



Evaluative and generative modes of thought during the creative process

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ABSTRACT

Psychological theories have suggested that creativity involves a twofold process characterized by a generative component facilitating the production of novel ideas and an evaluative component enabling the assessment of their usefulness. The present study employed a novel fMRI paradigm designed to distinguish between these two components at the neural level. Participants designed book cover illustrations while alternating between the generation and evaluation of ideas. The use of an fMRI-compatible drawing tablet allowed for a more natural drawing and creative environment. Creative generation was associated with preferential recruitment of medial temporal lobe regions, while creative evaluation was associated with joint recruitment of executive and default network regions and activation of the rostrolateral prefrontal cortex, insula, and temporopolar cortex. Executive and default regions showed positive functional connectivity throughout task performance. These findings suggest that the medial temporal lobe may be central to the generation of novel ideas and creative evaluation may extend beyond deliberate analytical processes supported by executive brain regions to include more spontaneous affective and viscerosensitive evaluative processes supported by default and limbic regions. Thus, creative thinking appears to recruit a unique configuration of neural processes not typically used together during traditional problem solving tasks.

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Introduction

What did Leonardo da Vinci, Albert Einstein, and Thomas Edison possess that allowed them to produce works and ideas that changed how we live our lives and understand the world? Creativity is a quintessential and uniquely human characteristic manifested in art galleries, concert halls, and science laboratories, as well as in everyday activities (Runco, 2004). Often defined in terms of its product, creativity is the ability to produce ideas that are both novel (original and unique) and useful (appropriate and meaningful) (Amabile and Tighe, 1993; Besemer and Treffinger, 1981; Bruner, 1962; Gardner, 1989; Sternberg, 1985). Paralleling this twofold definition of creativity, psychological findings have suggested a twofold creative process that includes generative and evaluative components (Basadur et al., 1982; Campbell, 1960; Finke et al., 1992; Israeli, 1962; Wallas, 1926). For example, one model of the creative process proposes that it begins with the generation of crudely formed ideas and associations, followed by their exploration through evaluation and testing (Basadur et al., 1982; Finke et al., 1992). Similarly, the creative process has been described as the “mutation” of a thought into many different variants

to generate ideas and the evaluation of the ideas to select the “fittest” or best variant (Campbell, 1960). Thus, the dichotomy between generation and evaluation appears to be ubiquitous in psychological theories of the creative process, with novel ideas produced during generative phases and their utility assessed during subsequent evaluative phases. This dichotomy is also present in artists' accounts of their own creative process, which they often describe as alternating between rough sketching of ideas and critiquing those ideas to guide the next cycle of sketching and critiquing (Fox, 1997; McMullan, 2010 Dec 2; Victore, 1997). The neural correlates of this distinction, however, have remained largely unknown, and revealing them could further our understanding of creativity and its component processes.

Do different neural networks and brain regions contribute differentially to creative generation and evaluation? While earlier neuroscientific studies of creativity emphasized large-scale brain distinctions such as hemispheric differences (Bekhtereva et al., 2000, 2001; Carlsson et al., 2000; Finkelstein et al., 1991; Martindale et al., 1984; Sperry, 1964) and frontal versus parietal lobe engagement in creative thinking (Bekhtereva et al., 2004; Chavez-Eakle et al., 2007; Fink et al., 2009; Fink and Neubauer, 2006; Geake and Hansen, 2005; Jung et al., 2010; Miller et al., 1998, 2000; Molle et al., 1996; Molle et al., 1999; Razoumnikova, 2000; Razoumnikova, 2007; Starchenko et al., 2003), recent findings point to the possible involvement of specific networks and brain regions in the different components of the creative process.

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One network that appears to contribute to creative thinking through its robust association with cognitive control is the executive network. Including, most prominently, the dorsolateral PFC (DLPFC) and dorsal anterior cingulate cortex (dACC), the executive network is specifically recruited during conditions of high cognitive control (Desimone and Duncan, 1995; Miller and Cohen, 2001). The DLPFC and dACC are known to be activated during a variety of creative tasks, including piano improvisation (Bengtsson et al., 2007; Berkowitz and Ansari, 2008), creative story generation (Bekhtereva et al., 2000, 2001; Howard-Jones et al., 2005), word association (Bekhtereva et al., 2004), divergent thinking (Carlsson et al., 2000; Seger et al., 2000), fluid analogy formation (Geake and Hansen, 2005), insight problem solving (Geake and Hansen, 2005; Kounios et al., 2008; Subramaniam et al., 2009), and visual art design (Kowatari et al., 2009). During these creative tasks, high cognitive control enables a deliberate, analytic mode of information processing that facilitates the evaluation of the utility of novel ideas (Howard-Jones and Murray, 2003) and allows individuals to focus on the pertinent task details and to select the relevant generated ideas (Dorfman et al., 2008; Gabora, 2010; Heilman et al., 2003; Lepine et al., 2005; Vartanian et al., 2007). Therefore, the executive network may contribute specifically to the evaluative mode of creative thought.

Another network that plays an important role during creative thought is the default network. It includes, most prominently, the medial prefrontal cortex (MPFC), posterior cingulate cortex (PCC)/precuneus, and temporoparietal junction (TPJ) (Raichle et al., 2001), which are frequently activated in creativity experiments. For example, enhanced TPJ activity has been found during divergent thinking tasks (Fink and Neubauer, 2006; Grabner et al., 2007), creative story generation (Bekhtereva et al., 2004), hypothesis generation (Jin et al., 2006), fluid analogy formation (Geake and Hansen, 2005), and remote associate insight problems (Jung-Beeman et al., 2004; Subramaniam et al., 2009). Creative story generation also recruits the MPFC (Howard-Jones et al., 2005), while insight problems activate both the MPFC and PCC/precuneus (Geake and Hansen, 2005; Jung-Beeman et al., 2004; Kounios et al., 2008; Subramaniam et al., 2009). Moreover, Limb and Braun (2008) found activation of the default network and deactivation of the executive network during improvisation by professional jazz pianists. However, with the exception of Limb and Braun's (2008) study, only parts of the default network, rather than the whole network, have been associated with creativity tasks.

There are two possibilities regarding the default network's role in creative generation and evaluation. On the one hand, because it is specifically activated during conditions of low cognitive control (Raichle et al., 2001; Shulman and Fiez, 1997), it may facilitate an associative mode of processing that supports the generation of novel ideas (Dorfman et al., 2008; Howard-Jones and Murray, 2003; Vartanian et al., 2007), thereby contributing to creative generation more than to creative evaluation. On the other hand, the default network may contribute more to creative evaluation than to generation, through its role in affective and viscerosensitive evaluative processes demonstrated during emotional paradigms. It is activated during the evaluation of emotional reactions (Fossati et al., 2003; Ochsner et al., 2004; Ruby and Decety, 2004) and internally generated affective information (Damasio et al., 2000; Gusnard et al., 2001; Lane et al., 1997; Zysset et al., 2002), which may facilitate the formation and awareness of "gut reactions" that individuals monitor during creative work (de Bono, 2000).

In addition to default network regions, medial temporal lobe (MTL) memory regions such as the hippocampus and the parahippocampus have also frequently been reported during creativity experiments, although they have received relatively little attention to date. For example, the hippocampus exhibits greater recruitment during visual art design (Kowatari et al., 2009) and divergent thinking (Fink et al., 2009). In general, studies have linked the MTL to memory

retrieval (Squire et al., 2004) and associative processing (Eichenbaum, 2000). The MTL is activated during the formation and retrieval of semantic and episodic associations (Aminoff et al., 2007; Bar et al., 2008; Henke et al., 1997, 1999; Rombouts et al., 1997), as well as during mental simulations of past, future, and novel events that require the recombination of stored associations (Addis et al., 2007; Botzung et al., 2008; Hassabis et al., 2007; Okuda et al., 2003; Szpunar et al., 2009). The associative function of the MTL implies that it may be particularly important for creative thought by facilitating the generation of novel ideas and associations and the recombination of old ones.

While all three aforementioned networks appear to play important roles in creative thought, their distinct contributions to the different components of the creative process remain unclear. On the basis of the previously reviewed neuroscientific findings, we could hypothesize that: (i) the MTL memory network may contribute to associative processes that would enable creative generation; (ii) the default network may contribute either to creative generation through its role in low cognitive control or to creative evaluation through its role in affective and visceral evaluative processing; and (iii) the executive network may contribute to the analytical evaluative processes required during creative evaluation.

To identify the specific contributions of various brain areas to the creative process, we developed a novel paradigm that separated and alternated between generative and evaluative modes during the performance of a visual book cover design task, used as a creativity exercise in visual arts and design programs. To complete the task, participants used a functional magnetic resonance imaging (fMRI)-compatible drawing tablet (Tam et al., 2010) that allowed them to actively draw and write their ideas and evaluations while in an fMRI scanner. By doing so, the study used an approach closer to real-life creative activities compared to previous studies, most of which required participants to only imagine their solutions and designs during creativity tasks (Fink et al., 2007).

Materials and methods

Participants

The participants ($N=15$, after one exclusion; 9 females; $M=22.14$ years, $SD=2.25$ years) were undergraduates from the Emily Carr University of Art and Design (ECUAD; Vancouver, BC, Canada). All were right-handed with normal or corrected-to-normal vision, had no psychiatric history, and were screened for MRI compatibility. All protocols were approved by the University of British Columbia (UBC; Vancouver, BC, Canada) Clinical Research Ethics Board and the UBC MRI Research Center. The participants gave informed written consent prior to participating and received payment as compensation. One participant was excluded from the analysis due to excessive motion (>5 mm in the z-direction).

Apparatus

Participants used a custom-built fMRI-compatible drawing tablet system (Fig. 1) that was an adapted version of the tablet that had been used by Tam et al. (2010). The tablet was located at waist-level and consisted of a resistive touch screen sensor panel and matching controller board (Microtouch, 3M Co., St. Paul, MN) mounted on a tilting, height-adjustable plastic table with an active area of $130\text{ mm} \times 98\text{ mm}$ and 4096×4096 pixels spatial resolution. The participants used a plastic stylus connected to the tablet to draw and write, pressing down on the tip of the microswitch to simulate a sustained left-button mouse click. Shielded cables passed the tablet and stylus signals through a filter (56-705-005-LI, Spectrum Control Inc., Fairview, PA) in the magnet room wave guide to an interface box containing the controller and joystick emulation circuitry for the

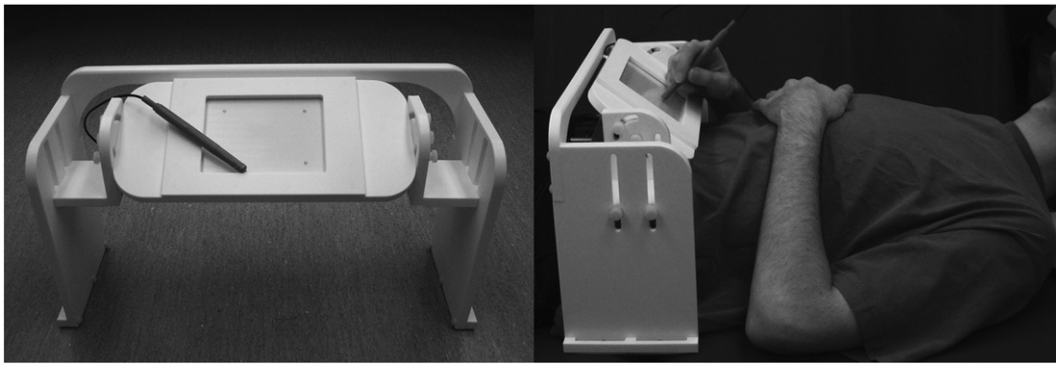


Fig. 1. fMRI-compatible drawing tablet system. The system consisted of a touch screen panel mounted on an adjustable plastic table and a plastic stylus that simulated a sustained left-button mouse click while drawing and writing.

stylus button. Universal Serial Bus (USB) cables connected the interface box to the fMRI stimulus computer, which displayed the stimuli via an LCD projector and a reflecting mirror. All components of the tablet were non-ferromagnetic, and no detrimental MRI artifacts were present during the experiment. The drawing environment, stimuli, and questions were implemented and presented using E-Prime 2.0 (Psychology Software Tools, Sharpsburg, PA).

Stimuli

Participants designed book cover illustrations according to book descriptions selected and adapted from documentary summaries from the 2000–2008 United Nations Association Film Festivals (<http://www.unaff.org>). The summaries contained abstract concepts and descriptions regarding public issues (e.g., war, immigration, and religion) that did not require specific knowledge and were relatively difficult to represent visually. The documentary blurbs were converted to book descriptions by removing or changing film-related words and edited down to 90 to 110 words each so that all could be easily read within 45 seconds. (See Appendix for a full list of book descriptions.)

Procedure

One to two days prior to the actual scanning session, participants engaged in a practice session to become familiar with the experimental procedures by performing the task and using the tablet in a mock scanner environment. The practice procedures were identical to the actual scanning procedures but used a different set of book

descriptions. During scanning, the participants worked on one book description per run for a total of 6 book descriptions in 6 runs. During each run, the participants viewed a book description for 45 s, and then drew or wrote down their ideas for 30 s (*generate*), traced lines for 3–11 s (*trace-g*), drew or wrote down their evaluations of the ideas for 20 s (*evaluate*), and traced lines again for 3–11 s (*trace-e*) (Fig. 2). This *generate-evaluate* cycle was repeated 5 times for each book description. The total length of each run was 6 minutes. (See Appendix for the complete instructions given to participants.)

Participants were given slightly longer blocks to *generate* than to *evaluate* (30 s vs. 20 s), because of pilot observations that indicated generation required a longer duration of time. Participants were also given baseline blocks, the *trace-g* and *trace-e* blocks, which kept the drawing component constant but prevented the participants from generating or evaluating. During the two tracing blocks, gray lines of different lengths appeared on the screen every 1.25 s with jittered durations (3, 5, 7, 9, or 11 s, randomly chosen for an average of 7 s). During the last 5 s of each block, the remaining time was shown at the top right corner of the screen to remind participants that the block was about to end. The drawings and evaluations produced during previous cycles were saved on the left side of the workspace for the participants' reference (see Fig. 2b).

After each 6-minute scanning run, the participants were shown the results of each *generate-evaluate* cycle and asked to verbally identify: (i) the ideas they wanted to convey; (ii) their evaluations of those ideas; and (iii) their ratings of how well they were able to engage in generation and evaluation separately, using a scale that ranged from 1 (*very unsuccessful*; i.e., generating when they should have been evaluating and vice versa) to 10 (*very successful*).

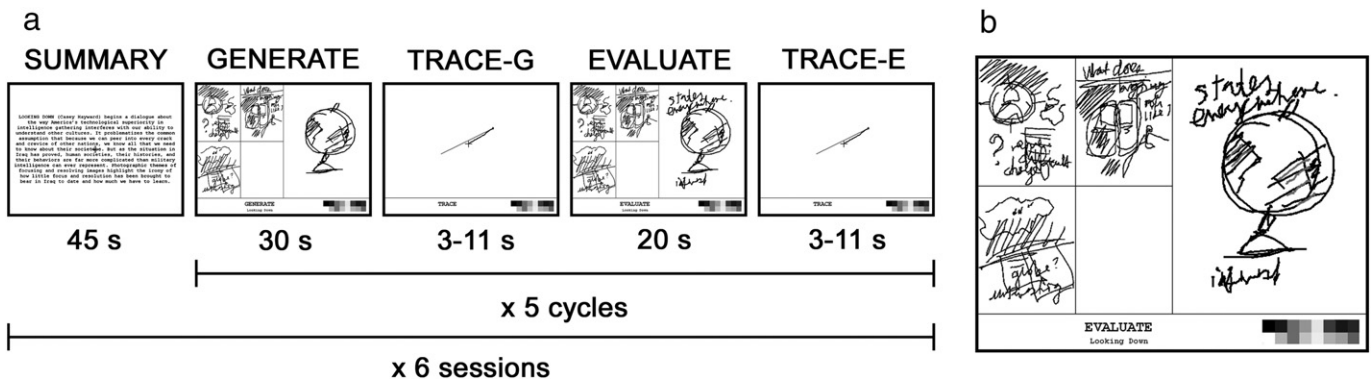


Fig. 2. (a) Schematic of experimental paradigm. For each of the 6 book descriptions, the participants performed 5 cycles of viewing the book description for 45 s, drawing or writing down their ideas for a book cover for 30 s (*generate*), tracing lines that appeared on the screen for 3–11 s (*trace-g*), drawing or writing down their evaluations of the ideas for 20 s (*evaluate*), and tracing lines again for 3–11 s (*trace-e*). During the tracing blocks, which served as baseline conditions, gray lines of different lengths appeared on the screen every 1.25 s with jittered durations (3, 5, 7, 9, or 11 s, randomly chosen for an average of 7 s). (b) Screenshot of an *evaluate* trial. Participants drew on the right side of the screen, while the drawings and evaluations produced during previous cycles were saved on the left side of the workspace for their reference. The instructions, book title, and color palette were shown at the bottom of screen.

fMRI data acquisition

Data were collected using a 3.0 Tesla Philips Intera MRI scanner (Best, Netherlands) with a standard head coil. Head movement was restricted using foam padding around the head. T2*-weighted functional images were acquired parallel to the anterior commissure/posterior commissure (AC/PC) line using a single shot gradient echo-planar sequence (EPI; repetition time [TR]=2 s, echo time [TE]=30 ms, flip angle [FA]=90°, field of view [FOV]=240×240×143 mm, matrix size=80×80, SENSE factor=1.0). A total of 191 functional volumes were acquired, each including 36 interleaved axial slices (3 mm thick with 1 mm skip) covering the entire brain. After functional imaging, an inversion recovery prepared T1-weighted structural volume was acquired in the same slice locations and orientation as had been the functional images using a fast spin-echo sequence (TR=2 s, TE=10 ms, FA=90°, FOV=224×224×143 mm, acquisition matrix size=240×235, reconstructed matrix size=480×470, inversion delay [IR]=800 ms, spin echo turbo factor=5).

fMRI data analysis

fMRI data for each participant were preprocessed and analyzed using SPM5 (Statistical Parametric Mapping, Wellcome Department of Imaging Neuroscience, London, UK). Slice timing correction was performed using sinc interpolation and resampling with the middle (18th) slice as a reference point. All functional volumes were realigned to the first volume to correct for between-scan motion. The structural volume was co-registered to the mean functional image and segmented to extract a gray matter image. The segmented structural volume was then spatially normalized to a gray matter image of the Montreal Neurological Institute (MNI) template and resliced to a voxel size of 2×2×4 mm. The derived spatial transformations were applied to the realigned functional volumes to bring them into standardized MNI space. Finally, the functional volumes were smoothed with an 8-mm full-width at half-maximum (FWHM) isotropic Gaussian kernel to compensate for residual between-subject variability after spatial normalization and permit application of

Gaussian random field theory for corrected statistical inference (Friston et al., 1994). To ensure that statistical analysis was performed in all brain regions, including those where signal may have been low due to susceptibility artifacts, a mask was created by averaging and thresholding the first preprocessed functional volume from all participants and explicitly specified during model estimation at the individual level. To remove low-frequency drift in the blood oxygen-level dependent (BOLD) signal, the data were high-pass filtered using an upper cut-off period of 128 s. No global scaling was performed.

Condition effects at each voxel were estimated according to the general linear model for the main whole brain analyses. The model included: (i) the observed time-series of intensity values, representing the dependent variable; (ii) covariates modeling session-specific effects (i.e., the six head movement parameters), later treated as confounds; and (iii) regressor functions constructed by convolving condition-specific boxcar functions with a synthetic hemodynamic response function. The regressor functions were constructed to model each of the *generate*, *trace-g*, *evaluate*, and *trace-e* conditions, and were compared using pairwise contrasts for each participant. Group random-effects analyses were then performed for each contrast. The resulting *T* maps were subsequently transformed to the unit normal *Z*-distribution to create a statistical parametric map for each contrast. Threshold for significance was set at $p < 0.05$ FDR-corrected for multiple comparisons and extent threshold $k > 20$ voxels.

Results

To identify the brain regions that demonstrated relatively increased recruitment during the different conditions, each condition was compared to the opposite condition (*generate*>*evaluate* and *evaluate*>*generate*). There was greater activation when participants were generating ideas than when evaluating them (Fig. 3a, Table 1) in the MTL, specifically the left hippocampus (peak $x, y, z = -32, -40, -4$; $Z = 4.40$), right hippocampus (peak $x, y, z = 36, -26, -12$; $Z = 3.92$), left parahippocampus (Brodmann area [BA] 36; peak $x, y, z = -30, -34, -20$; $Z = 4.35$), and right parahippocampus (BA 36; peak $x, y, z = 34, -38, -16$; $Z = 3.65$). Greater activations during generation were also observed in bilateral inferior parietal lobule

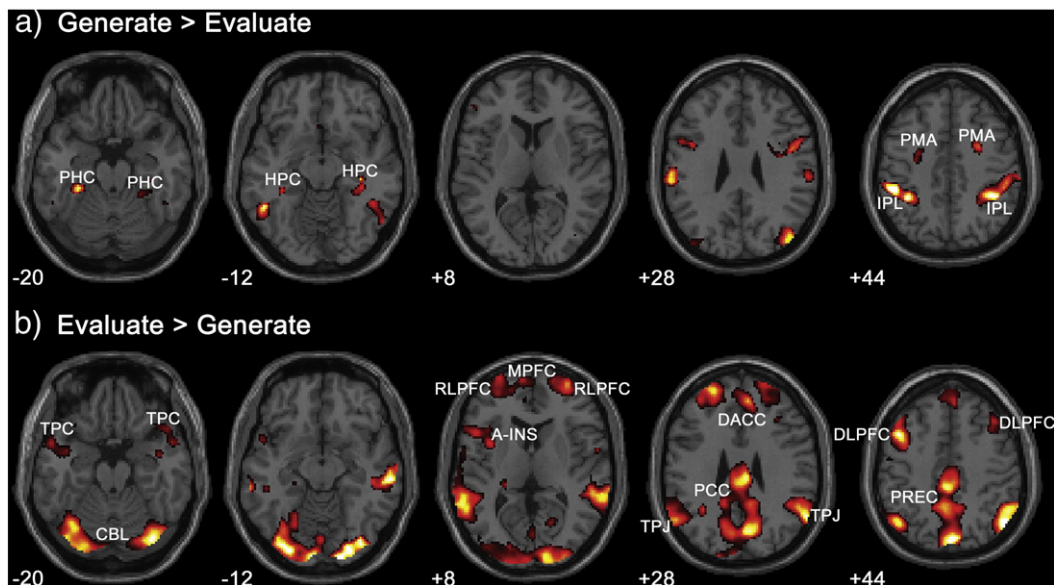


Fig. 3. Activation maps for creative generation and evaluation. (a) Generation (*generate*>*evaluate*) was associated with activation of the hippocampus (HPC) and parahippocampus (PHC) in the medial temporal lobe, as well as the inferior parietal lobule (IPL) and premotor area (PMA). Activations were also observed in the left inferior frontal gyrus (IFG), bilateral superior parietal lobule (SPL), bilateral fusiform gyrus, bilateral middle temporal gyrus (MTG), and left cerebellum. (b) Evaluation (*evaluate*>*generate*) was associated with activation of the executive (DLPFC and dACC) and default (MPFC, PCC/precuneus, and TPJ) networks, as well as the RLPFC, cerebellum (CBL), temporopolar cortex (TPC), and left anterior insula (A-INS). Activations were also observed in the supplementary motor area, bilateral IFG, bilateral SPL, bilateral MTG, bilateral lingual gyrus, bilateral middle occipital gyrus, and bilateral cuneus. The right side of the brain is on the right side of the figure. All activations were significant at $p < .05$ FDR-corrected and $k > 20$.

Table 1
Activation peaks during creative generation (*generate*>*evaluate*).

Region	MNI coordinates					Voxels	Z value
	L/R/M	BA	x	y	z		
<i>Frontal</i>							
Premotor area	L	6	-26	-2	56	271	4.30
Premotor area	R	6	28	2	52	185	4.45
Inferior frontal gyrus	L	45	-50	38	12	35	3.69
<i>Parietal</i>							
Superior parietal lobule	L	7	-28	-52	64	22	3.21
Superior parietal lobule	R	7	32	-48	64	32	3.01
Inferior parietal lobule	L	40	-48	-36	44	601	5.22
Inferior parietal lobule	R	40	40	-42	44	851	4.72
<i>Temporal</i>							
Hippocampus	L	-	-32	-40	-4	80	4.40
Hippocampus	R	-	36	-26	-12	99	3.92
Parahippocampus	L	36	-30	-34	-20	71	4.35
Parahippocampus	R	36	34	-38	-16	74	3.65
Fusiform gyrus	L	37	-50	-52	-12	64	4.28
Fusiform gyrus	R	37	40	-68	-4	161	4.42
Middle temporal gyrus	L	19	-30	-80	36	121	3.64
Middle temporal gyrus	R	19	46	-76	24	165	4.34
<i>Subcortical</i>							
Cerebellum	L	-	-14	-72	-48	55	3.58

All activations were significant at $p < .05$ FDR-corrected and $k > 20$.

(IPL) and bilateral premotor area (PMA), as well as in the left inferior frontal gyrus (IFG), bilateral superior parietal lobule (SPL), bilateral fusiform gyrus, bilateral middle temporal gyrus (MTG), and left cerebellum.

There was greater activation when participants were evaluating ideas than when generating them (Fig. 3b, Table 2) in the executive network, including dACC (BA 24/32; peak $x, y, z = 8, 44, 28$; $Z = 3.94$), left DLPFC (BA 9; peak $x, y, z = -44, 14, 44$; $Z = 4.51$), and right DLPFC (BA 9; peak $x, y, z = 42, 26, 44$; $Z = 3.20$). Greater activations during evaluation were also observed in the default network regions, including MPFC (BA 10; peak $x, y, z = -8, 64, 4$; $Z = 3.27$), PCC/precuneus (BA 31/7; peak $x, y, z = 4, -30, 24$; $Z = 4.50$), left TPJ (BA 39/40; peak $x, y, z = -68, -38, 0$; $Z = 4.09$), and right TPJ (BA 39/40; peak $x, y, z = 66, -40, 4$; $Z = 4.34$). In addition, increases in activation during evaluation were observed in bilateral rostrolateral PFC (RLPFC), bilateral cerebellum, bilateral temporopolar cortex, and left anterior insula. Other increases in activation were observed in the supplementary motor area, bilateral IFG, bilateral SPL, bilateral MTG, bilateral lingual gyrus, bilateral middle occipital gyrus, and bilateral cuneus.

To ensure that the observed differences between the *generate*>*evaluate* and *evaluate*>*generate* contrasts were due to activations rather than deactivations, the signal levels during *generate* and *evaluate* blocks were compared to the signal levels during *trace-g* and *trace-e* baseline blocks. To do this, activation time courses were extracted from the preprocessed functional images from each run for each participant using the SPM5 Volumes Toolbox. The extraction volumes were specified by constructing 4-mm radius spheres centered on local maxima from the group-level contrasts, including regions of interest (ROIs) in the MTL, default network, and executive network. The signal was band-pass filtered using high and low-pass cut-offs of 0.015625 Hz and 0.15 Hz, respectively. Time courses for each condition were averaged. The peak condition values from each participant were then used to construct BOLD percent signal change (PSC) bar graphs for each ROI (Fig. 4). Peak BOLD percent signal change in the hippocampus, parahippocampus, dACC, DLPFC, MPFC, PCC/precuneus, and TPJ showed that they were more active during generation and evaluation compared to the tracing baselines, demonstrating that the observed results were not due to deactivations during the opposite conditions. While the evaluation condition

tended to involve more writing ($M = 76.33$ words, $SD = 31.21$) than the generation condition ($M = 45.33$, $SD = 62.33$) [$t(14) = 1.80$, $p = .047$], regressing out the number of words written did not alter the significance of the results.

To identify the neural activations correlated with successful generation and evaluation, the success ratings for each of the *generate* and *evaluate* conditions were averaged across all trials and runs. The average *generate* success values for each participant were entered as a covariate in the *generate*>*evaluate* group-level contrast, and the average *evaluate* success values were entered as a covariate in the *evaluate*>*generate* group-level contrast. Correlations were computed and scatter plots were constructed using centered covariate values and parameter estimates extracted by the SPM5 Plot Function from local maxima (from the original group-level contrasts) in the MTL, default network, and executive network regions. The covariate analyses revealed that generation success ratings (Fig. 5a) were positively correlated with responses in the MTL, specifically the left parahippocampus ($r = .668$, $p = .006$) and right parahippocampus ($r = .563$, $p = .029$), as well as the left IPL ($r = .784$, $p < .001$), right IPL ($r = .675$, $p = .006$), left PMA ($r = .623$, $p = .013$), and right PMA ($r = .671$, $p = .006$). Meanwhile, evaluation success ratings (Fig. 5b) were positively correlated with responses in the executive network regions, including the dACC ($r = .764$, $p < .001$) and left DLPFC

Table 2
Activation peaks during creative evaluation (*evaluate*>*generate*).

Region	MNI coordinates					Voxels	Z value
	L/R/M	BA	x	y	z		
<i>Frontal</i>							
Dorsal ACC	M	24/32	8	44	28	40	3.94
Medial frontal gyrus (MPFC)	M	10	-8	64	4	88	3.27
Superior frontal gyrus (RLPFC)	L	10	-22	54	28	1170	4.19
Superior frontal gyrus (RLPFC)	R	10	32	58	16	1073	4.19
Middle frontal gyrus (DLPFC)	L	9	-44	14	44	382	4.51
Middle frontal gyrus (DLPFC)	R	9	42	26	44	183	3.20
Inferior frontal gyrus	L	47	-32	56	-4	168	3.24
Inferior frontal gyrus	R	47	22	58	0	39	3.48
Inferior frontal gyrus	R	45	48	22	0	37	2.79
Inferior frontal gyrus	L	45	-60	20	0	36	3.14
Supplementary motor area	M	6	-2	12	68	141	3.03
<i>Parietal</i>							
Precuneus	M	7	0	-32	44	773	4.35
Posterior cingulate cortex	M	23/31	4	-30	24	1035	4.50
Inferior parietal lobule (TPJ)	L	39/40	-68	-38	0	96	4.09
Inferior parietal lobule (TPJ)	R	39/40	66	-40	4	469	4.34
Superior parietal lobule	L	7	-44	-66	48	563	4.36
Superior parietal lobule	R	7	50	-66	44	1906	5.02
<i>Temporal</i>							
Temporopolar cortex	L	38	-32	6	-40	70	3.30
Temporopolar cortex	R	38	54	8	-28	287	3.60
Middle temporal gyrus	L	22	-66	-32	-8	3219	4.54
Middle temporal gyrus	R	22	56	-30	-8	739	4.68
<i>Occipital</i>							
Cuneus	L	19	-28	-88	-12	2720	4.76
Cuneus	R	19	24	-88	-8	12111	5.23
Middle occipital Gyrus	L	18	-22	-94	24	705	3.88
Middle occipital Gyrus	R	18	18	-94	-8	39	5.06
Lingual gyrus	L	17	-8	-94	-12	752	4.48
Lingual gyrus	R	17	14	-92	4	124	4.40
<i>Subcortical</i>							
Anterior insula	L	-	-36	6	8	215	3.46
Cerebellum	L	-	-34	-84	-12	39	4.58
Cerebellum	R	-	36	-80	-16	355	4.66

All activations were significant at $p < .05$ FDR-corrected and $k > 20$.

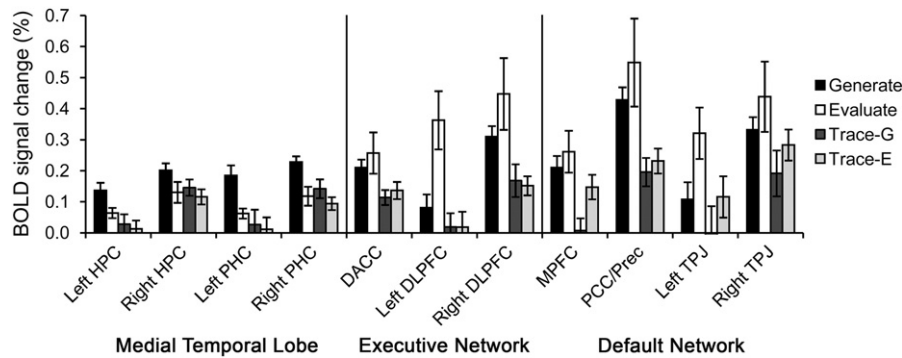


Fig. 4. BOLD percent signal change in activated regions. Histograms represent mean peak BOLD percent signal change for each condition in 4-mm radius spheres centered on local maxima (from the group-level contrasts) in the medial temporal lobe (*left*), executive network (*middle*), and default network (*right*), showing the results were not due to deactivation relative to the tracing baselines. Error bars represent the standard error of the mean.

($r = .713, p = .003$), as well as the default network regions, including the MPFC ($r = .603, p = .017$), PCC/precuneus ($r = .725, p = .002$), left TPJ ($r = .638, p = .011$), and right TPJ ($r = .779, p < .001$). Evaluation success ratings were also positively correlated with responses in the left RLPFC ($r = .688, p = .005$), right RLPFC ($r = .718, p = .003$), left anterior insula ($r = .674, p = .006$), left temporopolar cortex ($r = .634, p = .011$), left cerebellum ($r = .702, p = .004$), and right cerebellum ($r = .744, p = .001$). The 95% confidence intervals for all correlations did not overlap with zero.

Finally, to examine the co-activation of the executive and default networks seen in the *evaluate* > *generate* contrast, functional connectivity analyses were conducted. Time courses from 4-mm radius spheres centered on local maxima in executive and default network regions (from the *evaluate* > *generate* group-level contrast) were extracted for each participant, globally scaled, and band-pass filtered (0.015625 Hz and 0.15 Hz cutoffs). The ROIs or seed regions included the dACC and right DLPFC from the executive network, and the MPFC and PCC from the default network, which were chosen to examine the functional connectivity patterns of the strongest activations in the regions typically associated with the executive and default networks. To map networks of brain regions with correlated activity throughout the entire experiment for each participant, the correlation between a seed region's time course and each voxel's time course were estimated according to the general linear model, using the seed region's time course as a regressor. Group random-effects analysis was then performed on the regression. The resulting T maps were subsequently transformed to the unit normal Z -distribution to create a statistical parametric map for each contrast. Threshold for significance was set at $p < 0.05$ FDR-corrected for multiple comparisons and $k > 20$ voxels. The functional connectivity analyses revealed that activity throughout the entire experiment in executive network regions, including the dACC (seed center $x, y, z = 8, 44, 28$; Fig. 6a) and right DLPFC (seed center $x, y, z = 42, 26, 44$; Fig. 6b), was highly correlated with activity in default network regions. Similarly, activity in default network regions, including the MPFC (seed center $x, y, z = -8, 64, 4$; Fig. 6c) and PCC (seed center $x, y, z = 4, -30, 24$; Fig. 6d), was also highly correlated with activity in executive network regions. The same patterns of functional connectivity were also observed for the *evaluate* condition separately.

Discussion

The current study examined the hypothesis that creative generation and evaluation are associated with the recruitment of distinct neural processes. To do this, the study employed a novel paradigm that allowed us to separate and alternate between these two fundamental components of the creative process. Consistent with the hypothesized preferential role of the MTL in creative generation, participants showed stronger activation in the MTL, including the

hippocampus and parahippocampus, when they generated ideas compared to when they evaluated them. Similarly, consistent with the hypothesized role of the executive network in creative evaluation, participants showed greater recruitment of executive network regions, including the DLPFC and dACC, when they evaluated ideas relative to when they generated them. Furthermore, participants showed more activation in default network regions, including MPFC, PCC/precuneus, and TPJ, during creative evaluation than during creative generation. Thus, a co-activation of the executive and default networks was observed during creative evaluation. In addition, functional connectivity analyses revealed that activity in the two networks were highly correlated throughout the task.

Examination of the ROIs revealed that activations during the tracing conditions were lower than during generation and evaluation, demonstrating that the activations during generation and evaluation were not due to deactivations during the opposite condition. Thus, while creative generation was associated with preferential recruitment of MTL regions and creative evaluation was associated with preferential recruitment of executive and default network regions, they do not rule out the MTL's involvement in evaluation and the executive and default networks' involvement in generation, although to a lower degree. However, covariate analyses across participants also revealed that the more successfully they were able to engage in creative generation while avoiding evaluative processes, the more they recruited MTL regions associated with creative generation. Similarly, the more successfully they were able to engage in creative evaluation while avoiding generative processes, the more they recruited executive and default regions associated with creative evaluation. These individual differences results provide further support for the hypothesized roles of MTL structures in creative generation and of executive and default network structures in creative evaluation.

Analytical evaluative processing during creative thinking

The pattern of activation identified in the current study suggests that evaluative processing during creative thinking recruits considerable cognitive control processes. Specifically, the activation of executive and top-down control networks during creative evaluation implies the engagement of a high level of cognitive control that may facilitate analytic processing. The executive network has been consistently linked to cognitive control functions (Desimone and Duncan, 1995; Miller and Cohen, 2001). The functions most often attributed to the dACC – attention focusing, attention shifting, and error detection – form the basis of a more general conflict monitoring and detection process that signals the need for increased cognitive control (Carter et al., 1998, 1999). The DLPFC may then implement the cognitive control required (Carter and van Veen, 2007; MacDonald et al., 2000) and select the necessary response (Bunge et al., 2005;

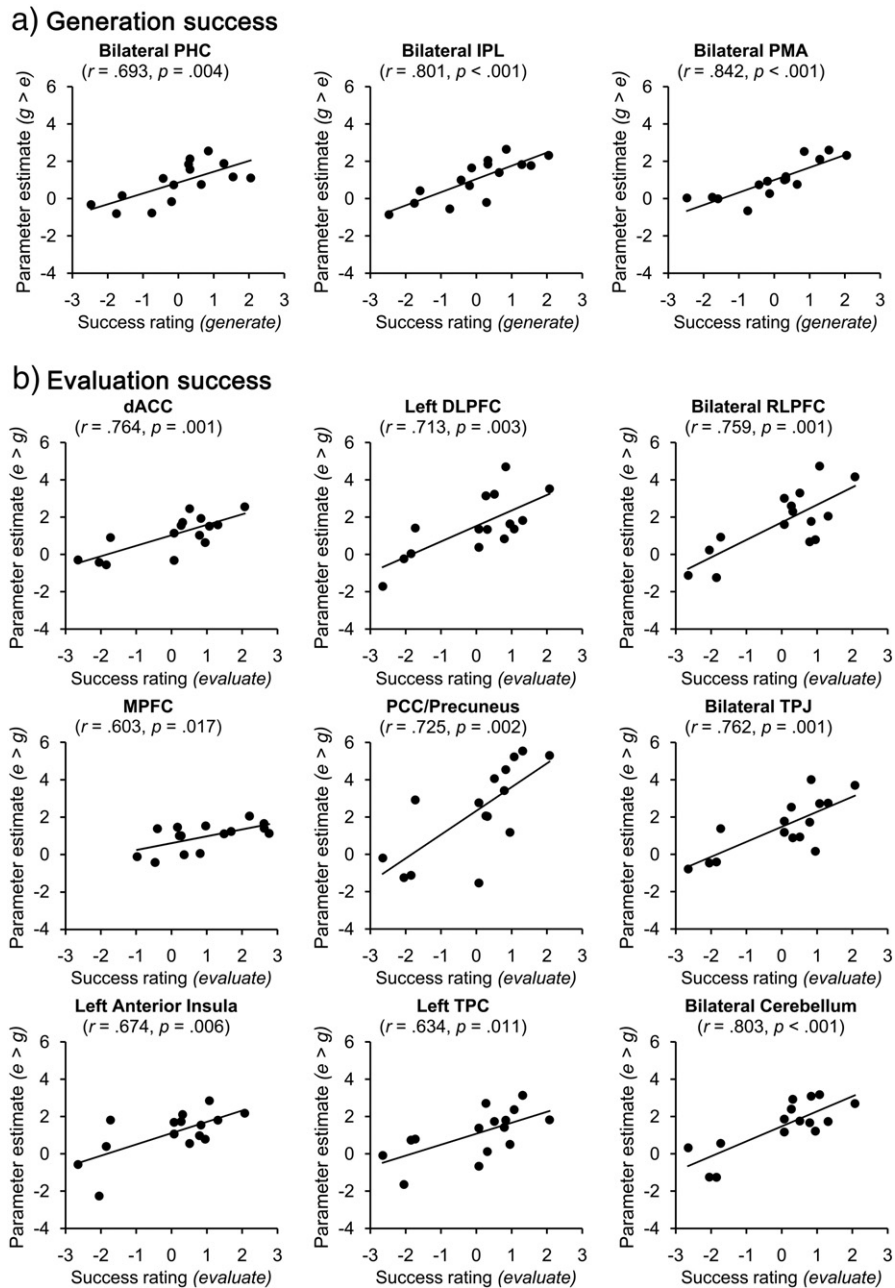


Fig. 5. Correlations between successful creative generation and evaluation and responses in activated regions. (a) Positive correlation between successfully engaging in generation while avoiding evaluation and parameter estimates in peak voxels (from the original group-level contrasts) of the bilateral parahippocampus (PHC), bilateral IPL, and bilateral PMA. (b) Positive correlation between successfully engaging in evaluation while avoiding generation and parameter estimates in peak voxels of the executive network (dACC and left DLPFC) and bilateral RLPFC, default network (MPFC, PCC/precuneus, and bilateral TPJ), and left anterior insula, left temporopolar cortex (TPC) and bilateral cerebellum. Points represent the centered covariate values (mean success self-ratings) and parameter estimates for each participant. Bilateral data were obtained by averaging data from each left and right region.

Hadland et al., 2001; Rowe et al., 2000) based on its integration and evaluation of the relevance (defined in terms of current task rules and goals) of inputs from the dACC, other prefrontal areas, memory regions, and association cortices (Fleck et al., 2006).

Creative evaluation was also associated with increased activation of brain regions theorized to be components of several top-down control networks. The lateral PFC, dACC, and inferior parietal lobule (IPL) make up a frontoparietal control system, which may integrate information from and regulate the activity of two opposing systems that each process external environmental information and store internal representations (Vincent et al., 2008). The DLPFC and IPL also form an executive control network proposed by Seeley et al. (2007) that directs attention and control processing in posterior sensorimo-

tor regions. Another frontoparietal control network consisting of the DLPFC, IPL, and precuneus initiates and adjusts top-down control (Dosenbach et al., 2008) along with a cingulo-opercular network that maintains task goals and consists primarily of the dACC and frontal operculum (Dosenbach et al., 2008). The cerebellum, which was found to be extensively activated during creative evaluation, may mediate activity between the two networks and optimize performance by transmitting error-related information (Dosenbach et al., 2008). Thus, the current results clearly suggest that deliberate analytical processing is an essential part of creative evaluation.

Although not necessarily considered part of the executive network, the rostralateral PFC (RLPFC), which was activated during creative evaluation, also contributes to cognitive control (Braver et al.,

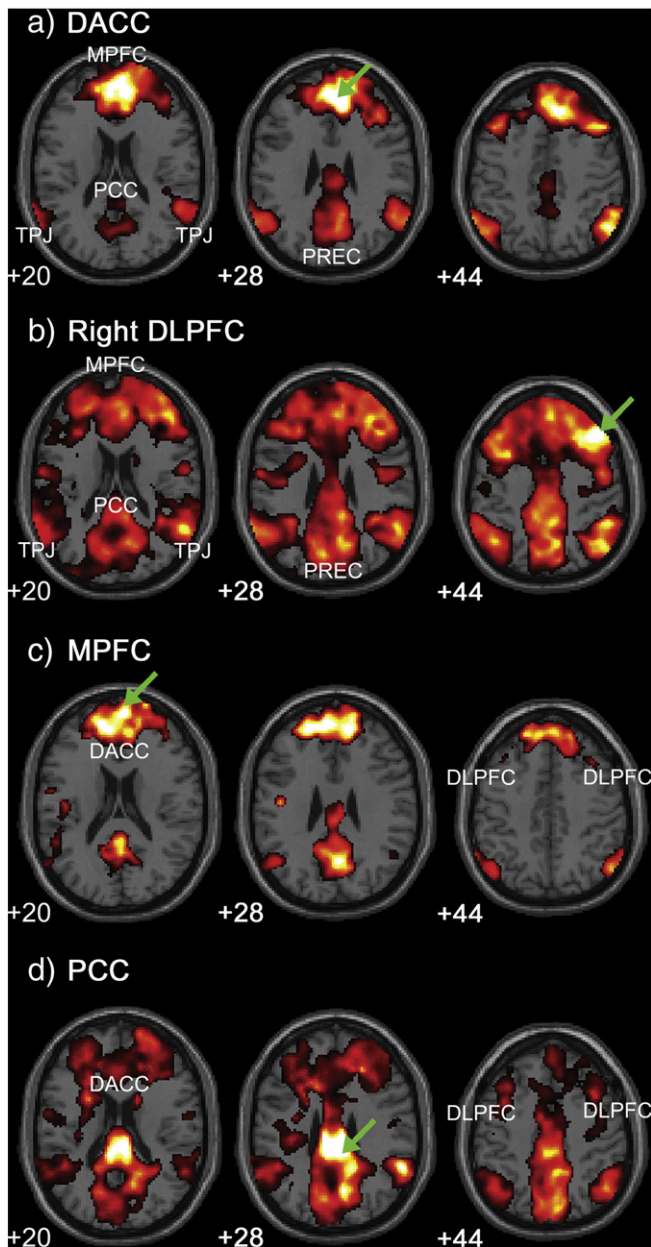


Fig. 6. Functional connectivity maps of executive and default network regions during task performance. Data from the entire time-series were used. Activity throughout the task in 4-mm radius spheres centered on local maxima (from the *evaluate>generate* group-level contrast) in the executive network, including the (a) dACC (center $x, y, z = 8, 44, 28$) and (b) right DLPFC (center $x, y, z = 42, 26, 44$), was highly correlated with activity in default network regions, such as the MPFC, PCC/precuneus, and bilateral TPJ. Activity in 4-mm radius spheres centered on local maxima in the default network, including the (c) MPFC (center $x, y, z = -8, 64, 4$) and (d) PCC (center $x, y, z = 4, -30, 24$), was also highly correlated with activity in executive network regions, such as the dACC and bilateral DLPFC. All correlations were significant at $p < .05$ FDR-corrected and $k > 20$.

2003; Ramnani and Owen, 2004) especially at high levels of abstraction in cognitive processing (Christoff et al., 2009b). The RLPFC is activated during complex cognitive processing across a wide range of domains including complex reasoning (Christoff et al., 2001; Kroger et al., 2002; Monti et al., 2007), memory retrieval (Rugg and Wilding, 2000; Velanova et al., 2003), multi-tasking (Braver and Bongiolatti, 2002; Koechlin et al., 1999), moral decision making (Greene et al., 2004), complex reward processing (Boorman et al., 2009; Huettel, 2006), and spontaneous thought (Christoff et al., 2009a; Christoff et al., 2004). Across this diverse set of domains,

neuroimaging and single-cell studies have suggested that RLPFC plays a higher-order meta-cognitive function that evaluates and integrates the outputs of prior stages of cognitive processing (Christoff and Gabrieli, 2000; Christoff et al., 2003; Fletcher and Henson, 2001; Petrides, 2005; Ramnani and Owen, 2004; Smith et al., 2007; Tsujimoto et al., 2010). Its activation during creative evaluation may reflect the involvement of such meta-cognitive evaluative processing, including judgments of the progress towards the initial creative idea or goal and the appropriateness of the final creative product.

Affective and viscerosensitive evaluative processing during creative thinking

Creative evaluation, however, was also associated with recruitment of areas not typically associated with deliberate analytical processing, such as the default network and the so-called “salience network”, which integrates highly processed sensory data with visceral, autonomic, and hedonic information to help an organism decide what to do or not to do (Seeley et al., 2007). There is increasing evidence that, in addition to resting state processes, default network regions engage in a range of affective and viscerosensitive evaluative processes. For example, it is activated during evaluation of self and others' emotional reactions (Fossati et al., 2003; Ochsner et al., 2004; Ruby and Decety, 2004) and emotional mental state attribution (Mitchell et al., 2005). The MPFC specifically has also been linked to the evaluation of internally generated affective information (Damasio et al., 2000; Gusnard et al., 2001; Lane et al., 1997; Zysset et al., 2002). At this time, however, only the present study as well as Limb and Braun's (2008) study with jazz improvisation show evidence for an association between creativity and the whole default network in a single creativity task, rather than just its individual components.

Based on these findings, recent theories have proposed a more general function of the default network as the processing of internally generated, affective information (Bar, 2007; Binder et al., 1999; Buckner et al., 2008). This processing is evaluative in nature, consisting of the inferential processing of information retrieved from memory (e.g., knowledge and rules) and integrated with external information (e.g., sensory information) (Legrand and Ruby, 2009). Integration may occur at the TPJ because it is one of the brain's association areas, processing inputs from multiple sensory and limbic areas (Decety and Lamm, 2007). The PCC/precuneus may further integrate information from the association cortices (e.g., TPJ) and memory regions (e.g., MTL), as well as serve as the interface between the MPFC and TPJ by representing the relevant internally generated information (Buckner et al., 2008; Vogt and Laureys, 2005). The MPFC may perform inductive inferences based on internal affective information to draw conclusions that guide behavior.

In addition, the anterior insula and temporopolar cortex, which were found to be activated during creative evaluation, are thought to integrate highly processed sensory data with interoceptive-autonomic information. As part of the “salience network” (Seeley et al., 2007), the anterior insula has been shown to process detailed representations of transient internal (e.g., visceral or emotional) states (Craig, 2002; Critchley et al., 2004). The temporopolar cortex, meanwhile, may bind complex perceptual input to visceral, emotional input from the anterior insula and amygdala (Olson et al., 2007). While evaluating the products of one's own creative activity, creative individuals frequently pay attention to their “gut reactions” (de Bono, 2000). In line with these observations, individuals in the present study were instructed to try to include such reactions as part of their evaluations. The enhanced activation of default and salience network regions during creative evaluation may therefore convey the importance of affective and viscerosensitive forms of evaluative processing during creative thought.

Medial temporal lobe structures and the generation of ideas

The present results suggest that MTL regions may be central to thought generation, and extend a number of previous studies that have indirectly linked the MTL to the spontaneous generation of thoughts and memories. For instance, a neural replay of recent experiences during periods of quiet wakefulness has been observed in the rat MTL (Foster and Wilson, 2006; Sutherland and McNaughton, 2000). The spontaneous re-activation of memories in humans has also been associated with neural activity in the MTL (Gelbard-Sagiv et al., 2008), and spontaneous mental processing during rest conditions has been found to consistently recruit the MTL (Binder et al., 1999; Christoff et al., 2004; Stark and Squire, 2001).

Furthermore, beyond the simple memory processing traditionally ascribed to the MTL, recent findings suggest an associative and constructive function of the MTL that may allow it to generate novel ideas and thought content. These findings suggest that the MTL may be more active during the formation and retrieval of semantic and episodic associations than during single item processing, especially in the parahippocampus (Aminoff et al., 2007; Bar et al., 2008; Henke et al., 1997, 1999; Rombouts et al., 1997). Although the MTL is activated during both past and future event processing (Botzung et al., 2008; Szpunar et al., 2009), future event simulation elicits greater activation, especially in the hippocampus (Addis et al., 2007; Okuda et al., 2003), suggesting that recombination to arrive at novel ideas or images may be specifically linked to MTL functions. Consistent with this, imagining novel, fictitious scenes activates the same MTL regions as future event simulation (Hassabis et al., 2007).

Mental simulations also appear to underlie the spatial navigation tasks and theory of mind judgments that frequently recruit the MTL (Schacter and Addis, 2009). The parahippocampus may form new or access old associations that are then recombined by the hippocampus with other information to construct episodic simulations (Schacter and Addis, 2009). Thus, preferential activation of MTL regions during creative generation is consistent with psychological accounts that describe creative generation as enhanced associative processing (Gabora, 2010) and the restructuring of preexisting ideas (Hospers, 1985; Weisberg, 1995).

A large body of neuropsychological and neuroimaging data have implicated the right PFC in generation during creativity tasks (e.g., Miller and Tippett, 1996), ill-structured design tasks (e.g., Goel and Grafman, 2000), and well-structured problem solving tasks (e.g., Newman et al., 2003), and attributed its activity to “set shifting” or “lateral transformation” processes during generation, or the breaking of conceptual or perceptual constraints imposed on the task. However, the preferential recruitment of the MTL during generation in the present study suggests that the participants, who were highly skilled art students exercising their abilities in a familiar task, may have generated ideas without the need for set shifting or dramatic conceptual reorganization, thus not requiring right PFC involvement. While the present results suggest an intriguing link between the generation of new thoughts during creative thinking and MTL processes, identifying the precise nature of the relationship between MTL recruitment and creative generation remains a task for future research.

Executive and default network co-activation

Creative evaluation was associated with parallel recruitment of the executive and default networks, which have traditionally been regarded as mutually opposing. While the experiment's block design does not rule out the possibility that the executive and default networks were activated at different times during evaluation, the functional connectivity analyses suggest that the two networks are not completely independent. In general, the executive and default networks have been theorized to act in opposition to each other such

that the “task-negative” default network becomes deactivated or actively suppressed when the “task-positive” executive network becomes activated, and vice versa (Fox et al., 2005; Greicius et al., 2003; Weissman et al., 2006). However, more recent studies have found co-activation of the executive and default networks in the context of mind wandering (Christoff et al., 2009a), continuous film viewing (Golland et al., 2007), narrative speech comprehension (Wilson et al., 2008), and autobiographical planning (Spreng et al., 2010). Similarly, creativity studies have found evidence of co-activation in parts of both the executive and default networks, such as the ACC, PCC/precuneus, and TPJ during insight problem solving (Kounios et al., 2008; Subramaniam et al., 2009) and DLPFC, ACC, PCC/precuneus, and TPJ during a fluid analogy task (Geake and Hansen, 2005). Hence, it appears that creative evaluation may allow for the combination and integration of both cognitive and affective as well as deliberate and spontaneous forms of evaluative thought. Creative evaluation may thus be an extended form of analytic processing that combines processes that do not ordinarily act in tandem in order to produce optimal thinking conditions for creativity.

Conclusions

By distinguishing between the processes of creative generation and evaluation, the current study allowed for a more fine-grained characterization of the contributions of various brain areas to the creative process. Furthermore, by allowing participants to draw and write while being scanned, the study also provided a more ecologically valid examination of the creative process. However, a number of questions remain to be answered by future studies. Although the participants were given the opportunity to explain what they drew or wrote after each task run, the constraints of fMRI design did not permit identification of the types of processing (e.g., focused vs. defocused attention, analytic vs. associative, cognitive vs. affective, or deliberate vs. spontaneous) that occurred during generation and evaluation and when and where they occurred, and processes that did not endure long enough to elicit significant activation (e.g., brief moments of insight during generation). An experiment employing the high temporal resolution of EEG measures, in combination with ongoing verbal self-reports (Ericsson and Simon, 1993) during an unrestricted generation-evaluation cycle, could enable such an examination. Future experiments could also investigate whether a population of participants with little to no visual arts training, less demanding or less “creative” generative and evaluative tasks (e.g., those provided with no instructions regarding what to draw, those requiring less abstract and specific book descriptions, and those calling for evaluation of other people's work), and comparisons of more versus less creative ideas or products would yield similar or different results. Finally, future research could investigate different creative modalities using a similar procedure to independently examine generative and evaluative phases to identify the similarities and differences among creative writing, musical composition, scientific hypothesis generation, and even insight problem solving.

Measuring neural activity during a creativity task that allowed us to separate between generative and evaluative modes of creative thought helped to provide a more definitive characterization of the contributions of various creativity-related brain areas to the creative process that had previously only been inferred indirectly. The results of this study indicate that creative thinking recruits an optimized, unique configuration of neural processes typically not used together in “regular” thinking. While creativity is observed across a variety of fields and human endeavors, from musical compositions and scientific theories to the invention of everyday conveniences like the iPhone and Post-it Notes, what creative individuals may share in common is a heightened ability to engage in contradictory modes of thought, including cognitive and affective, and deliberate and spontaneous

processing. Although questions remain, the findings provide a valuable starting point for future studies that can provide an even more detailed account of how the brain supports creative thinking and the types of processes that facilitate it.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at [doi:10.1016/j.neuroimage.2011.08.008](https://doi.org/10.1016/j.neuroimage.2011.08.008).

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