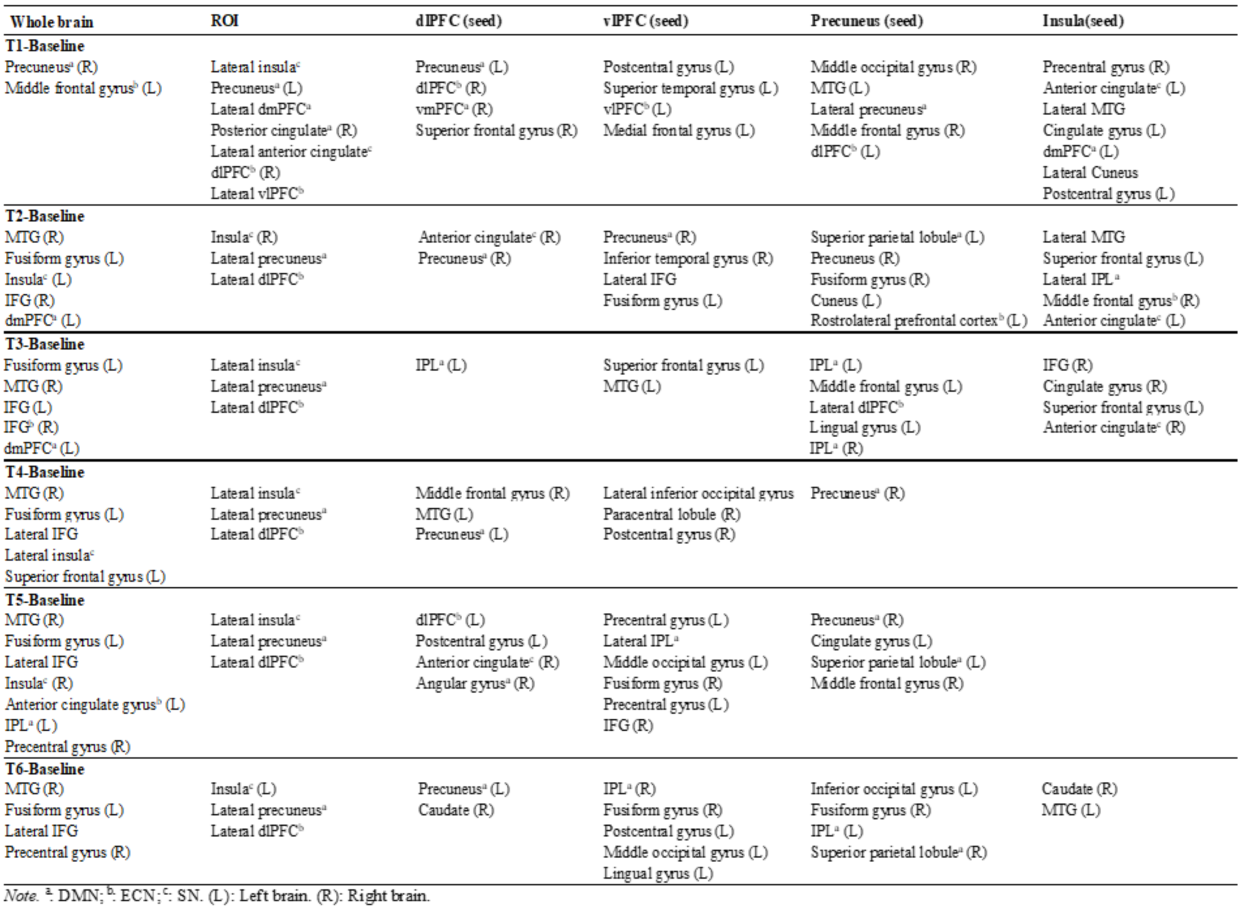
Integrating the similarity of brain activation in the six time windows, the cognitive functions of activated brain regions, and the stage theories of creativity (e.g., Amabile, 1996; Lin & Vartanian, 2017; Yeh, 2017; Ward et al., 1999), we propose a tentative three-stage model of product-based creativity. The stages are "exploration and association" (T1 and T2), "incubation and insight" (T3 and T4), and "evaluation and decision making" (T5 and T6). Moreover, top-down thinking that relates to cognitive control, emotional regulation, attention, and working memory, as well as bottom-up thinking that relates to spontaneous thoughts, memory and emotion association, occurs throughout the three stages. The integrated critical brain regions found in all the analyses in this study are shown in Figure 7 and Figure 8.

In the "exploration and association" stage, in addition to the right MTG, all the ROI selected in this study were activated, and strong connectivity among the ECN, DMN, and SN were identified. The strong activation of large-scale brain regions illustrates intensive exploration and association at this stage. Activation of the SN, as well as its coupling with the DMN and ECN, supports the finding that salience-related dopaminergic activity energizes exploration in response to the incentive value of the possibility of gaining information (DeYoung, 2013). In addition, the activation of the dmPFC and PCC (two major nodes of the DMN) suggests that the participants may experience internally-focused, self-referential cognition, and top-down regulation (Hare, Camerer, & Rangel, 2009; Di Domenico & Ryan, 2017; Takeuchi, Sekiguchi, Taki, Yokoyama, Yomogida, Komuro, & Kawashima, 2010; Wei, Yang, Li, Wang, Zhang, & Qiu, 2014) during exploration and association of creative ideas. The activation of the dlPFC and vlPFC in the ECN, on the other hand, suggests the importance of working memory and executive functions during cognitively demanding tasks (Dixon & Christoff, 2014).

At the stage of "incubation and insight", the right MTG, lateral IFG, lateral precuneus, lateral insula, left fusiform gyrus, and lateral vlPFC continue to be activated; connectivity among the dlPFC or vlPFC, DMN, and SN, however, disappeared. Notably, the dlPFC deactivated while the left superior frontal gyrus and lateral IPL joined in. The deactivation of the dlPFC and the decoupling of the ECN with other networks may inhibit conscious thought and results in mind wandering, which then evokes spontaneous thinking and insight (Beaty et al., 2016; Sawyer, 2011). Meta-analytic studies found strong links between the occurrence of spontaneous thought processes and activation in brain regions comprising the DMN and other non-DMN regions, such as the bilateral posterior IPL, frontoparietal control network areas, and the vlPFC; DMN activation alone is insufficient to provoke spontaneous thought (Fox, Spreng, Ellamil, Andrews-Hanna, & Christoff, 2015). The coupling activation within the DMN (left precuneus and lateral IPL) as well as the activation of the vlPFC suggests that spontaneous and bottom-up thoughts occur at this stage.

At the stage of "evaluation and decision making", the right MTG, left IFG, lateral precuneus, lateral insula, left fusiform gyrus, and left vlPFC maintained activation, while the precentral gyrus (BA 6) and postcentral gyrus (BA 2) joined in the process. The precentral gyrus (BA 6) and the postcentral gyrus (BA 2) are related to decision-making (Litt, Plassmann, Shiv, & Rangel, 2010; Pisauro, Fouragnan, Retzler, & Philiastides, 2017). Evaluation and decision making involves eliciting internal attention or top-down activity (Hao et al., 2016). The coupling of the DMN and the vlPFC found in this study supports that executive and default regions associated with creative evaluation (Ellamil et al., 2012). One significant finding of this study was that the activation of vlPFC got stronger across time windows, suggesting the vlPFC plays an important role in value-based decision making and convergent thinking. The synthesis of these results from the whole-brain, ROI, and connectivity analysis indicates a great cooperation between brain regions involved in cognitive control, working memory, and decision making.

Notably, the right MTG, left fusiform gyrus, lateral insula, lateral precuneus, lateral vlPFC, and right IFG remained active during all the three stages of product-based creative thinking. The activation of these brain regions suggests that emotion and working memory influence creativity throughout the thinking process. It is suggested that the MTG and fusiform gyrus have strong connections to function during emotion identification and emotional expression (Vartanian & Goel, 2004; Vartanian et al., 2013), the insula integrates information with incoming sensory inputs (Menon, 2015) and emotional awareness with cognitive control (Simmons, Avery, Barcalow, Bodurka, Drevets, & Bellgowan, 2013), and the precuneus is linked to emotional and memory-related processes (Lundstrom, Ingvar, & Petersson, 2005; Reske et al., 2009). Moreover, the vlPFC is a key region for evaluating the emotional significance of external stimuli (Downar & Daskalakis, 2013). The continued activation of these brain regions supports that emotion is an integral part of creativity, and that emotion regulation is critical to attention and flexibility during creative thinking (Baas et al., 2008; Fredrickson et al., 2008). On the other hand, the vlPFC plays an important role in mediating working memory which is closely related to selective attention (Burnham, Sabia, & Langan, 2014; Dixon & Christoff, 2014). The IFG involves in sustained attention, cognitive flexibility, working memory, goal-directed planning (Zhu et al., 2016), as well as the maintenance of working memory and memory retrieval (Beaty et al., 2015; Wei et al., 2014). Creative processes largely comprise the retrieval, integration, and retention of knowledge as well as close connections between cues and the activation of knowledge (Yeh, 2017); activation of the attention system and the function of working memory therefore contributes to creative performance.



Whole brain	ROI	dlPFC (seed)	vlPFC (seed)	Precuneus (seed)	Insula(seed)
T1-Baseline					
Precuneus[a] (R) Middle frontal gyrus[b] (L)	Lateral insula[c] Precuneus[a] (L) Lateral dmPFC[a] Posterior cingulate[a] (R) Lateral anterior cingulate[c] dlPFC[b] (R) Lateral vlPFC[b]	Precuneus[a] (L) dlPFC[b] (R) vmPFC[a] (R) Superior frontal gyrus (R)	Postcentral gyrus (L) Superior temporal gyrus (L) vlPFC[b] (L) Medial frontal gyrus (L)	Middle occipital gyrus (R) MTG (L) Lateral precuneus[a] Middle frontal gyrus (R) dlPFC[b] (L)	Precentral gyrus (R) Anterior cingulate[c] (L) Lateral MTG Cingulate gyrus (L) dmPFC[a] (L) Lateral Cuneus Postcentral gyrus (L)
T2-Baseline					
MTG (R) Fusiform gyrus (L) Insula[c] (L) IFG (R) dmPFC[a] (L)	Insula[c] (R) Lateral precuneus[a] Lateral dlPFC[b]	Anterior cingulate[c] (R) Precuneus[a] (R)	Precuneus[a] (R) Inferior temporal gyrus (R) Lateral IFG Fusiform gyrus (L)	Superior parietal lobule[a] (L) Precuneus (R) Fusiform gyrus (R) Cuneus (L) Rostrolateral prefrontal cortex[b] (L)	Lateral MTG Superior frontal gyrus (L) Lateral IPL[a] Middle frontal gyrus[b] (R) Anterior cingulate[c] (L)
T3-Baseline					
Fusiform gyrus (L) MTG (R) IFG (L) IFG[b] (R) dmPFC[a] (L)	Lateral insula[c] Lateral precuneus[a] Lateral dlPFC[b]	IPL[a] (L)	Superior frontal gyrus (L) MTG (L)	IPL[a] (L) Middle frontal gyrus (L) Lateral dlPFC[b] Lingual gyrus (L) IPL[a] (R)	IFG (R) Cingulate gyrus (R) Superior frontal gyrus (L) Anterior cingulate[c] (R)
T4-Baseline					
MTG (R) Fusiform gyrus (L) Lateral IFG Lateral insula[c] Superior frontal gyrus (L)	Lateral insula[c] Lateral precuneus[a] Lateral dlPFC[b]	Middle frontal gyrus (R) MTG (L) Precuneus[a] (L)	Lateral inferior occipital gyrus Paracentral lobule (R) Postcentral gyrus (R)	Precuneus[a] (R)	
T5-Baseline					
MTG (R) Fusiform gyrus (L) Lateral IFG Insula[c] (R) Anterior cingulate gyrus[b] (L) IPL[a] (L) Precentral gyrus (R)	Lateral insula[c] Lateral precuneus[a] Lateral dlPFC[b]	dlPFC[b] (L) Postcentral gyrus (L) Anterior cingulate[c] (R) Angular gyrus[a] (R)	Precentral gyrus (L) Lateral IPL[a] Middle occipital gyrus (L) Fusiform gyrus (R) Precentral gyrus (L) IFG (R)	Precuneus[a] (R) Cingulate gyrus (L) Superior parietal lobule[a] (L) Middle frontal gyrus (R)	
T6-Baseline					
MTG (R) Fusiform gyrus (L) Lateral IFG Precentral gyrus (R)	Insula[c] (L) Lateral precuneus[a] Lateral dlPFC[b]	Precuneus[a] (L) Caudate (R)	IPL[a] (R) Fusiform gyrus (R) Postcentral gyrus (L) Middle occipital gyrus (L) Lingual gyrus (L)	Inferior occipital gyrus (L) Fusiform gyrus (R) IPL[a] (L) Superior parietal lobule[a] (R)	Caudate (R) MTG (L)

Note. [a]: DMN; [b]: ECN; [c]: SN. (L): Left brain. (R): Right brain.

Figure 7. Activated brain regions of whole-brain, ROI, and functional connectivity analyses.

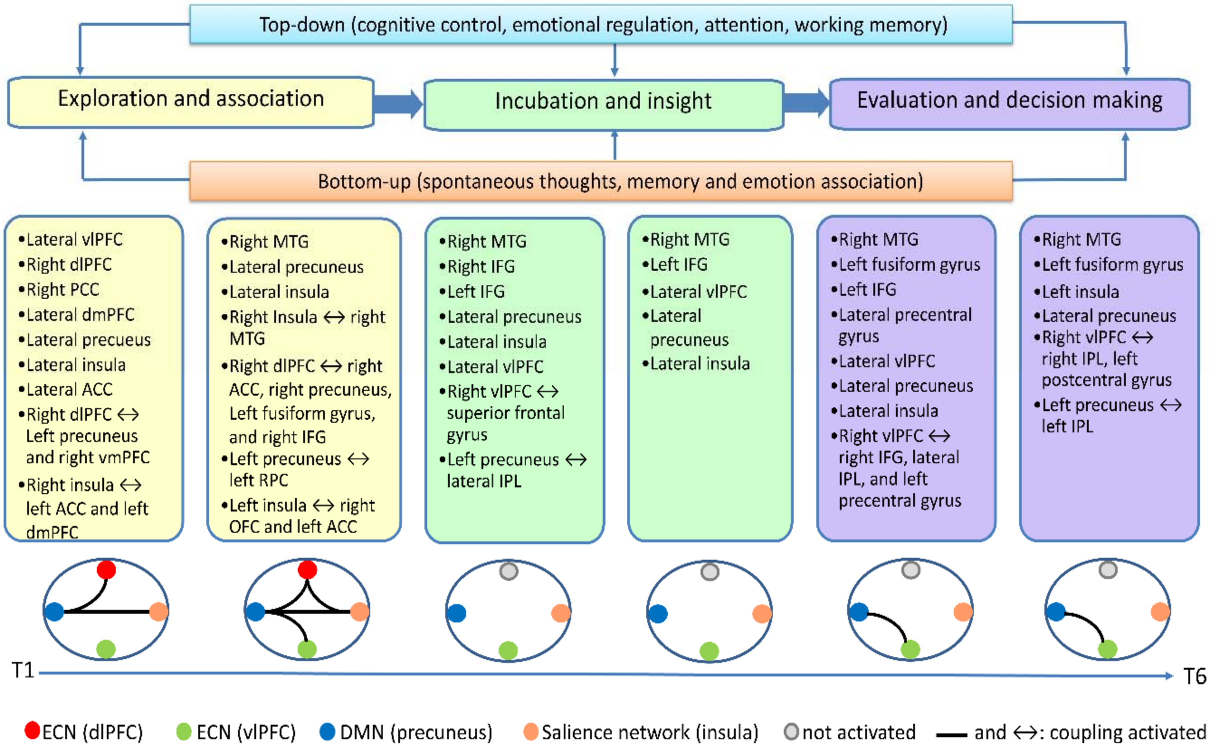


Figure 8. An integrated model and underlying neural substrates during product-based creative thinking. Note: Integrated results show similarities of brain activation between T1 and T2, between T3 and T4, and between T5 and T6.

Conclusions

The neural bases of creative processes have recently been investigated among a growing body of empirical evidence. Consensus of creativity research suggests that the measurement of both originality and valuableness of creative products is necessary when designing creativity tasks. However, few studies have employed product-based creativity tasks to explore underlying neural substrates and connectivity during creative thinking over time. We therefore employed the ROI analyses to confirm the activation of seven identified brain regions during product-based creative thinking, in addition to the whole-brain analysis. Moreover, the utilization of PPI techniques examining the interplay between the DMN, ECN, and SN during product-based creativity tasks through time windows had yet to be conducted prior to this study.

The integrated results support our hypotheses and shed light on the mechanisms underlying dynamic connectivity between the ECN, DMN, and SN during product-based creative thinking, and demonstrate dynamic relationships among these brain networks over time. Based on our integrated results, we propose a three-stage model of product-based creative thinking. Notably, the identified ROIs (especially insula, precuneus, and vlPFC) as well as the right IFG, right MTG, and left fusiform gyrus, are found to be fundamental across the stages during the product-based creative thinking. To conclude, product-based creative thinking involves dynamic interactions of bottom-up and top-down thinking. As bottom-up thinking weakens as time proceeds, top-down thinking gets stronger during the later stages; meanwhile, emotion and working memory seem to play important roles.

Limitations and Implications

Due to the limitation of instruments, we did not let participants draw out the products they thought of during the scan. After the scan, they verbally explained their thoughts that occurred during the brain scan, and then drew pictures of what they had imagined. Future studies can overcome this difficulty and examine whether drawing within the scanner activates different brain regions to drawing outside of it.

The implications of this finding are pertinent to questions relating to what makes people more or less creative, and why. Our experiment falls in line with this discovery and offers another perspective by employing varied creative tasks, and analyzing neural substrates over time. Among the few studies with time window analyses, our findings support Beaty et al. (2018) who advocate that more research within the specific realm of connectivity is needed. However, our results are different from Beaty et al.'s (2015) findings. First, we found that the DMN and SN only coupled during the first stage when participants tried to make associations with information. Second, we found that the ECN and DMN disconnected during the middle stage of incubation and insight, and then reconnected in the final stage of evaluation and decision making. These differences may result from the type of tasks utilized and the period of time allowed for responses. While Beaty et al. (2015) employed the typical divergent-thinking verbal tasks with a response time of 12 s, we used product-based visual tasks with an emphasis on producing a multi-functional original product within 60 s, which may be more valuable in creativity training outside the laboratory. Accordingly, our method provides a deep insight into the creative thinking process of generating valuable and original products in real life situations.

Finally, the three-stage model we propose is still tentative; more important brain regions can be included in ROI and connectivity analyses to verify and enrich the model. Nevertheless, this model provides a thinking frame for further research and classroom instruction. The right IFG, right MTG, and left fusiform gyrus that were active throughout all stages of our product-based creative thinking can be included in further studies.

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