

**DIFFERENT MODES OF THOUGHT DURING THE CREATIVE PROCESS**

by

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# ABSTRACT

Creativity is most often defined as the ability to produce ideas that are both novel and useful. Consistent with this twofold definition, psychological theories have suggested that creativity involves a twofold process characterized by a generative (or associative) component that facilitates the production of novel ideas, and an evaluative (or analytic) component that enables the assessment of these ideas as to their usefulness. To investigate this, the present study employed a novel paradigm that was specifically designed to allow for separately examining the generative and evaluative components of the creative process. Functional magnetic resonance imaging (fMRI) was used to identify the contribution of particular brain regions to creative generation and evaluation. Participants were presented with short book descriptions and, using an fMRI-compatible drawing tablet, designed corresponding book cover illustrations while alternating between the generation and evaluation of ideas. Creative generation and evaluation were associated with recruitment of distinct neural circuits, with generation preferentially recruiting medial temporal lobe regions, and evaluation showing joint recruitment of executive and default network regions. These findings suggest that the medial temporal lobe may play an important role in the generation of novel ideas, and that creative evaluation may extend beyond deliberate and cognitive analytical processes supported by executive resources to include spontaneous, affective, and viscerosensitive analytical processes. In summary, separating and alternating between generative and evaluative modes during a creative task helped to provide a better characterization of the contributions of creativity-related brain areas to the creative process, which had previously only been inferred indirectly. The results of this study suggest that creative thinking recruits a unique configuration of neural processes not typically used together in more traditional tasks.

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# 1 INTRODUCTION

What did Beethoven, Einstein, Picasso, and da Vinci possess that allowed them to produce works and ideas in a manner that changed how we perform activities and understand the world? As a quintessential and uniquely human characteristic manifested in art galleries, concert halls, bookstores, and science laboratories, as well as in everyday activities, creativity has long intrigued the public, especially artists, philosophers, and scientists. By allowing us to innovate and adapt within continually changing cultural and technological environments, creativity is both a contribution and a reaction to change (Runco, 2004). As such, its understanding and development is a key concern for educational institutions, business organizations, and scientific research.

Consequently, creativity has been studied extensively across numerous activities, such as divergent thinking, insight problem solving, musical improvisation, visual imagery, and design, and across diverse populations, including artists, musicians, scientists, and students (Fink, Benedek, Grabner, Staudt, & Neubauer, 2007). Furthermore, the advancement of technology, particularly brain imaging techniques like electroencephalography (EEG), positron emission tomography (PET), and functional magnetic resonance imaging (fMRI), has allowed us to gather a considerable amount of information about the “creative brain” (Fink et al., 2007). However, the existing neuroscientific accounts of the creative process that have resulted from this research can be further refined by the division and independent study of its components (Dietrich, 2007). Psychological theories and research point to a twofold process that consists of generative (or associative) and evaluative (or analytic) phases. While the pattern of neural recruitment that has been identified in neuroscientific creativity experiments also suggests a combined use of generative and evaluative processes during creative thinking, they have so far not been examined

separately in terms of their neural correlates.

## **1.1 Psychological accounts of creativity**

### **1.1.1 Twofold definition of creativity**

Often defined in terms of its product, creativity is the ability to produce ideas that are both novel (i.e., original and unique) and useful (i.e., appropriate and meaningful) within a particular social context at either the individual or historical level (e.g., Amabile & Tighe, 1993; Besemer & Treffinger, 1981; Bruner, 1962; Gardner, 1989; Sternberg, 1985). Novelty without utility is usually associated with eccentricity and sometimes even mental illness (Flaherty, 2005). For example, during John Forbes Nash's struggle with schizophrenia, he frequently worked with base 26 arithmetic, which required assigning a number to the 26 letters in the alphabet (i.e.,  $a = 1$  and  $z = 26$ ) to analyze names for hidden meanings. While certainly unusual, such arithmetic cannot be called creative in the manner that the Nash equilibrium for non-cooperative game theory, for which he received the Nobel Prize for Economics, is considered creative (Nasar, 1998). Although ideas deemed creative tend to depart from prevailing norms, they do not depart as much as other ideas that do not become widely acclaimed, as revealed by computerized content analysis of the melodic structure of classical music compositions (Simonton, 1980). Furthermore, the ideas appreciated as most creative do not arise completely independently of preceding works, instead rearranging or building upon previous ideas and connecting the results thereof with existing theories (Hospers, 1985; Ward, 1995; Weisberg, 1995). Even Einstein acknowledged that he could not have formulated the theory of relativity without the benefit of the discoveries of great physicists who came before him (Holton, 1981). Thus, although novelty is necessary for an idea to be judged as creative, it is not sufficient, suggesting the need for a twofold criterion of creativity.

### **1.1.2 Twofold process of creativity**

Paralleling this twofold definition of creativity, empirical findings have suggested a twofold creative process that includes generative and evaluative components. Interviews with and observations of artists, writers, musicians, scientists, and leaders have revealed they tend to alternate between generative and evaluative phases during creative work, though different theories have called them different names. For example, in insight problem solving, imagination enables the generation of solutions during the incubation and illumination stages, while reason allows the evaluation of relevant information and solutions during the preparation and verification stages (Wallas, 1926). Meanwhile, during painting, artists tend to fall into sequences starting with the generation and exploration of ideas, and following through with the evaluation and decomposition of the initial structures, which lead back to the re-generation and reconstruction of ideas (Israeli, 1962).

One model of the creative process termed the Geneplore model proposes that it begins with the generation of crudely formed ideas and associations, followed by their exploration through evaluation and testing (Finke, Ward, & Smith, 1992). Similarly, Campbell (1960) described the creative process 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. Basadur, Graen, and Green (1982) likewise divided the creative process into the subprocesses of ideation and evaluation. Thus, generation and evaluation appear to be a ubiquitous dichotomy in theories of the creative process, with novel ideas produced during the generative phase and their utility assessed during the subsequent evaluative phase.

### **1.1.3 The role of cognitive control in creativity**

Creative generation and evaluation are considered to be associated with employment of

different levels of cognitive control, which can be defined as the process of regulating information flow through attention and working memory functions (Desimone & Duncan, 1995; Miller & Cohen, 2001; Norman & Shallice, 1986). On the one hand, low cognitive control enables an associative mode of information processing that facilitates and ensures the generation of novel ideas (Howard-Jones & Murray, 2003). By allowing individuals to notice and store details that may be missed under conditions of high cognitive control (Gabora, 2010), low cognitive control gives them access to more diverse, non-obvious pieces of information to combine and use as building blocks for novel ideas (Vartanian, Martindale, & Kwiatkowski, 2007). It also lets them retrieve and process more information simultaneously (Wallach, 1970), a process that, combined with diffuse attention and encoding, increases their probability of forming more comprehensive and unusual connections or combinations. Not surprisingly, creative individuals are good at tasks requiring low cognitive control (Martindale, 1999) and display defocused attention, the tendency to not only focus on the relevant aspects of a situation but also notice seemingly irrelevant aspects (Ansburg & Hill, 2003; Carson, Peterson, & Higgins, 2003; Howard-Jones & Murray, 2003). Creative individuals are also good at tasks that require divergent thinking, a process that allows them to generate more and unusual ideas, solutions, and associations (Howard-Jones & Murray, 2003; Mednick, 1962).

On the other hand, high cognitive control enables an analytic mode of information processing that facilitates and ensures the evaluation of the utility of novel ideas (Howard-Jones & Murray, 2003). By doing so, it allows individuals to focus on the pertinent details of a task and to select the relevant generated ideas, keeping the information in working memory long enough to be evaluated as a possible solution (Gabora, 2010; Lepine, Bernardin, & Barrouillet, 2005). Creative individuals are also good at tasks that involve high cognitive control (Dietrich, 2004)

and require attention to be specifically focused on the relevant aspects of a task (Baker-Sennett & Ceci, 1996; Fodor, 1995; Marr & Sternberg, 1998). They are also good at convergent thinking tasks that require the analysis and integration of information in order to arrive at the relevant solution (Guilford, 1950).

Thus, in general, low cognitive control appears to facilitate creative generation while high cognitive control enables efficient creative evaluation. However, cognitive control can also hinder the creative process when used too much during generation, or too little during evaluation. For example, low cognitive control can slow down the processes required to choose an appropriate solution, thereby hindering the evaluation of novel ideas and associations (Dorfman, Martindale, Gassimova, & Vartanian, 2008; Vartanian et al., 2007). Similarly, high cognitive control can prevent non-obvious but relevant solutions from being noticed, thereby hindering creative generation (Dorfman et al., 2008; Vartanian et al., 2007). Hence, it has been proposed that it is advantageous for the creative individual to engage in generation and evaluation separately to minimize the interference evaluation may have on generation and vice versa (Finke et al., 1992; Gabora, 2010; Howard-Jones & Murray, 2003). Consistent with this, the practice of brainstorming, which involves the generation of ideas while deferring their evaluation, is known to increase the creativity of outputs (Basadur, Graen, & Green, 1982; Parnes & Meadow, 1959). Furthermore, alternating between low cognitive control to facilitate generation and high cognitive control to facilitate evaluation has been associated with greater creativity. Creative individuals exhibit differential focusing of attention during different tasks, suggesting that they alternate flexibly between low and high cognitive control depending on the situation (Ansburg & Hill, 2003; Dorfman et al., 2008; Rawlings, 1985; Vartanian et al., 2007). Thus, consistent with a twofold definition of creativity emphasizing both novelty and utility, the optimal creative process

appears to alternate between a generative mode facilitated by low cognitive control and an evaluative mode facilitated by high cognitive control. Consequently, an investigation of the neural correlates of these two modes of creative thought can help us obtain a more complete account of the neural basis of creativity.

## **1.2 Neuroscientific accounts of creativity**

### **1.2.1 Hemispheric differences and interactions**

Although extensive, neuroscientific research on creative thinking so far has yielded somewhat ambiguous results. One of the earliest and best-known brain theories of creativity emphasizes the importance of the right hemisphere, supported by the finding that patients often demonstrate enhanced artistic creativity following damage to the left prefrontal cortex, an area thought to inhibit creative right hemisphere processes (Finkelstein, Vardi, & Hod, 1991; Mendez, 2004; Miller et al., 1998, 2000). Sperry's (1964) research into split-brain patients suggests that the right hemisphere carries out associative, intuitive, and holistic processing that may facilitate creative generation (Barrett, Beversdorf, Crucian, & Heilman, 1998; Beeman et al., 1994; Faust & Lavidor, 2003; Robertson, Lamb, & Knight, 1988). Consistent with this, EEG studies have found evidence of right hemisphere dominance in artists (Bhattacharya & Petsche, 2002, 2005), as well as during insight (Jung-Beeman et al., 2004; Kounios et al., 2008) and divergent thinking tasks (Martindale, Hines, Mitchell, & Covello, 1984).

Follow-up studies of Sperry's split-brain patients, however, found that these patients lack integrated thought and have an impoverished fantasy life (Hoppe & Kyle, 1991; TenHouten, 1994). Furthermore, EEG and PET studies have also found increased activation in the left parietal cortex during hypothesis generation (Jin, Kwon, Jeong, Kwon, & Shin, 2006) and word association (Starchenko, Bekhtereva, Pakhomov, & Medvedev, 2003), as well as activation in

both hemispheres during creative story generation (Bekhtereva et al., 2000, 2001; Carlsson, Wendt, & Risberg, 2000). These findings suggest that left hemisphere functions, such as logical and detail-oriented processing (Sperry, 1964), may be as important as right-hemisphere processes for creative thinking, possibly by enabling the analytic, evaluative processing employed during creative thought (Heilman, Nadeau, & Beversdorf, 2003). Thus, despite the original emphasis on right hemisphere processes, the body of neuroscientific research indicates that hemispheric interactions may be more important for creativity than isolated right hemisphere activation.

### **1.2.2 Posterior-anterior cortical differences and interactions**

Another prevalent brain theory of creativity focuses on posterior-anterior cortical differences and interactions. Sudden increases in visual or musical artistic expression have been associated with primary progressive aphasia (frontotemporal degeneration usually accompanied by parietal gray matter increase) (Seeley et al., 2008), and frontotemporal dementia (Miller & Hou, 2004; Miller et al., 1998, 2000; Thomas Anterion, Honore-Masson, Dirson, & Laurent, 2002), suggesting disinhibition of creative parietal cortex processes. Consistent with this, altered states of consciousness associated with hypofrontality that occur during dreaming, drug use, and certain mental illnesses (e.g., schizophrenia and bipolar disorder) have often been linked to creative inspiration (Dietrich, 2003, 2007). EEG studies have also found evidence of decreased prefrontal cortex arousal during divergent thinking tasks (Fink & Neubauer, 2006; Molle et al., 1996, 1999; Razoumnikova, 2000, 2007). Thus, some researchers have theorized that the parietal cortex in the posterior part of the brain may facilitate creative generation through its broad attention and associative processes (Jung et al., 2009), enabling integration of multimodal sensory information for elaboration and abstraction (Jung & Haier, 2007).

However, with the exception of several isolated cases, more recent studies have found no evidence that a general increase in creativity results from frontal lobe dementias (Rankin et al., 2007). Other studies have found that creativity tends to peak several years before symptom onset and structural brain changes, subsequently decreasing when the disease becomes established (Seeley et al., 2008). In fact, deficits in creativity-related abilities, such as cognitive flexibility, abstraction, and integration, have been observed in patients after frontal lobectomies (Milner, 1984) and frontal lobe lesions (Flaherty, 2004; Jamison, 1989), and in schizophrenics showing hypofrontality (Norlander, 2000). Several EEG and PET studies have also found activation in both the frontal and parietal cortices during creative story generation (Bekhtereva et al., 2004), divergent thinking (Chavez-Eakle, Graff-Guerrero, Garcia-Reyna, Vaugier, & Cruz-Fuentez, 2007; Fink et al., 2009), fluid analogy formation (Geake & Hansen, 2005), and word association (Starchenko et al., 2003). These findings suggest that the frontal lobes are as important as posterior cortical regions for creative thinking, possibly by exerting a level of cognitive control that facilitates the analytic, evaluative processing required for creativity (Dietrich, 2004).

### **1.2.3 Neural network contributions**

#### **1.2.3.1 *Default network***

At the same time, other neuroscientific findings suggest that creative thinking may be supported by a highly distributed neural network rather than a single hemisphere or brain region. One network that may contribute to creative thinking is the default network (Raichle et al., 2001), which includes, most prominently, the medial prefrontal cortex (mPFC), posterior cingulate cortex (PCC)/precuneus, and temporoparietal junction (TPJ). Typically activated during conditions of low cognitive control, the default network becomes increasingly recruited during easy, familiar tasks or the absence of a task relative to novel, attention-demanding tasks

(Raichle, 1998; Shulman et al., 1997).

Default network regions have frequently been activated in creativity experiments. EEG, PET, and fMRI studies have found evidence of enhanced TPJ activity during divergent thinking tasks (Fink & Neubauer, 2006; Grabner, Fink, & Neubauer, 2007), creative story generation (Bekhtereva et al., 2004), hypothesis generation (Jin et al., 2006), fluid analogy formation (Geake & Hansen, 2005), and remote associates insight problems (Jung-Beeman et al., 2004; Subramaniam, Kounios, & Parrish, 2009). Creative story generation also recruits the mPFC (Howard-Jones, Blakemore, Samuel, Summers, & Claxton, 2005), while insight problems activate both the mPFC and PCC/precuneus (Geake & Hansen, 2005; Jung-Beeman et al., 2004; Kounios et al., 2006; Subramaniam et al., 2009). Moreover, Limb and Braun (2008) found activation of the default network and deactivation of the executive network (see Section 1.2.3.3) during improvisation by professional jazz pianists. The default network's relationship to low cognitive control suggests it may facilitate associative processing conducive to creative generation.

### *1.2.3.2 Medial temporal lobe memory network*

Often activated alongside default network regions, the medial temporal lobe memory network has been directly linked to memory retrieval (Squire, Stark, & Clark, 2004) and associative processing (Eichenbaum, 2000). The medial temporal lobe memory network, which includes the hippocampus and parahippocampus, is activated during the formation and retrieval of semantic and episodic associations (Aminoff, Gronau, & Bar, 2007; Bar, Aminoff, & Schacter, 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, Wong, & Schacter, 2007; Botzung, Denkova, & Manning, 2008; Hassabis, Kumaran, &

Maguire, 2007; Okuda et al., 2003; Szpunar, Watson, & McDermott, 2007). Moreover, the medial temporal lobe has also been implicated in the spontaneous replay of memories during rest in rats (Foster & Wilson, 2006; Sutherland & McNaughton, 2000), the spontaneous re-activation of memories in humans (Gelbard-Sagiv, Mukamel, Harel, Malach, & Fried, 2008), and spontaneous mental processing during rest (Christoff, Ream, & Gabrieli, 2004). Although it has not received substantial attention to date, medial temporal lobe activation is frequently reported during creativity experiments. For example, the hippocampus exhibits greater recruitment during visual art design (Kowatari et al., 2009) and divergent thinking (Fink et al., 2009). The associative function of the medial temporal lobe 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.

#### *1.2.3.3 Executive network*

Yet another network, the executive network, may contribute to creative thinking through its robust association with cognitive control. 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 & Duncan, 1995; Miller & Cohen, 2001). It is consistently activated during complex, cognitively demanding tasks requiring problem solving and reasoning, such as inductive and probabilistic reasoning tasks (Goel, Gold, Kapur, & Houle, 1997; Osherson et al., 1998), the Tower of London Test (Baker et al., 1996), the Wisconsin Card Sorting Test (WCST; Berman et al., 1995; Goldberg et al., 1998; Nagahama et al., 1996), and the Raven's Progressive Matrices Test (RPM; Prabhakaran, Smith, Desmond, Glover, & Gabrieli, 1997).

The dlPFC and dACC have also been found to be reliably activated during a variety of

creative tasks, including piano improvisation (Bengtsson, Csikszentmihalyi, & Ullen, 2007; Berkowitz & 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, Desmond, Glover, & Gabrieli, 2000), fluid analogy formation (Geake & Hansen, 2005), insight problem solving (Kounios et al., 2006; Subramaniam et al., 2009), visual art design (Kowatari et al., 2009), and hypothesis generation (Vartanian & Goel, 2005). Furthermore, in contrast to Limb and Braun's (2008) results of default network activation and executive network deactivation during music improvisation, Berkowitz and Ansari (2008) found activation of executive network areas and deactivation of default network regions during improvisation by classically-trained undergraduate pianists. The executive network is theorized to help implement the cognitive control required to activate and manipulate non-obvious but task-relevant information while inhibiting prepotent but irrelevant information (Heilman et al., 2003), thus facilitating the analytic, evaluative processing also required for performing creativity tasks.

#### **1.2.4 Questions that remain unanswered**

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 executive network may contribute to the cognitive control processes required during creative evaluation; *(ii)* the medial temporal lobe memory network may contribute associative processes that would enable creative generation; and *(iii)* the default network may contribute to creative generation through its role in low cognitive control. However, these predictions are indirect conjectures and have not been examined in the context of a single creative task.

Furthermore, no empirical investigations so far have directly investigated the distinction between creative generation and evaluation. In fact, some of the conflicting results in the neuroscientific literature on creativity may be accounted for by the lack of attention towards this dichotomy. For example, different tasks may require more or less generation and/or evaluation than other tasks, and thus lead to recruitment of different brain regions. Moreover, studies that do not investigate both processes or that do not independently study each process cannot definitively identify the individual roles of the different brain regions in creative thinking, and thus are only able to indirectly infer their roles. Thus, to address this research gap, the current study investigated the generative and evaluative modes independently of each other during the performance of a creativity task that required alternation between the two to identify the specific contributions of various brain areas to the creative process.

## **1.3 Current research**

### **1.3.1 Research objectives and overall approach**

The current study aimed to provide the first examination of both the generative and evaluative components of the creative process. It also aimed to investigate whether these two components differ at the neural level and, if so, which brain regions are associated with each component. In addition, it aimed to examine individual differences in neural activations related to the ability to engage in the two processes of creative generation and evaluation independent of each other, a characteristic of highly creative people.

To conduct such an examination, a novel paradigm was developed that separated and alternated between generative and evaluative modes during the performance of a modified creativity exercise (a visual book cover design task) used in visual arts and design programs. To complete the task, participants used an fMRI-compatible drawing tablet (Tam, Churchill,

Strother & Graham, 2009) that allowed them to actually draw or write their ideas and evaluations while in an fMRI scanner. By doing so, the study used a more ecologically valid approach compared to previous studies, most of which only required imagining solutions and designs during creativity tasks (Fink et al., 2007).

### **1.3.2 Hypotheses**

1. Creative generation and evaluation will differ at the neural level.
  - a. Generation will be associated with preferential activation of default network regions (mPFC, PCC/precuneus, and TPJ), as well as medial temporal lobe memory network regions (hippocampus and parahippocampus).
  - b. Evaluation will be associated with preferential activation of executive network regions (dlPFC and dACC).
2. Self-report measures of success during creative generation and evaluation will be positively correlated with recruitment of the brain regions involved in each process.
  - a. High self-reported success of engaging in creative generation while avoiding intrusions from evaluation will correspond to greater default network and medial temporal lobe recruitment.
  - b. High self-reported success of engaging in creative evaluation while avoiding intrusions from generation will correspond to greater executive network recruitment.

## 2 METHODS

### 2.1 Participants

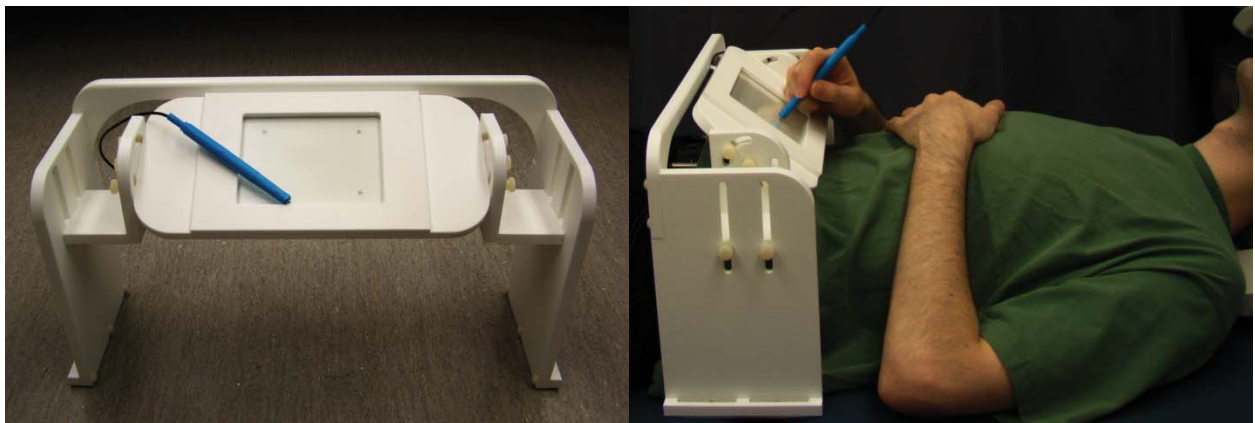
The participants ( $N = 15$ ; 9 females;  $M = 22.14$  years,  $SD = 2.25$  years) were undergraduates from the Emily Carr University of Art and Design (ECUAD; Vancouver, BC, Canada). All were right-handed with normal or corrected-to-normal vision, had no psychiatric history, and were screened for MRI compatibility. ECUAD students were recruited because they were able to continue generating new ideas during the task for the required 6-minute period of time. In contrast, in a pilot study, a sample of University of British Columbia (UBC) undergraduates had been unable to continue generating new ideas for the entire duration of a 6-minute session. All protocols were approved by the UBC Clinical Research Ethics Board and the UBC MRI Research Center (Appendix A). 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).

### 2.2 Book cover descriptions

Participants designed book covers 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 B for a full list of book descriptions.)

## 2.3 fMRI-compatible drawing tablet system

Participants used a custom-built fMRI-compatible drawing tablet system (Figure 1) that was an adapted version of the tablet that had been used by Tam et al. (2009). The tablet 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 that had an active area of 130 mm  $\times$  98 mm and was capable of 4096  $\times$  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 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).



**Figure 1. fMRI-compatible drawing tablet system.**

## 2.4 Procedure

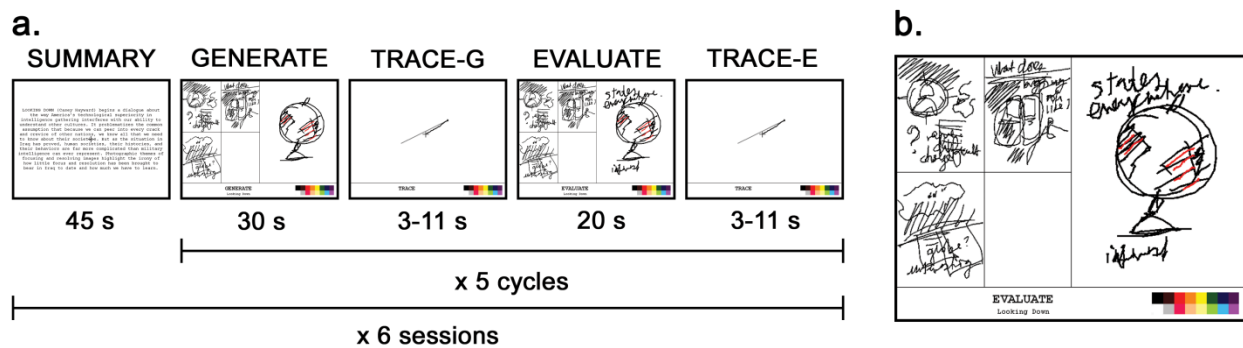
One to two days prior to the actual scanning session, participants engaged in a practice run to become familiar with the experimental procedures by performing the task and using the tablet in a mock scanner environment. The practice procedures were identical to the actual scanning procedures but used a different set of book descriptions (Appendix B). Before the task, participants completed two 3-minute practice creativity exercises selected from a group of related tasks that had been adapted from the Torrance Test of Creative Thinking (Torrance, 1966). One task was a figural task in which the participants added details to 10 shapes (circles, squares, diamonds, or jellybeans) to make as many different pictures as they could, and one was a verbal task in which they identified as many alternative uses for an item (a brick, carton, shoe, or tin can) as they could. The participants performed both visual and verbal exercises as warm ups to prevent the formation of drawing or writing biases that could affect their completion of the actual task.

For the main task, the participants worked on 6 book descriptions during separate scanning sessions. During each session, 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*) (Figure 2; see Appendix C for detailed instructions). This *generate-evaluate* cycle was repeated 5 times for each book description. The total length of each session was 6 minutes.

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. The *trace-g* and *trace-e* blocks provided a baseline that 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 each block, the remaining time was shown at the top right corner of the screen when only 5 s were left. The works produced during previous cycles were saved on the left side of the workspace for the participants' reference (see Figure 2).

After each 6-minute scanning session, 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*) (Appendix D).



**Figure 2. (a) Schematic of experimental paradigm. (b) Screenshot of an *evaluate* trial.**

## 2.5 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  $[FA] = 90^\circ$ , field of view  $[FOV] = 240 \times 240 \times 143$  mm, matrix size =  $80 \times 80$ , SENSE factor = 1.0). 191 functional volumes were acquired,

each with 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,  $FA = 90^\circ$ ,  $FOV = 224 \times 224 \times 143$  mm, acquisition matrix size =  $240 \times 235$ , reconstructed matrix size =  $480 \times 470$ , inversion delay [IR] = 800 ms, spin echo turbo factor = 5).

## **2.6 fMRI data preprocessing**

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 (18<sup>th</sup>) 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  $2 \times 2 \times 4$  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, Jezzard, & Turner, 1994).

## **2.7 fMRI data analyses**

### **2.7.1 Whole brain analyses**

Statistical analysis was performed at each voxel to assess the magnitude of differences

between the conditions of interest. 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. 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. The model included: (i) the observed time-series of intensity values, representing the dependent variable; (ii) covariates modeling session-specific effects, later treated as confounds; and (iii) regressor functions constructed by convolving condition-specific boxcar functions with a synthetic hemodynamic response function. Regressors 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  $p < 0.05$  false discovery rate (FDR) corrected for multiple comparisons and  $k > 20$  voxels.

### **2.7.2 Regions of interest analyses**

Activation time courses were extracted from the preprocessed functional images from each session 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 medial temporal lobe, 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.

### **2.7.3 Self-rated success covariates**

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 sessions. 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 peak voxels in the medial temporal lobe, default network, and executive network. Threshold for significance was set at  $p < 0.005$  uncorrected for multiple comparisons and  $k > 5$  voxels.

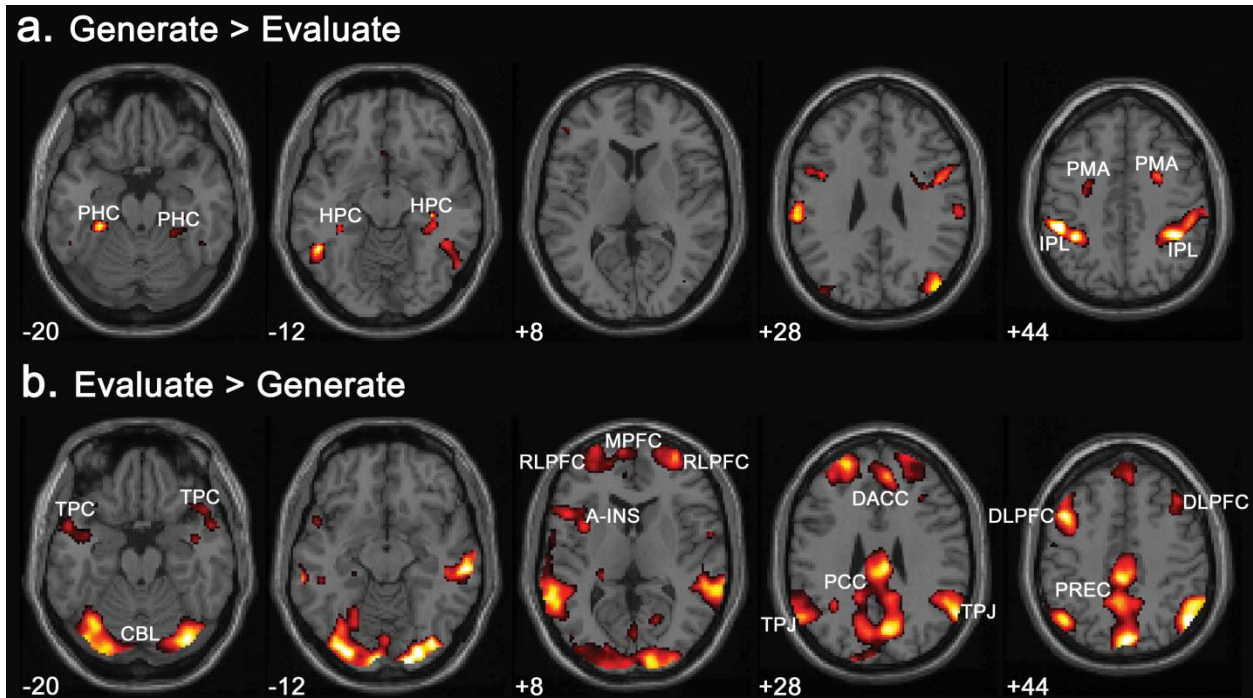
### **2.7.4 Functional connectivity**

To perform functional connectivity analyses, time courses from 4-mm radius spheres centered on local maxima in executive and default networks regions (from the *evaluate* > *generate* group-level contrast) were extracted for each participant, globally scaled, and band-pass filtered (using the cut-offs from Section 2.7.2). The ROIs or seed regions included the dACC and right dlPFC from the executive network, and the mPFC and PCC from the default network. 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.

### 3 RESULTS

To identify the brain regions that demonstrated relatively increased recruitment during the different tasks, each condition was compared to the opposite condition (*generate* > *evaluate* and *evaluate* > *generate*) and to its corresponding baseline (*generate* > *trace-g* and *evaluate* > *trace-e*). The *generate* > *evaluate* contrast (Figure 3a, Table 1) revealed significant activation in the medial temporal lobe, 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  $x, y, z = 34, -38, -16$ ;  $Z = 3.65$ ). The *evaluate* > *generate* contrast (Figure 3b, Table 2) revealed significant activation in the executive network, including dACC (BA 24/32; peak  $x, y, z = 8, 44, 28$ ;  $Z = 3.94$ ), left dlPFC (BA 8/9; peak  $x, y, z = -44, 14, 44$ ;  $Z = 4.51$ ), and right dlPFC (BA 8/9; peak  $x, y, z = 42, 26, 44$ ;  $Z = 3.20$ ), and in the default network, including mPFC (BA 9/10; peak  $x, y, z = 6, 44, 32$ ;  $Z = 3.69$ ), 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  $x, y, z = 66, -40, 4$ ;  $Z = 4.34$ ). Notable activations were also observed in bilateral rostromedial PFC (rIPFC), bilateral cerebellum, bilateral temporopolar cortex, and left anterior insula for the *evaluate* > *generate* contrast.



**Figure 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). (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 rIPFC, cerebellum (CBL), temporopolar cortex (TPC), and left anterior insula (A-INS). All activations were significant at  $p < .05$  FDR-corrected and  $k > 20$ .

**Table 1. Activation peaks during creative generation.**

Region	L/R/M	BA	MNI coordinates			Voxels	Z value
			x	y	z		
Frontal							
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
Parietal							
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
Temporal							
Hippocampus (HPC)	L	-	-32	-40	-4	80	4.40
Hippocampus (HPC)	R	-	36	-26	-12	99	3.92
Parahippocampus (PHC)	L	36	-30	-34	-20	71	4.35
Parahippocampus (PHC)	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
Subcortical							
Cerebellum	L	-	-14	-72	-48	55	3.58

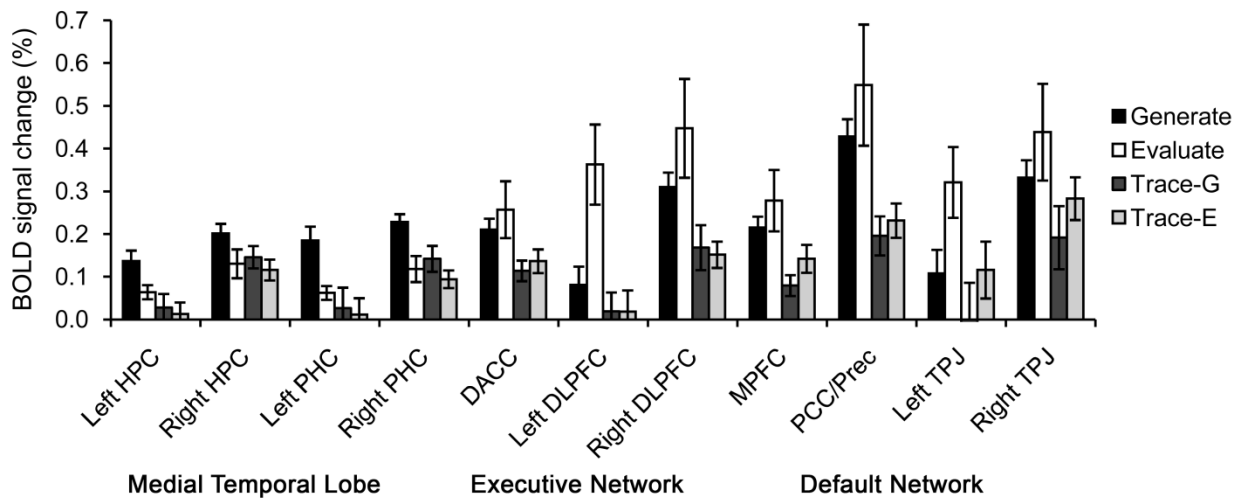
*Generate > evaluate* contrast. All activations were significant at  $p < .05$  FDR-corrected and  $k > 20$ .

**Table 2. Activation peaks during creative evaluation.**

Region	L/R/M	BA	MNI coordinates			Voxels	Z value
			x	y	z		
Frontal							
Supplementary motor area	M	6	-2	12	68	141	3.03
Dorsal ACC	M	24/32	8	44	28	40	3.94
Medial frontal gyrus (mPFC)	M	9/10	6	44	32	75	3.69
Superior frontal gyrus (rlPFC)	L	9/10	-22	54	28	1170	4.19
Superior frontal gyrus (rlPFC)	R	9/10	32	58	16	1073	4.19
Middle frontal gyrus (dlPFC)	L	8/9	-44	14	44	382	4.51
Middle frontal gyrus (dlPFC)	R	8/9	42	26	44	183	3.20
Inferior frontal gyrus (vlPFC)	L	47	-32	56	-4	168	3.24
Inferior frontal gyrus (vlPFC)	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
Parietal							
Superior parietal lobule	L	7	-44	-66	48	563	4.36
Superior parietal lobule	R	7	50	-66	44	1906	5.02
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
Precuneus	M	7	0	-32	44	773	4.35
Posterior cingulate cortex	M	23/31	4	-30	24	1035	4.50
Temporal							
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
Occipital							
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
Subcortical							
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

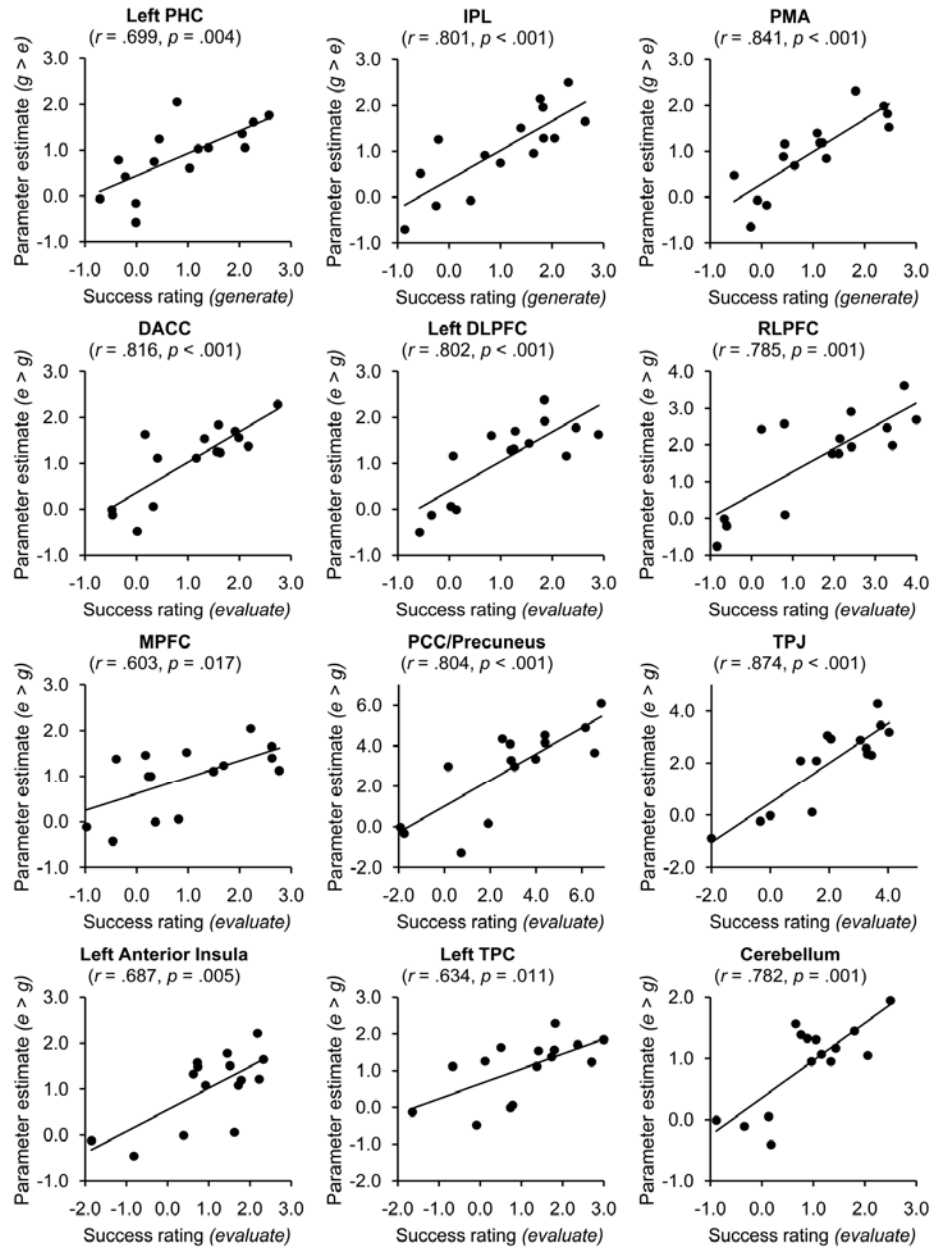
*Evaluate > generate* contrast. All activations were significant at  $p < .05$  FDR-corrected and  $k > 20$ .

Due to the low power of comparing 30-s generation blocks and 20-s evaluation blocks to much shorter 3 to 11-s tracing blocks, the *generate* > *trace-g* and *evaluate* > *trace-e* contrasts could not indicate the presence of significant activations at the specified threshold. However, a more lenient threshold of  $p > .05$  uncorrected for multiple comparisons revealed the same pattern of activations as the *generate* > *evaluate* and *evaluate* > *generate* contrasts. In addition, peak BOLD percent signal change from ROI spheres centered on local maxima in the medial temporal lobe (hippocampus and parahippocampus), executive network (dACC and dlPFC), and default network (mPFC, PCC/precuneus, and TPJ) showed that they were more active during generation and evaluation relative to the tracing baselines (Figure 4), demonstrating that the observed results were not due to deactivations during the opposite conditions.



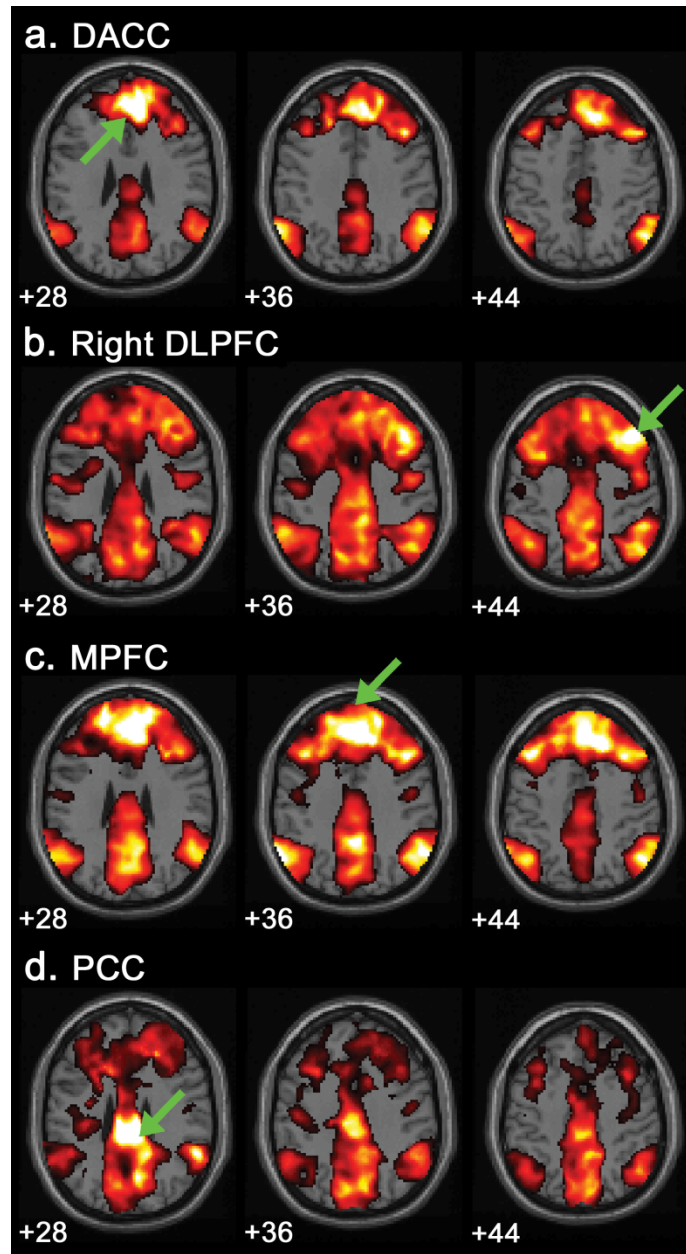
**Figure 4. BOLD percent signal change in activated regions.** Histograms represent mean peak BOLD percent signal change for each condition in 4-mm radius spheres centered on local maxima in the medial temporal lobe (*left*), executive network (*middle*), and default network (*right*), showing the results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

Furthermore, covariate analyses (Figure 5) revealed that generation success ratings were positively correlated with responses in the medial temporal lobe, specifically the left parahippocampus (BA 36; peak  $x, y, z = -30, -36, -20$ ;  $r = .699, p = .004$ ), as well as the left IPL (BA 40; peak  $x, y, z = -48, -36, 44$ ;  $r = .784, p = .001$ ), right IPL (BA 40; peak  $x, y, z = 40, -42, 44$ ;  $r = .675, p = .006$ ), left PMA (BA 6; peak  $x, y, z = -28, -2, 52$ ;  $r = .639, p = .010$ ), and right PMA (BA 6; peak  $x, y, z = 30, 4, 52$ ;  $r = .679, p = .005$ ). Meanwhile, evaluation success ratings were positively correlated with responses in the executive network, including the dACC (BA 24/32; peak  $x, y, z = 8, 42, 32$ ;  $r = .816, p < .001$ ) and left dlPFC (BA 8/9; peak  $x, y, z = -38, 8, 44$ ;  $r = .802, p < .001$ ), as well as the default network, including the mPFC (BA 9/10; peak  $x, y, z = -8, 64, 4$ ;  $r = .603, p = .017$ ), PCC/precuneus (BA 31/7; peak  $x, y, z = -2, -32, 40$ ;  $r = .804, p < .001$ ), left TPJ (BA 39/40; peak  $x, y, z = -56, -64, 32$ ;  $r = .742, p = .002$ ), and right TPJ (BA 39/40; peak  $x, y, z = 48, -64, 44$ ;  $r = .914, p < .001$ ). Evaluation success ratings were also positively correlated with responses in the left rlPFC (BA 9/10; peak  $x, y, z = -22, 50, 24$ ;  $r = .753, p = .001$ ), right rlPFC (BA 9/10; peak  $x, y, z = 32, 56, 20$ ;  $r = .768, p = .001$ ), left anterior insula (peak  $x, y, z = -34, 4, 8$ ;  $r = .687, p = .005$ ), left temporopolar cortex (BA 38; peak  $x, y, z = -52, 6, -24$ ;  $r = .634, p = .011$ ), left cerebellum (peak  $x, y, z = -24, -74, -36$ ;  $r = .665, p = .007$ ), and right cerebellum (peak  $x, y, z = 18, -76, -36$ ;  $r = .731, p = .002$ ).



**Figure 5. Correlations between successful creative generation and evaluation and responses in activated regions.** Scatter plots show a positive correlation between successfully engaging in generation while avoiding evaluation and parameter estimates in peak voxels (from the covariate analyses) of the left parahippocampus (PHC), bilateral IPL and bilateral PMA (*first row*), and 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 (*second row*), default network (mPFC, PCC/precuneus, and bilateral TPJ) (*third row*), and left anterior insula, left temporopolar cortex (TPC) and bilateral cerebellum (*fourth row*). Points represent the mean success self-ratings during generation or evaluation for each participant. Bilateral data were obtained by averaging data from each left and right region, which also showed significant positive correlations between success ratings and parameter estimates.

Finally, confirming the co-activation of the executive and default networks seen in the *evaluate* > *generate* contrast, functional connectivity analyses revealed that activity throughout the entire experiment in executive network regions, including the dACC (seed center  $x, y, z = 8, 44, 28$ ; Figure 6a) and right dlPFC (seed center  $x, y, z = 42, 26, 44$ ; Figure 6b), was highly correlated with activity in default network regions, with the left dlPFC showing similar results as the right dlPFC. Similarly, activity in default network regions, including the mPFC (seed center  $x, y, z = 6, 44, 32$ ; Figure 6c) and PCC (seed center  $x, y, z = 4, -30, 24$ ; Figure 6d), was also highly correlated with activity in executive network regions, with the left and right TPJ showing similar results as the mPFC and PCC. The same patterns of functional connectivity were also observed for the *evaluate* condition separately.



**Figure 6. Functional connectivity maps of executive and default network regions.** Activity throughout the task in 4-mm radius spheres centered on local maxima (from the *evaluate* > *generate* 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. The left dLPFC showed similar results as the right dLPFC. Activity in 4-mm radius spheres centered on local maxima in the default network, including the (c) mPFC (center  $x, y, z = 6, 44, 32$ ) and (d) PCC (center  $x, y, z = 4, -30, 24$ ), was also highly correlated with activity in executive network regions. The left and right TPJ also showed similar results as the mPFC and PCC. All correlations were significant at  $p < .05$  FDR-corrected and  $k > 20$ .

## 4 DISCUSSION

To examine the hypothesis that creative generation and evaluation are associated with the recruitment of distinct neural processes, the current study aimed to identify and distinguish between the roles of different brain networks during creative thought by separately examining the two fundamental processes of creative generation and evaluation. Consistent with the hypothesized preferential role of the medial temporal lobe in creative generation, contrasting generation with evaluation demonstrated activation in the medial temporal lobe, including the hippocampus and parahippocampus. Similarly, consistent with the hypothesized role of the executive network in creative evaluation, contrasting evaluation with generation was found to be associated with the recruitment of executive network regions, including the dlPFC and dACC. However, contrary to the prediction of preferential default network involvement in creative generation, default network regions, including mPFC, PCC/precuneus, and TPJ, were found to be preferentially activated during creative evaluation to a greater extent than during creative generation. Confirming this co-activation of the executive and default networks, functional connectivity analyses revealed that activity in the two networks were highly correlated throughout the task. Thus, creative evaluation was found to be associated with parallel recruitment of the executive and default network regions.

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 deactivations during the opposite condition. Covariate analyses across participants revealed that the more successfully they were able to engage in creative generation while avoiding evaluative processes, the stronger was the recruitment of medial temporal lobe regions associated with creative generation in the group analysis. Similarly,

the more successfully they were able to engage in creative evaluation while avoiding generative processes, the stronger was the recruitment of executive and default regions associated with creative evaluation in the group analysis.

#### **4.1 Generative processing during creative thinking**

The current results suggest that medial temporal lobe regions may be central to thought generation, supporting a number of previous studies that indirectly suggested the medial temporal lobe is linked 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 medial temporal lobe (Foster & Wilson, 2006; Sutherland & McNaughton, 2000). The spontaneous re-activation of memories in humans has also been associated with neural activity in the medial temporal lobe (Gelbard-Sagiv et al., 2008), and spontaneous mental processing during rest conditions has been found to consistently recruit the medial temporal lobe (Binder et al., 1999; Christoff et al., 2004; Stark & Squire, 2001).

Furthermore, beyond the simple memory processing traditionally ascribed to the medial temporal lobe, recent findings suggest an associative and constructive function of the medial temporal lobe that may allow it to generate novel ideas and thought content. These findings suggest that the medial temporal lobe may be more active during the formation and retrieval of semantic and episodic associations than during single item processing, with specifically pronounced activation in the parahippocampus (Aminoff et al., 2007; Bar et al., 2008; Henke et al., 1997, 1999; Rombouts et al., 1997). Although the medial temporal lobe is activated during both past and future events processing (Botzung et al., 2008; Szpunar et al., 2007), 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 medial temporal lobe functions. Consistent with this, imagining novel, fictitious scenes activates the same medial temporal lobe regions as future event simulation, suggesting the results are not restricted to the latter (Hassabis et al., 2007).

Mental simulations also appear to underlie the spatial navigation tasks and theory of mind judgments that frequently recruit the medial temporal lobe (Schacter & 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 & Addis, 2009). Thus, preferential activation of medial temporal lobe regions during creative generation is consistent with psychological accounts that describe creative thinking as enhanced associative processing (Gabora, 2010) and the restructuring of preexisting ideas (Hospers, 1985; Weisberg, 1995). While the present results suggest an intriguing link between the generation of new thoughts during creative thinking and medial temporal lobe processes, identifying the precise nature of the relationship between medial temporal lobe recruitment and creative generation remains a task for future research.

## **4.2 Evaluative processing during creative thinking**

### **4.2.1 Cognitive control**

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 & Duncan, 1995; Miller & 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 either increased or decreased cognitive control (Carter, Botvinick, & Cohen, 1999; Carter et al., 1998). The dlPFC may then implement the cognitive control required (Carter & van Veen, 2007; MacDonald, Cohen, Stenger, & Carter, 2000) and select the necessary response (Bunge, Wendelken, Badre, & Wagner, 2005; Hadland, Rushworth, Passingham, Jahanshahi, & Rothwell, 2001; Rowe, Toni, Josephs, Frackowiak, & Passingham, 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, Daselaar, Dobbins, & Cabeza, 2006).

Although not necessarily considered part of the executive network, the rostrolateral PFC (rlPFC), which was activated during creative evaluation, also contributes to cognitive control (Braver, Reynolds, & Donaldson, 2003; Ramnani & Owen, 2004). Various mental processes ranging from relational integration (Christoff et al., 2001) and rule induction (Strange, Henson, Friston, & Dolan, 2001) to post-retrieval evaluation of memory (Rugg, Fletcher, Frith, Frackowiak, & Dolan, 1996) and prospective memory (Burgess, Quayle, & Frith, 2001) have been linked to the rlPFC, suggesting that a unifying function of the rlPFC may be the evaluation of internally or self-generated cognitive information to guide behavior (Christoff & Gabrieli, 2000; Christoff, Ream, Geddes, & Gabrieli, 2003).

Creative evaluation has also been 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, Kahn, Snyder, Raichle, &

Buckner, 2008). The dlPFC and IPL also form an executive control network proposed by Seeley and colleagues (2007) that directs attention and control processing in posterior sensorimotor regions. Another frontoparietal control network consisting of the dlPFC, IPL, and precuneus initiates and adjusts top-down control (Dosenbach, Fair, Cohen, Schlaggar, & Petersen, 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 and cognitive analytical processing is an essential part of creative evaluation.

#### **4.2.2 Affective and viscerosensitive evaluative processing**

Creative evaluation, however, was also associated with recruitment of areas not typically associated with deliberate or cognitive analytical processing, such as the default network and the so-called 'salience network'. 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 & Decety, 2004) and emotional mental state attribution (Mitchell, Banaji, & Macrae, 2005). The mPFC specifically has also been linked to the evaluation of internally generated affective information (Damasio, 2000; Gusnard, Akbudak, Shulman, & Raichle, 2001; Lane, Fink, Chau, & Dolan, 1997; Zysset, Huber, Ferstl, & von Cramon, 2002).

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, Andrews-Hanna, & Schacter, 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 & 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 & Lamm, 2008). The PCC/precuneus may further integrate information from the association cortices (e.g., TPJ) and memory regions (e.g., medial temporal lobe), as well as serve as the interface between the mPFC and TPJ by representing the relevant internally generated information (Buckner et al., 2008; Vogt & 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 part of the 'salience network', which integrates highly processed sensory data with interoceptive-autonomic information to allow individuals to decide what to do or not to do next (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, Wiens, Rotshtein, Ohman, & Dolan, 2004). The temporopolar cortex, meanwhile, may bind complex perceptual input to visceral, emotional input from the anterior insula and amygdala (Olson, Plotzker, & Ezzyat, 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 convey the importance of affective and viscerosensitive forms of evaluative processing during creative thought.

### **4.2.3 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. In general, the executive and default networks have been theorized to act in opposition to each other such that the default network becomes deactivated or actively suppressed when the executive network becomes activated, and vice versa (Fox et al., 2005; Greicius, Krasnow, Reiss, & Menon, 2003; Weissman, Roberts, Visscher, & Woldorff, 2006). However, more recent studies have found co-activation of the executive and default networks in the context of mind wandering (Christoff, Gordon, Smallwood, Smith, & Schooler, 2009) and naturalistic film viewing (Golland et al., 2006). 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., 2006; Subramaniam et al., 2009) and dlPFC, ACC, PCC/precuneus, and TPJ during a fluid analogy task (Geake & Hansen, 2005). Hence, it appears that creative evaluation is a unique combination of otherwise mutually exclusive processes, one that recruits deliberate and spontaneous, and cognitive and affective processes. Creative evaluation may thus be an enhanced form of analytic processing that combines information and processes that do not usually act in tandem to produce optimal thinking conditions.

## **4.3 Future directions**

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 session, 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. Obtaining similar results in an experiment employing the high temporal resolution of EEG measures, in combination with ongoing verbal self-reports (Ericsson & Simon, 1993) during an unrestricted generation-evaluation cycle, could provide further support for and augment the current fMRI results. Future experiments could also investigate whether a population of participants with little to no visual arts training would yield results similar to those from the present study, as well as whether 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) would produce similar or different results. One caveat that will need to be kept in mind is that the UBC undergraduates who participated in the pilot study could only perform the task for a short period of time before running out of ideas, which would have led to fewer trials and thus lower statistical power.

In addition, 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. Future work could also investigate the neural mechanisms of different generative (e.g., application, analogy, combination, or abstraction) and evaluative (e.g., verification, judgment, testing, or inference) operations in the context of a creative task (Welling,

2007). Finally, research aimed at determining whether creative thinking training that emphasizes separating and alternating between the generation and evaluation of creative thinking leads to enhanced activation in the brain regions and networks described in the current study could provide further insights into the neural mechanisms of creative thought.

## **4.4 Conclusions**

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 and not directly examined. 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 and flexibly alternate between contradictory modes of thought, such as the generation of novel ideas and their critical evaluation, and deliberate, cognitive, spontaneous, and affective processing. Although questions remain, the findings provide a valuable starting point for designing studies that can provide an even more detailed account of how the brain supports creative thinking and of the types of processing that facilitate it.

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# APPENDICES

## Appendix A: Ethics approval certificate

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1 of 1



The University of British Columbia  
Office of Research Services  
Clinical Research Ethics Board – Room 210, 828 West 10th Avenue, Vancouver, BC  
V5Z 1L8

### ETHICS CERTIFICATE OF EXPEDITED APPROVAL: RENEWAL

<b>PRINCIPAL INVESTIGATOR:</b> Kalina Christoff	<b>DEPARTMENT:</b> UBC/Arts/Psychology, Department of	<b>UBC CREB NUMBER:</b> H08-02632
<b>INSTITUTION(S) WHERE RESEARCH WILL BE CARRIED OUT:</b>		
<b>Institution</b> UBC Other locations where the research will be conducted: N/A		<b>Site</b> Vancouver (excludes UBC Hospital)
<b>CO-INVESTIGATOR(S):</b> Irene Liu Ronald Graeme McCaig Melissa Ellamil Heather Mann		
<b>SPONSORING AGENCIES:</b> - Natural Sciences and Engineering Research Council of Canada (NSERC) - "Functions and organization of the human lateral prefrontal cortex"		
<b>PROJECT TITLE:</b> Visual and verbal problem solving		
<b>EXPIRY DATE OF THIS APPROVAL:</b> November 18, 2010		
<b>APPROVAL DATE:</b> November 18, 2009		
<b>CERTIFICATION:</b> <b>In respect of clinical trials:</b> 1. The membership of this Research Ethics Board complies with the membership requirements for Research Ethics Boards defined in Division 5 of the Food and Drug Regulations. 2. The Research Ethics Board carries out its functions in a manner consistent with Good Clinical Practices. 3. This Research Ethics Board has reviewed and approved the clinical trial protocol and informed consent form for the trial which is to be conducted by the qualified investigator named above at the specified clinical trial site. This approval and the views of this Research Ethics Board have been documented in writing.		
The Chair of the UBC Clinical Research Ethics Board has reviewed the documentation for the above named project. The research study, as presented in the documentation, was found to be acceptable on ethical grounds for research involving human subjects and was approved for renewal by the UBC Clinical Research Ethics Board.		
Approval of the Clinical Research Ethics Board by one of:  Dr. Peter Loewen, Chair Dr. James McCormack, Associate Chair		

## Appendix B: Book descriptions

### Practice session

*ASK NOT* (Johnny Symons) explores the effects of the U.S. military's "don't ask, don't tell", and exposes the tangled political battles that led to the discriminatory law and examines the societal shifts that have occurred since its passage in 1993. Current and veteran gay soldiers reveal how the policy affects them during their tours of duty, as they struggle to maintain a double life, uncertain of whom they can trust. From a national speaking tour of conservative universities to protests at military recruitment offices, these public events question how the U.S. military can claim to represent democracy and freedom while denying one segment of the population the right to serve.

*IMMACULATE CONFESSION* (Simone Grudzen) chronicles the extraordinary lives of Roman Catholic priests and nuns forced to make a choice between religious celibacy and romantic intimacy. These featured priests and nuns felt called to dedicate their lives to God. After years of working side-by-side in service to the church, something happened that changed everything: they fell in love. Faced with excommunication, financial ruin, and rejection by family and the religious community, they were forced to make an excruciating decision. The film explores the conflict between loyalty to the Church and acceptance of individual truth and the difficulty of merging spiritual and sexual identities among the clergy.

Abortion is illegal in Ireland, North and South, potentially punishable by life imprisonment. Yet at least 8,000 Irish women a year travel to England for abortions. *LIKE A SHIP IN THE NIGHT* (Melissa Thompson) follows a young painter, a working class mother of five, and a self-proclaimed country girl as they plan their secret journeys across the Irish Sea. At the end of a long, often emotional journey, they are afraid to tell anyone where they have been or what they have been through. Although the three women begin their journeys with different views on abortion rights, they all return silenced, terrified and angry at their country.

*SOLDIERS IN THE ARMY OF GOD* (Marc Levin) presents the tin soldiers who are behind more than 2,400 incidents of violence against doctors and abortion clinics in the past 28 years. This is a story about the people who are not exercising first amendment rights, they are not trying to "counsel" patients; they are not peaceful picketers. They are - intentionally, openly and usually without restraint - terrorizing people and encouraging others to do the same. They joyfully celebrate murder and maiming, hold banquets and give awards lauding those guilty of arson, bombing, and murder. And yet it's all done as an act of faith.

War is fought one bullet, one rifle, one soldier at a time. *SOLDIERS OF CONSCIENCE* (Gary Weimberg) looks at what it takes to enable soldiers to kill, and what it takes for some soldiers to refuse to kill. From West Point grads to drill sergeants, from Abu Ghraib interrogators to low ranking reservist-mechanics, soldiers in the U.S. Army today reveal their deepest moral concerns about what they are asked to do in war. Their message: every soldier wrestles with his conscience over killing. Although most decide to kill, some refuse. The book reveals that far more soldiers refuse to kill than we might expect.

Millions of Americans fought for the liberation of Europe from Hitler's grip during World War II. Yet 40,000 Americans refused to shoulder weapons in "the good war" because their conscience would not allow them to kill another human being. *THOSE WHO REFUSED TO FIGHT* (Rick Tejada) is a book about personal courage, idealism, and nonconformity based on both ethical and religious beliefs - about men whose love of country could not extend to killing their fellow man. In the face of criticism and scorn, the men went against the tide of the most popular and justifiable war of the 20th century and challenged the limits of democracy in wartime.

## Scanning session

Set in Kenya and Uganda, *ABSTAINING FROM REALITY* (Daniele Anastasion) demonstrates in stark and powerful detail the grave consequences of the Bush administration's abstinence-only approach to HIV prevention as part of its global HIV/AIDS assistance, and examines how these ideologically-driven programs are actually endangering the people they're supposed to be protecting. This policy is disconnected from the reality of the lives of women and young people, who are disproportionately affected by the epidemic. It urges a balanced, comprehensive approach to preventing HIV infections by providing full and accurate information and a range of services that empower individuals to make informed decisions.

*BROTHERS AND OTHERS* (Nicolas Rossier) follows a number of immigrant and American families as they struggle under the heightened climate of suspicion, Federal Bureau and Immigration and Naturalization Service investigations, and economic hardships that erupted in the United States following the attacks on the World Trade Center and the Pentagon on September 11, 2001. In interviews with Arab and Muslim immigrants, government representatives, and a select group of legal and historical experts, this book explores how America's fear of terrorism has negatively impacted a substantial portion of the American population.

Focusing on the human costs of the war in Iraq, *INDEPENDENT INTERVENTION* (Tonje Schei) contrasts the American mass media's coverage of the invasion of Iraq with independent reports of the brutal realities on the ground. As the major U.S. networks remove human suffering from their presentation of war, Operation Iraqi Freedom is portrayed as a success for the spread of democracy and freedom. The book brings awareness to the disparity between the war the American people see through the corporate-controlled media and the realities on the ground in Iraq, and explores how the growing media democracy movement in the U.S. works to challenge the mass media.

Does the solution to the conflict between Israelis and Palestinians rest in the classroom rather than in the angry, fearful streets of the region? *LESSONS IN FEAR* (James Cullingham) explores how ordinary kids, who find themselves on the front lines intellectually and physically, are educated in one of the world's trouble spots. Their battleground is one of knowledge and self-examination. Their challenges are a deeply engrained culture of violence, the denial of history, and legacies of hatred, propaganda and segregation. The book is not a litany of wrongs, but

rather an unvarnished look at the struggle to make education a positive force in Israel and Palestine.

*LOOKING DOWN* (Casey Hayward) begins a dialogue about the way America's technological superiority in intelligence gathering interferes with our ability to understand other cultures. It problematizes the common assumption that because we can peer into every crack and crevice of other nations, we know all that we need to know about their societies. But as the situation in Iraq has proved, human societies, their histories, and their behaviors are far more complicated than military intelligence can ever represent. Photographic themes of focusing and resolving images highlight the irony of how little focus and resolution has been brought to bear in Iraq to date and how much we have to learn.

*WELL-FOUNDED FEAR* (Shari Robertson) looks at the process of granting political asylum to the United States. Who deserves it? Who gets it? Who decides? Entering the closed corridors of the U.S. Immigration and Naturalization Service the authors uncover a world where American ideals about human rights collide with the nearly impossible task of trying to know the truth. The authors talk to the asylum officers, lawyers, translators, economic migrants, and refugees looking for protection, focusing on the confidential interviews that are at the heart of the asylum process and for some, a matter of life or death.

## Appendix C: Instructions

*TASK:* Design a book cover according to the summary given.

*GENERATE:* Draw or write down ideas or images for the cover you have at that moment. Everything that pops into your head is OK. The most important thing is to come up with as many ideas as you can. The more you come up with, the better. It may be difficult to do, but try not to evaluate or criticize those ideas - try to do that only in the *EVALUATE* phase.

*TRACE:* Trace over the lines that appear on the screen.

*EVALUATE:* Consider the success of the results of the previous *GENERATE* phase. Which ideas work and which do not? Pay attention to your gut reaction. Do you want to develop any of the ideas further, leave them for further consideration, or replace them altogether? Record your gut reaction with whatever evaluation shorthand suits you: a few words, phrases, checkmarks, question marks, or crossings out. It may be difficult to do, but try not to generate new ideas - try to do that only in the *GENERATE* phase.

## Appendix D: Debriefing questions

What ideas did you want to convey with this image?

On a scale of 1 to 10, how successful were you in following the instructions during this  
*GENERATE* phase?

-

1 = *UNSUCCESSFUL*. You were evaluating the whole time.

10 = *SUCCESSFUL*. You were able to avoid any evaluation.

What reactions or evaluations did you have?

On a scale of 1 to 10, how successful were you in following the instructions during this  
*EVALUATE* phase?

-

1 = *UNSUCCESSFUL*. You were generating the whole time.

10 = *SUCCESSFUL*. You were able to avoid any generation.