Creativity and the brain: Uncovering the neural signature of conceptual expansion

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ABSTRACT

Neurophysiological studies of creativity thus far have not allowed for clear conclusions to be made regarding the specific neural underpinnings of such complex cognition due to overgeneralizations concerning the creativity construct, heterogeneity in the type of creativity tasks used, and the questionable efficacy of the employed comparison tasks. A novel experimental design was developed in the present fMRI study which rendered it possible to investigate a critical facet of creative cognition – that of conceptual expansion – as distinct from general divergent thinking, working memory, or cognitive load. Brain regions involved in the retention, retrieval and integration of conceptual knowledge such as the anterior inferior frontal gyrus, the temporal poles and the lateral frontopolar cortex were found to be selectively involved during conceptual expansion. The findings go against generic ideas that argue for the dominance of the right hemisphere during creative thinking and indicate the necessity to reconsider the functions of regions such as the anterior cingulate cortex to include more abstract facets of cognitive control. This study represents a new direction in the investigation of creativity in that it highlights the necessity to adopt a process based perspective in which the multifaceted nature of creativity can be truly grasped.

1. Introduction

Our fundamental capacity to be creative is a subject of much fascination to scientists and lay people alike. Although several efforts in the field of psychology and neuroscience have been levelled at dispelling the aura of inscrutability surrounding this complex ability, far more conceptual and empirical work is necessary to develop a thorough understanding of this multi-faceted construct (Dietrich, 2007; Dietrich & Kanso, 2010).

While psychological investigations of creativity are challenging for several reasons, the neuroscientific study of creative thinking is especially problematic because of implementation difficulties associated with adapting common creativity tasks when using almost any method (Abraham & Windmann, 2007). For instance, most creativity tasks do not have an objective yes/no answer (e.g., Carlsson, Wendt, & Risberg, 2000) and often require drawing or verbal responses (e.g., Jung-Beeman et al., 2004), which can lead to movement related artefacts in brain data. Many

tasks are also untimed or of long duration or consist of very few trials (e.g., Chavez-Eakle, Graff-Guerrero, Garcia-Reyna, Vaugier, & Cruz-Fuentes, 2007)—in both these cases what is compromised is the possibility of having a large enough number of trials to ensure a good average response. There are also conceptual problems that are difficult to overcome (Dietrich & Kanso, 2010) such as not being able to prompt creativity volitionally or predictably as well as being unable to often define the actual time point at which a person produced a creative response within an extended trial (e.g., Fink et al., 2009).

Another severe problem in most neuroimaging studies of creativity is that the comparison control task is usually less difficult or cognitively demanding than the creative task (e.g., Bechtereva et al., 2004; Fink et al., 2009; Starchenko, Bekhtereva, Pakhomov, & Medvedev, 2003; Howard-Jones, Blakemore, Samuel, Summers, & Claxton, 2005). For instance, Howard-Jones and colleagues (2005) used a paradigm where the task was to generate a story from three unrelated words (e.g., flea, sing, sword) or from three related words (e.g., magician, trick, rabbit). Piecing together a story from unrelated words predictably led to more creative responses than doing the same for related words. However, it is undeniably also more cognitively demanding to build a story from unrelated words compared to related words.

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So, in this case, mental operations both specific and unspecific to creativity would influence the pattern of brain activity that was generated.

A further problem is that creativity has generally been investigated in the neurosciences as a unitary and coherent construct (Dietrich, 2004; Dietrich & Kanso, 2010). For instance, many studies erroneously equate creative thinking with divergent thinking despite the fact that convergent thinking also clearly leads to creative thinking, such as during insight problem solving (Bowden, Jung-Beeman, Fleck, & Kounios, 2005). Moreover, there are tasks that would qualify as divergent thinking tasks, such as those of future thinking where responses are open-ended and subjective (e.g., Abraham, Schubotz, & von Cramon, 2008), but these principally assess hypothetical thinking and not creative thinking. Such issues highlight the need to study specific operations underlying creativity. Apart from the process of insight (e.g., Jung-Beeman et al., 2004), few other specific creative cognitive operations have been targeted.

Given the manifestly multifaceted nature of creativity, the necessity of adopting a process-driven approach while investigating creativity has been stressed by many researchers (Dietrich, 2004; Smith, Ward, & Finke, 1992). Several candidate cognitive processes have been outlined and investigated by examining normative cognitive processes under explicitly generative conditions (Finke, Ward, & Smith, 1992; Smith, Ward, & Finke, 1995). One such operation is "conceptual expansion" which refers to the ability to widen the conceptual structures of acquired concepts, a process that is especially critical in the formulation of novel ideas (Ward, 1994). The original conceptual expansion task required participants to imagine and draw an animal that lives on an alien planet. What was commonly found was that generic features of Earth animals posed considerable limitations on the capacity to create a new type of animal. This overwhelming tendency to resort to the cognitively least demanding route reflects the most commonly employed "path-of-least-resistance" strategy when faced with generative tasks (Ward, 1994; Ward, Patterson, Sifonis, Dodds, & Saunders, 2002). Evidence of this strategy can also be gleaned from the findings of the aforementioned study on story generation (Howard-Jones et al., 2005). Regardless of whether subjects were instructed to "be creative" or "be uncreative", stories generated from unrelated words were more creative than those generated from related words, which is revealing in that it is easier to give in to the path-of-least-resistance in the latter case.

The process of conceptual expansion is also assessed in the alternate uses task, a widely employed task of creative thinking (Abraham & Windmann, 2007; Wallach & Kogan, 1965) where participants are asked to generate multiple uses for common objects, such as a shoe. The originality of the responses is assessed by the infrequency or uniqueness of the generated uses. To take the example of a shoe, a highly unusual response would be to use a shoe as a flowerpot. So here the concept of a shoe has been vitally expanded beyond the customary use of foot protection to be associated with a far less common use. Which regions of the brain are activated as a function of greater conceptual expansion will be possible to uncover by contrasting participants' performances when carrying out a difficult divergent thinking task like the Alternative Uses task (AU) relative to a simple divergent thinking task,[1] such as an Object-Location (OL) task where participants are required to report objects that are commonly

found in a particular location. The path of least resistance strategy would be more readily employed in the OL task compared to the AU task because it is more cognitively demanding to forge novel associations between unrelated concepts (e.g., shoe as a plant pot) than it is to recall generic associations to concepts (e.g., office: desk, chair, computer, table lamp). Due to the greater associative strength between concepts in the latter case of the OL task, they are easier to access and retrieve from our semantic knowledge stores (e.g., Tse, 2009). This difference between the two divergent thinking tasks should be demonstrated by significantly more items generated during the OL task than the AU task. While the divergent thinking processes in the case of the alternate uses task necessitate the expansion of one's conceptual structures, this is not so in the case of the divergent thinking processes in the object-location task. Other creative cognitive processes, such as imagery and overcoming the constraints posed by recently activated knowledge (Abraham & Windmann, 2007), will be expected to play a less significant role as they are likely to be involved in both divergent thinking tasks (imagery) or are irrelevant to the situation at hand (recently activated knowledge).

In the current study, we sought to rectify some of the problems associated with the neuroscientific study of creative thinking with four objectives in mind. First, a novel experimental design was developed that enables uncovering not only what brain areas are associated with divergent thinking in general but, more significantly, what regions of the brain are specifically associated with the process of conceptual expansion in creative thinking. Second, the design was optimized so as to make the trial events comparable across conditions (e.g., trial length, comparable number of button presses, etc.). Third, a cognitively demanding control task was included which allows overruling the argument that any of the relevant regions are activated solely as a function of task difficulty. Fourth, by having the participants explicitly indicate every time an idea is generated during the experiment, it is possible to assess which brain regions are involved at the actual time point of the creative idea generation.

To control for the differences in levels of cognitive demand associated with the divergent thinking tasks, two n-back tasks (1-back and 2-back) were employed as control tasks in the current study. The n-back task is a highly established task in the investigation of working memory (Cohen et al., 1997), which refers to the capacity to actively monitor and manipulate information in mind in service of a goal (e.g., Baddeley, 2010). Participants are presented with a sequence of stimuli in an n-back task and are required to respond when the current stimulus is identical to the stimulus that was displayed just prior to it (1-back task), two stimuli before (2-back task), and so on. The further back the comparison stimulus is, the greater the working memory load. By including these conditions, it is possible to carry out fMRI statistical analyses such that the effects of the cognitive demand differences between the two divergent thinking conditions are partialled out (see Section 2). To be able to claim this, the 2-back control condition must be perceived by the participants to be more cognitive demanding than the other conditions. The experimental design of the current fMRI study (Fig. 1) was therefore a repeated measures design with factors Task Type (divergent, control) and Cognitive Demand (high, low).

Using this design, the aim of the current study was to uncover which brain regions are specifically activated as a function of conceptual expansion as distinct from regions that are generally active as a function of divergent thinking, working memory, or high cognitive demand. It was predicted that Conceptual Expansion would lead to activations in select brain regions such as the left anterior inferior frontal gyrus (BA 45/47), temporal poles (BA 38), and lateral frontopolar cortex (BA 10). These regions are known to play key roles in semantic retrieval, semantic memory

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[1] The Object Location task is a novel task that was devised for the current study. It can be classified as a divergent thinking task as it necessitates the generation of multiple solutions to a problem and thereby involves cognitive operations related to divergent production. This is is in accordance with J. P. Guilford's conceptualization of divergent thinking (Guilford, 1967).

representation and the integration of multiple conceptual relations respectively (Badre, Poldrack, Pare-Blagoev, Insler, & Wagner, 2005; e.g., Kroger et al., 2002b; Patterson, Nestor, & Rogers, 2007a).

Divergent thinking, in comparison, was expected to involve additional regions that are critical for declarative memory and semantic cognition, hypothetical thinking and evaluative judgement, such as the hippocampus, posterior cingulate cortex (BA 30/31), medial prefrontal cortex (BA 8/9/10), angular gyrus (BA 39) and lateral inferotemporal cortex (BA 20/21) (Abraham, et al., 2008; Binder, Desai, Graves, & Conant, 2009; Cappa, 2008; e.g., Fiebach, Friederici, Smith, & Swinney, 2007). Activations related to Working Memory were expected in regions known to be involved in cognitive control such as the left dorsolateral prefrontal cortex (BA 9/46/8), anterior cingulate cortex (BA 24/32) and superior parietal lobule (BA 40), (e.g., Badre & Wagner, 2004; Olson & Berryhill, 2009). These areas were also expected to be active to a wider extent as a function of high cognitive demand alongside basal ganglia regions (Graybiel, 2005).

2. Materials and methods

2.1. Participants

The final sample included 19 healthy volunteers (11 female; mean age: 22.42; age range: 19–29) with normal or corrected-to-normal visual acuity after excluding participants who and/or displayed movement artefacts in their fMRI data ($n = 4$) or did not reach the behavioral performance criterion ($n = 7$, see below for details). All participants were right handed (mean laterality index: 0.88; Oldfield, 1971) social science students at the University of Giessen who were native German speakers with no reported history of neurological or psychiatric illness. None of the participants were taking medication at the time of measurement. All gave informed consent before participation and received either payment (€ 20) or course credits for their participation. The experimental standards of the study were approved by the Ethics Commission of the German Psychological Society (DGPs).

2.2. Experimental design

A 2×2 repeated measures factorial design was employed with Task Type (divergent, control) and Cognitive Demand (high, low) as the factors. The experimental design, examples of all four conditions and the trial events are shown in Figs. 1 and 2. The experiment included 20 trials per condition as well as 8 resting baseline trials. All stimuli were presented visually in a pseudo-randomised order such that the frequency of all trial transition types was counterbalanced and all conditions occurred equally often in the first and second halves of the experiment. With a trial length of 25 s and total of 88 trials, the experimental session lasted approximately 38 min. The participants were given task instructions and performed a 10-min practice session on a laptop prior to the imaging session where they were trained to ensure that they understood what each of the tasks entailed and correctly performed all tasks. They were also informed that they would be asked to report the uses they generated in the scanner for each object (alternate uses task) as well as the objects they generated for each location (object location task) during the feedback session which took place after the experimental session. They were made aware that the experimenter had a record on hand of how many objects and uses were generated per trial during the experiment and that these would be checked with the feedback report to examine performance accuracy.

Participants were also required to complete a difficulty rating scale during the feedback session to indicate how difficult they experienced each of the four task types to be. The scale ranged from 1 (extremely difficult) to 7 (extremely easy). All

	High Cognitive Demand	**Low Cognitive Demand**
Divergent thinking	**D-H**: Think of uses for objects (e.g. Shoe)	**D-L**: Think of objects in a situation (e.g. Office)
Control task	**C-H**: 2-back task (e.g. L H C H L K C K N)	**C-L**: 1-back task (e.g. L L C H S L C C N)

Fig. 1. The examples of stimuli from each of the four conditions (D-H: divergent-high, D-L: divergent low, C-H: control high, C-L: control low) resulting from the 2×2 repeated measures experimental design.

Jitter	CUE START	Pause	TASK	Pause	CUE END
2–5s	500ms	250ms	20s	250ms	500ms
D-H	Begin: Uses		Uses -> Newspaper		End: Uses
D-L	Begin: Objects		Objects -> Office		Ende: Objects
C-H	Begin: 2-back		L H R J R K …		End: 2-back
C-L	Begin: 1-back		T J K L L M …		End: 1-back

Fig. 2. The trial events were the same for all conditions. Each trial began with a jitter period (blank screen) that varied from trial to trial (2000–5000 ms). This was directly followed by a "Start Cue" for 500 ms which indicated the commencement of the experimental task. Following a brief pause (250 ms), the experimental task was presented for 20 s during which the participants responded via button presses. After another brief pause (250 ms), the End Cue was presented for 500 ms which indicated the end of the experimental task. For each trial, the total duration was 25 s. The cues "Uses" correspond to the alternate uses task (D-H) whereas the cues "Objects" indicated that the object-location task was to be performed (D-L). The cues "2-back" and "1-back" correspond to the 2-back (C-H) and 1-back (C-L) conditions respectively. Event-related fMRI analyses were carried out by time-locking each event as beginning 1000 ms before the elicitation of each individual response during task performance in every trial.

participants also completed the vocabulary scale of the Hamburg Wechsler Intelligence Test for Adults (HAWIE; Tewes, 1994). The HAWIE vocabulary scale requires reading aloud 32 words with increasing difficulty to the participants. Upon hearing each word, the participants are required to give a brief definition of each word. The resulting number of correctly defined words is transformed into a standardized value which takes the participant's age into consideration.

2.3. Experimental tasks

(a) Divergent-high (D-H): The Alternate Uses task was employed in this condition and each trial began with the Trial Cue "Start Uses". This was followed by a Task Cue which showed the word "Uses" coupled with an Object (e.g., Uses -> Shoe). The Task Cue remained on the screen for the duration of the trial and indicated for which particular Object different Uses need to be generated. The Object was different in each trial. Participants were required to indicate with a button press as soon as they conceived of a new Use. The end of each trial was indicated with the Cue "End Uses". The recorded measures included the average number of generated Uses per trial (as indicated via button presses) during the experiment and the number of verbally reported Uses after the experiment. The verbally reported uses were checked at the end of the session to verify the acceptability of the responses and to control for poor performers. None of the participants were found to generate nonsense items on this task.

(b) Divergent-low (D-L): The Object-Location task was employed in this condition and each trial began with the Trial Cue "Start Objects". This was followed by a Task Cue which showed the word "Objects" coupled with a Location (e.g., Objects -> Office). The Task Cue remained on the screen for the duration of the trial and indicated for which particular Location different Objects would have to be generated. The Location was different in each trial. Participants were required to indicate with a button press as soon as they thought of a new Object. The end of each trial was indicated with the Cue "End Objects". The recorded measures included the average number of generated objects per trial during the experiment and the number of Objects verbally reported during the feedback session. The verbally reported objects were checked at the end of the session to verify the acceptability of the responses and to control for poor performers. None of the participants were found to generate nonsense items on this task.

(c) Control-high (C-H): The 2-back task was employed in this condition and each trial of this type began with the Trial Cue "Start 2-back". This was followed by presentation of a string of single letters for the entire duration of the trial. Each letter was presented for 500 ms with a 500 ms pause between letters. Participants were required to keep track of the presented stimuli and indicate with a button press every time the currently presented letter was the same as the letter presented 2 letters before. The end of each trial was indicated with the Cue "End 2-back". The recorded measures included the average number of responses per trial and the percentage of correct responses. The latter was recorded to exclude participants who did not attain the required performance criterion (minimum 75% correct). This criterion was set in order to overrule the argument that the findings on the divergent-high task relative to the control-high task could be undermined due to poor performance on the latter task. As behavioral pilot studies indicated that participants generate

approximately 4 uses per trial during the D-H condition, the C-H condition was programmed to have 4 hits within each trial.

(d) Control-low (C-L): The 1-back task was employed in this condition and each trial began with the Trial Cue "Start 1-back". This was followed by presentation of a string of single letters for the entire duration of the trial. Each letter was presented for 500 ms with a 500 ms pause between letters. Participants were required to keep track of the presented stimuli and indicate with a button press every time the currently presented letter was the same as the letter presented directly before. The end of each trial was indicated with the Cue "End 1-back". The recorded measures included the average number of responses per trial and the percentage of correct responses. The latter was recorded to exclude participants who did not attain the required performance criterion (minimum 75% correct). As behavioral pilot studies indicated that participants generate approximately 8 uses per trial during the D-L condition, the C-L condition was programmed to have 8 hits within each trial.

2.4. MRI scanning procedure

Functional and anatomical imaging was carried out using a 1.5 T whole-body tomography system (Siemens Symphony) with a standard head coil. Participants were placed in the scanner in a supine position with their right index finger positioned on the response button of a response box. The participants' hands were carefully stabilized and form-fitting cushions were used to prevent head, arm and hand movements. Earplugs were also provided to the participants so that scanner noise would be attenuated. The structural image acquisition consisted of 160 T1-weighted sagittal images (MPRAGE, 1mm slice thickness). One run of functional imaging was carried out with a total of 902 volumes which were recorded using a T2*-weighted gradient echo-planar imaging sequence (EPI) with 25 slices covering the whole brain (slice thickness = 5 mm; gap = 1 mm; descending slice order; TA = 100 ms; TE = 55 ms; TR = 2.5 s; flip angle = 90°; field of view = 192 mm × 192 mm; matrix size = 64 × 64). The orientation of the axial slices was tilted to parallel the OFC tissue–bone transition to keep susceptibility artefacts to a minimum. The stimuli were visually projected onto a screen at the end of the scanner (visual field = 18°) using an LCD projector (EPSON EMP-7250) and were viewed by the participants through a mirror mounted on the head coil. Presentation® software (www.neurobs.com) was used to present the stimuli (resolution: 800 × 600).

2.5. fMRI data analysis

The fMRI data were processed using the LIPSIA software package (Lohmann et al. 2001) (http://www.cbs.mpg.de/institute/software/lipsia/index.html). This freeware contains tools for preprocessing, registration, statistical evaluation and presentation of fMRI data. Functional data were first motion-corrected using a matching metric based on linear correlation. To correct for the temporal offset between the slices acquired in one scan, a sinc-interpolation based on the Nyquist–Shannon–Theorem was applied. Low-frequency signal changes and baseline drifts were removed using a temporal highpass filter with a cut-off frequency of 1/150 Hz. Spatial smoothing was performed with a Gaussian filter of 8 mm FWHM. The functional data were registered to the anatomical data via a rigid linear registration with 6 degrees of freedom (3 rotational, 3 translational) and were then normalized to the Talairach standard space. The normalized parameters were then used to transform the functional slices using trilinear interpolation, thus generating output data with a spatial resolution of 3 mm × 3 mm × 3 mm (voxel size: 27 mm³).

The statistical evaluation was based on a least-squares estimation using the general linear model for serially autocorrelated observations (Friston et al., 1995; Worsley & Friston, 1995). The design matrix used for modeling the data consisted of onset vectors each the four experimental conditions with an additional onset vector for null events or rest trials. The onsets for the experimental conditions were recorded as beginning 1 s before each response. This is because the responses in the experiment indicated either a hit in the case of the 2-back (C-H) or 1-back (C-L) tasks, or the generation of a new use (D-H) or object (D-L) in the divergent thinking tasks. The mental operations of interest were therefore taking place just prior to the generation of the response. The design matrix was generated with a box-car function, convolved with the hemodynamic response function. Brain activations were analyzed in an event-related design, time-locked to the responses. The model equation, including the observation data, the design matrix, and the error term, was convolved with a Gaussian kernel dispersion of 4 s FWHM to account for the temporal autocorrelation (Worsley & Friston, 1995). Contrast images or beta value estimates of the raw-score differences between specified conditions were generated for each participant. As all individual functional data sets were aligned to the same stereotactic reference space, the single-subject contrast images were entered into a second-level random-effects analysis for each of the contrasts. One-sample *t* tests were employed for the group analyses across the contrast images of all subjects which indicated whether observed differences between conditions were significantly distinct from zero. *t* values were subsequently transformed into *z* scores.

The results were corrected for multiple comparisons using double thresholding, a combination of single voxel probability thresholding on one hand (here *z* > 3.09,

p < .001), and cluster-size and cluster-z-value thresholding on the other (here *p* < .01), which is computed using Monte-Carlo simulations (Lohmann, Neumann, Muller, Lepsien, & Turner, 2008). Two types of contrasts were carried out: three direct contrasts and an inclusive mask analysis. The three main direct contrasts were (a) Divergent (D-H & D-L) > Convergent (C-H & C-L), (b) Convergent (C-H & C-L) > Divergent (D-H & D-L), (c) High Demand (C-H & D-H) > Low Demand (C-L & D-L). The inclusive mask analysis (D-H > D-L with inclusive mask D-H > C-H) was carried out from the corrected direct contrasts of the single conditions whereby the statistic parametric map of the random-effects analysis of the divergent-high versus control-high contrast (D-H > C-H) was used as an inclusive mask in the random-effects analysis of the divergent-high versus divergent-low contrast (D-H > D-L) contrast. The findings that result from this inclusive masked analysis indicate which brain areas were significantly activated during D-H relative to D-L, but only if the same regions were also more highly activated during D-H relative to C-H.

3. Results

3.1. Behavioral findings

The descriptive data (mean and standard deviation) for all the dependant variables are presented in Table 1. Preliminary correlational analyses (Spearman's rho) that were carried out to assess the correlation between the HAWIE IQ measure (Mean: 12.37, SD: 2.24) and all the dependant variables as well as Age indicated that all the correlations were non-significant (all $P > .05$). There were also no sex differences in relation to HAWIE IQ measure ($t_{17} = 0.83$, $P = .42$). Inferential analyses were then carried out to estimate condition-specific effects on difficulty ratings, average number of responses per trial, and the average number of responses during the experiment versus the feedback session.

A 2×2 repeated measures ANOVA (Task type & Cognitive demand) on the difficulty ratings revealed that high cognitive demand tasks were rated as being more difficult than low cognitive demand tasks (Main effect: $F_{1, 18} = 118.76$, $P < .001$; partial-eta squared/$h_p^2 = 0.87$) and that control tasks were rated as being more difficult than divergent thinking tasks (Main effect: $F_{1, 18} = 11.78$, $P = .003$; $h_p^2 = 0.4$). The significant interaction ($F_{1, 18} = 57.32$, $P = .001$; $h_p^2 = 0.5$) between the two factors was driven by the fact that the C-H condition (2-back task) was judged significantly more difficult than the D-H (alternate uses task), the D-L (object location task) and the C-L (1-back task) conditions (all $t_{18} > 4.6$, all $P < .001$; all $d > 1.3$). D-H was judged to be the second-most difficult condition as it was rated to be more difficult than the D-L and C-L conditions (all $t_{18} > 4.8$, all $P < .001$; all $d > 1.3$). C-L and D-L were rated to be comparable in difficulty ($t_{18} = 0.18$, $P = .85$).

The 2×2 repeated measures ANOVA (Task Type & Cognitive Demand) on the average number of responses per trial revealed that high cognitive demand conditions (D-H and C-H) were associated

Table 1
Descriptive data (mean and standard deviation) of all the behavioral measures (D-H: divergent-high, D-L: divergent-high, C-H: convergent-high, C-L: convergent-low, FB: Feedback Session).

	Mean	SD
C-H difficulty rating	2.00	1.05
D-H difficulty rating	3.79	1.55
C-L difficulty rating	5.58	0.84
D-L difficulty rating	5.63	1.16
C-H average responses per trial	4.24	0.54
D-H average responses per trial	4.21	1.21
C-L average responses per trial	8.02	0.16
D-L average responses per trial	8.26	2.60
D-H average responses per trial (FB)	3.74	1.12
D-L average responses per trial (FB)	7.63	2.23
D-H average response originality	10.65	2.02
C-H response accuracy	83.88	6.01
C-L response accuracy	98.19	1.70

with fewer responses than to the low cognitive demand conditions (D-L and C-L) (Main effect: $F_{1,18} = 358.17$, $P < .001$; $h_p^2 = 0.95$). There was no significant effect of Task Type ($F_{1, 18} = 0.07$, $P = .79$), nor a significant interaction effect ($F_{1, 18} = 0.36$, $P = .55$).

A final 2×2 repeated measures ANOVA (Divergent task type: D-H, D-L; Testing session: Imaging, Feedback) on the average number of responses per trial revealed a significant main effect for divergent task type ($F_{1, 18} = 93.53$, $P < .001$; $h_p^2 = 0.84$) indicating that the D-H condition was associated with fewer responses than the D-L condition across testing sessions. Furthermore, a significant main effect for testing session ($F_{1, 18} = 14.6$, $P = .001$; $h_p^2 = 0.45$) indicated that the fewer responses were reported in the feedback session compared to the imaging session for both divergent thinking conditions. The interaction effect between the factors was not significant ($F_{1, 18} = 2.39$, $P = .14$). Correlational analyses (Pearson's product moment correlation) were also carried out to assess the relationship between the number of uses/objects generated during the imaging session with that of the feedback session. The results were found to be highly significant for both D-H ($r_{19} = 0.9$, $P < .001$) and D-L ($r_{19} = 0.96$, $P < .001$).

3.2. fMRI Findings

3.2.1. Conceptual expansion (contrast: D-H > D-L with inclusive mask D-H > C-H)

Regions predicted to be involved in this contrast included the left anterior inferior frontal gyrus (IFG: BA 45/47), the lateral frontopolar cortex (FPC: BA 10) and the temporal poles (TP: BA 38). As shown in Table 2 and Fig. 3, all three regions were found to be involved during conceptual expansion. Other relevant regions of activation included posterior regions in the inferior frontal gyrus (BA 44), the middle frontal gyrus (BA 9/8), the anterior cingulate cortex (BA 32/24), the dorsomedial prefrontal cortex (BA 8) and the inferior parietal lobule (BA 40). What is

Table 2
Conceptual Expansion. Anatomical specification, Talairach coordinates, maximum Z value and volume (mm³) of the significantly activated areas (l.m.: local maxima within each volume) in the D-H > D-L contrast (inclusive mask: D-H > C-H contrast). The results were corrected for whole brain multiple comparisons at the cluster level ($P < .01$).

| Area	x	y	z	BA	mm³	z-max
Middle and inferior frontal gyrus	−44	13	24	9, 8, 44	27,756	5.452
Inferior frontal gyrus	−47	19	6	44, 45	l.m.	5.494
Inferior frontal gyrus	−41	34	−6	45, 47	l.m.	6.273
Inferior/middle frontal gyrus	−32	31	12	10, 46	l.m.	5.074
Temporal poles	−50	10	−21	38	l.m.	4.815
Anterior cingulate cortex	−2	19	27	32, 24	l.m.	4.253
Medial prefrontal cortex	−5	13	48	6, 8	5697	5.003
Middle frontal gyrus	−35	4	39	6	l.m.	4.537
Inferior parietal lobule	−56	−35	36	40	1080	5.287
Inferior parietal lobule	−41	−29	45	40	135	3.480
Putamen/globus pallidus	−32	−11	0		1080	4.682
Inferior temporal gyrus	−47	−56	−9	37	621	4.372
Cerebellum	31	−74	−33		9639	5.077
Cerebellum	16	−86	−18		l.m.	3.993
Lingual gyrus/inferior orbital gyrus	22	−95	−9	17, 18	l.m.	3.970
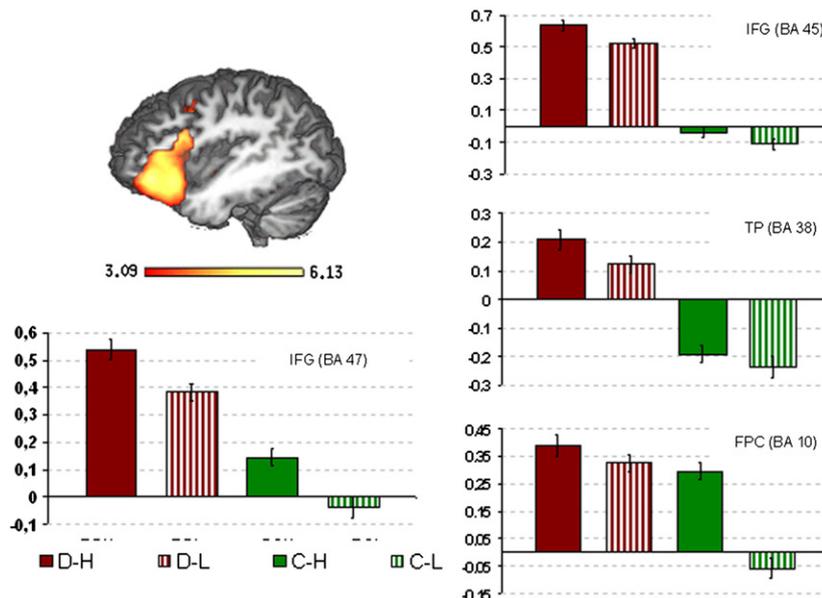
Fig. 3. Conceptual expansion: Regions of the brain activated as a function of conceptual expansion (D-H > D-L with inclusive mask D-H > C-H) encompassed regions in the left anterior IFG (BA 47), left mid-anterior IFG (BA 45), left temporal pole (TP: BA 38), and left lateral frontopolar cortex (FPC: BA 10). The graphs show the average percentage signal change (PSC) response associated with all conditions within a peak voxel and its 26 adjacent neighboring voxels in the left anterior IFG (BA 47, peak voxel: −41, 34, −6), the left mid IFG (BA 45, peak voxel: −47, 19, 6), the left temporal pole (BA 38, peak voxel: −50, 10, −21), and the left frontopolar cortex (BA 10/46, peak voxel: −34, 46, 3). The zero point in the graphs represents the resting baseline. The results were corrected for whole brain multiple comparisons at the cluster level ($P < .01$).

additionally notable is that the activation pattern is strongly lateralized to the left hemisphere.

3.2.2. Divergent thinking (contrast: D-H & D-L > C-H & C-L)

In line with predictions, all three regions involved in conceptual expansion were found to be activated in this contrast as well as regions in the hippocampal formation and amygdala (Fig. 4), the posterior cingulate cortex (PCC: BA 30/31), the dorsal medial prefrontal cortex (dmPFC: BA 8/9), ventral medial prefrontal cortex (vmPFC: BA 10) and the angular gyrus (BA 39). For a list of activations in this contrast, please refer to Table S1 in the Supplementary Material. Just as in the case of the conceptual expansion contrast, the overall brain activation pattern as a function of divergent thinking is stronger in the left hemisphere of the brain.
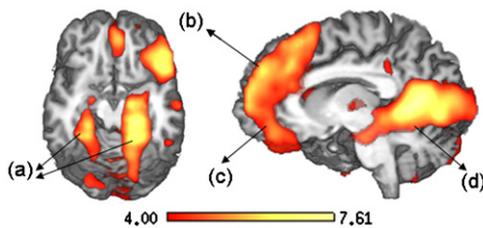

Fig. 4. Divergent thinking: Regions of the brain activated as a function of divergent thinking relative to convergent thinking (D-H & D-L > C-H & C-L) in the (a) hippocampal formation & amygdala, (b) dorsal medial prefrontal cortex (including BA 9, 8), (c) ventral medial prefrontal cortex (including BA 10, 11, 12), and (d) posterior cingulate cortices (BA 30/31/29). The results were corrected for whole brain multiple comparisons at the cluster level ($P < .01$).
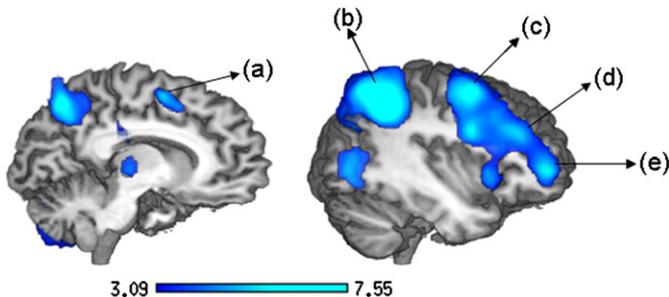

Fig. 5. Convergent Thinking: Regions of the brain activated as a function of convergent thinking relative to divergent thinking (C-H & C-L > D-H & D-L) in the (a) right posterior medial cortex (BA 6), (b) right superior parietal lobule (BA 40), (c) right dorsolateral frontal cortex (BA 6), (d) right dorsolateral prefrontal cortex (BA 8/46/9) and (e) right frontopolar cortex (BA 10). The results were corrected for whole brain multiple comparisons at the cluster level ($P < .01$).
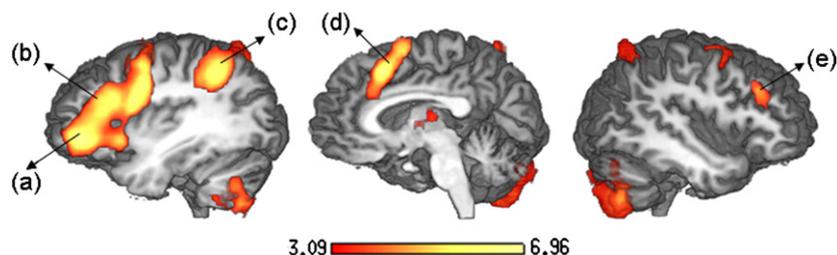
3.2.3. Working memory (contrast: C-H & C-L > D-H & D-L)

Regions in the left dorsolateral prefrontal cortex (dlPFC: BA 9/46/8), the anterior cingulate cortex (ACC: BA 24) and the superior parietal lobule (SPL: BA 40) were expected to be responsive as a function of working memory. The hypotheses were only partially supported as only the bilateral SPL alongside the right dlPFC was found to be activated (Fig. 5). The overall brain activation pattern as a function of working memory was stronger in the right hemisphere of the brain (Table S2 in Supplementary Material).

3.2.4. High cognitive demand (contrast: C-H & D-H > C-L & D-L)

In line with predictions, activations in the dorsolateral prefrontal cortex (dlPFC: BA 9/46/8), the anterior cingulate cortex (ACC: BA 24/32) and the superior parietal lobule were found bilaterally in this contrast alongside activations in the basal ganglia (Table S3 in Supplementary Material, Fig. 6).

4. Discussion

The objective of this study was to assess a specific operation of creative thinking, namely that of conceptual expansion as opposed to general divergent thinking, working memory or cognitive load, by means of a novel event-related experimental design. To be able to test the various hypotheses with reference to condition specific activations, it was necessary to show that the divergent-high condition (alternate uses task) was not judged to be more cognitive demanding task than control-high condition (2-back), and that the divergent-low condition (object location task) resulted in more responses than the divergent-high condition.

The behavioral results confirmed both of these stipulations. The 2-back control task was perceived to be the most difficult task of all, followed by the alternate uses divergent task. The average number of responses was also found to be comparable between the alternate uses divergent task and the 2-back control task, and between the object location divergent task and the 1-back control task. This clearly indicates that any discussion of the brain regions activated as a function of conceptual expansion cannot be simply attributed to factors such as higher cognitive or response preparation demands as these were controlled for within the experimental design.

In addition, far more objects were generated during the object location task in comparison to uses during the alternate uses task, and the alternate uses task was also rated as being significantly more difficult than the object-location task. These findings suggest that it was easier to resort to the path of least resistance strategy in the case of the object-location task.

Another issue of note was the discrepancy between the number of uses and objects generated during the imaging session compared to the feedback session such that less uses/objects were reported during the feedback session. This pattern was also

Fig. 6. Cognitive Demand: Regions of the brain activated as a function of high relative to low cognitive demand (C-H & D-H > C-L & D-L) in the (a) left ventral lateral prefrontal cortex (BA 44/45), (b) left dorsal lateral prefrontal cortex (46/8/9), (c) left superior parietal lobule (BA 40), (d) left anterior cingulate cortex (BA 32/24) and (e) right dorsolateral prefrontal cortex (BA 46/8). The results were corrected for whole brain multiple comparisons at the cluster level ($P < .01$).

observed in the behavioral pilot studies. This discrepancy was, however, very small (on average 4.21 versus 3.74 recalled uses in D-H; 8.36 versus 7.63 recalled objects in D-L) and may have resulted from forgetting or a general failure to recall all the generated responses (Wixted, 2004). This was highly likely given that subjects were required to recall a great number of uses (on average 4 responses × 20 trials = 80 uses to be recalled) and objects (on average 8 responses × 20 trials = 160 objects to be recalled). It should also be noted that the correlations between the number of uses and objects generated during the imaging session and during the feedback session were extremely high.

All in all, the behavioral findings indicate that the conditions underlying the efficacy and validation of the experimental design have been met which renders possible the optimal testing of the hypotheses regarding the condition specific brain activations.

4.1. Conceptual expansion

In order to uncover which brain regions are selectively involved in conceptual expansion, the brain activations generated during the alternate uses task was compared to that of the object location task, but only in regions of the brain where activations during the alternate uses task were also significantly higher relative to the 2-back control task. This allowed for the assessment of which regions are selectively involved in creative conceptual expansion compared to other aspects of divergent thinking while at the same time overruling the possible argument that the regions in question are simply involved in due to the differences between both divergent tasks in cognitive demand or response preparation.

Conceptual expansion was associated with greater brain activity in all three hypothesized regions of the brain, namely the left anterior inferior frontal gyrus (IFG: BA 45/47), the lateral frontopolar cortex (FPC: BA 10) and the temporal poles (TP: BA 38). These anterior regions of the left IFG have been commonly discussed in the language literature with reference to semantic processing (Bookheimer, 2002) and are known for their role in semantic selection (Thompson-Schill, D'Esposito, Aguirre, & Farah 1997; Thompson-Schill et al., 2002) and semantic retrieval (Badre, Poldrack, Pare-Blagoev, Insler, & Wagner, 2005; Badre & Wagner, 2007; Wagner, Pare-Blagoev, Clark, & Poldrack, 2001). These regions are particularly sensitive to the influence of semantic distance or associative strength between concepts, with weaker associative strength, for instance, leading to a stronger BOLD response in these areas (Bunge, Wendelken, Badre, & Wagner, 2005; Green, Kraemer, Fugelsang, Gray, & Dunbar, 2010). Of particular relevance to semantic cognition are also the TP, which have been dubbed the "semantic hub" of the brain (for competing views, see Simmons, Reddish, Bellgowan, & Martin, 2010; Simmons & Martin, 2009) based on studies using functional imaging, TMS and semantic dementia patients indicating that the TP are likely to underlie the domain-general conceptual knowledge stores of the brain (Lambon Ralph, Pobric, & Jefferies, 2009; Lambon Ralph, Cipolotti, Manes, & Patterson, 2010; Lambon Ralph & Patterson, 2008; Patterson, Nestor, & Rogers 2007).

The lateral FPC, in contrast, is heralded as the structure that mediates cognitive control at the most abstract level of information processing (Badre, 2008) and plays a key role in relational reasoning or the integration of information containing multiple relations (Bunge, Wendelken, Badre, & Wagner, 2005; Christoff et al., 2001; Christoff, Ream, Geddes, & Gabrieli, 2003; Green, Fugelsang, Kraemer, Shamosh, & Dunbar, 2006; Kroger et al., 2002) with the left FPC playing a particularly relevant role (Bunge, Helskog, & Wendelken, 2009; Green et al., 2010). Given the unique cytoarchitecture of the FPC as well as its involvement in

a variety of other operations including the processing of internal states, prospective memory, source memory and cognitive branching, it has been proposed that this area is involved when a higher-order behavioral goal requires the integration of information from two or more separate cognitive operations (for a review, see Ramnani & Owen, 2004), such as working memory and semantic retrieval (Bunge, Wendelken, Badre, & Wagner, 2005).

That these three regions of the brain (IFG, TP and FPC) are involved during conceptual expansion is fitting given that generation of a novel use for an object necessitates the access, selection, retrieval and integration of concepts that are not customarily associated with one another (Kroger et al., 2012; Rutter et al., 2012). These regions have also been implicated in other functional neuroimaging studies of creative thinking (Aziz-Zadeh, Kaplan, & Iacoboni, 2009; Carlsson et al., 2000; Chavez-Eakle et al., 2007; Howard-Jones et al., 2005; Jung-Beeman et al., 2004), but not in recent fMRI studies that have used the alternate uses task (Chrysikou & Thompson-Schill, 2011; Fink et al., 2009). Possible reasons for the discrepancy between findings of these latter studies and the current study are likely to be due to key differences in the experimental designs which have already been highlighted in the Introduction and are explored in detail below (Section 4.5).

4.2. Divergent thinking, working memory & high demand

Comparing activations resulting during divergent thinking to that of working memory was expected to lead to activity in the left IFG, TP and FPC alongside regions such as the hippocampal formation, the amygdala, the posterior cingulate cortex (PCC: BA 30/31), the dorsal medial prefrontal cortex (dmPFC: BA 8/9), ventral medial prefrontal cortex (vmPFC: BA 10), the angular gyrus (BA 39) and the lateral temporal cortex (BA 20/21). The results confirmed the involvement of all these regions which is fitting given their well documented roles in declarative memory and semantic cognition, language processing, hypothetical thinking, and evaluative judgement (e.g., Abraham et al., 2008; Binder et al., 2009; Cappa, 2008; Fiebach et al., 2007; Legrand & Ruby, 2009).

In contrast, comparing working memory to divergent thinking was expected to lead to activations in the dorsolateral prefrontal cortex (dlPFC: BA 9/46/8), the anterior cingulate cortex (ACC: BA 24/8/6) and the superior parietal lobule (SPL: BA 40), regions known to be involved in cognitive control processes (e.g., Badre & Wagner, 2004; Botvinick, 2007; Olson & Berryhill, 2009). This hypothesis was partially confirmed as only the dlPFC and SPL were found to be more strongly activated. However, while the bilateral regions of the SPL were implicated, only the right dlPFC and ACC were found to be involved during the working memory tasks relative to the divergent thinking tasks, which was contrary to expectations.

It must be noted though that the divergent thinking tasks and control working memory tasks were qualitatively very different from one another, not only in terms of the cognitive operations they necessitated, but also in terms of stimulus material, task instructions and trial presentation. Such differences are also likely to have contributed to the differences in the activated brain regions associated with the divergent thinking tasks compared to the control working memory tasks, and vice versa.

The final contrast of high cognitive load compared to low cognitive load though led to activations in the left ACC, the bilateral dlPFC, the bilateral SPL and the bilateral basal ganglia, which were in line with predictions. As the pattern of activations that resulted from both the working memory contrast and the high demand contrast strongly overlap, whether the observed

brain activation patterns are specifically related to working memory processes or generally to higher cognitive tasks demands remains to be determined.

4.3. Further relevant brain regions for conceptual expansion

Apart from the brain regions predicted to be activated as a function of conceptual expansion, the analyses also showed stronger brain activity in other relevant regions including the left posterior IFG (BA 44), the inferior parietal lobule (IPL: BA 40), the ACC (BA 32/24), the left dlPFC (BA 8/9) and the dorsomedial prefrontal cortex (dmPFC: BA 8). While the posterior IFG and IPL have been widely implicated in the language and semantic cognition literature, the ACC, dlPFC and dmPFC, however, are not usually at the forefront of such discussions.

The roles of the ACC and the dlPFC are particularly noteworthy given the pattern of activation in these regions in the current study. Not only were they found to be more activated during divergent thinking compared to working memory, more importantly, they were also found to be most responsive as a function of conceptual expansion. This is an interesting finding because these regions are commonly discussed from the perspective of response or decision conflict, response monitoring and higher cognitive demand (e.g., Mansouri, Tanaka, & Buckley, 2009). However, in the current study, the alternate uses condition was not experienced as being the most cognitive demanding condition, which implies that a simple difficulty based argument for the these findings would be implausible. What is true though is that unlike the case of the 2-back condition, the alternate uses task did not involve the generation of objective or binary responses. So the activation of these regions possibly reflect qualitatively different kinds of cognitive control processes which may arise due to executive control processes that modulate the selection of competing alternatives that are retrieved from one's own semantic stores in the brain. In any case, the current findings highlight the necessity to consider these cognitive control regions as underlying more complex and fine-grained functions that cannot be simply attributed to greater cognitive demand (e.g., Pochon, Riis, Sanfey, Nystrom, & Cohen, 2008).

The posterior aspect of the dmPFC was also activated as a function of conceptual expansion. Interestingly, this region was also found to be activated during other kinds of divergent thinking tasks, such as when contemplating the future (Abraham et al., 2008). For instance, this region was found to be activated not just during "mental time travel" such as during episodic past thinking (e.g., Have you ever given a speech at a wedding celebration?) and episodic future thinking (e.g., Are you likely to still go clubbing at the age of 40?), but also during semantic future thinking (e.g., Is Sydney likely to have a Disneyland in 50 years?). As this region has been discussed with reference to concepts that are central to hypothetical reasoning, such as constructive processes in cognition (Abraham et al., 2008) which involve flexible recombination of representations from memory (Schacter, Norman, & Koutsaal, 1998), and evaluative judgement (Zysset, Huber, Samson, Ferstl, & von Cramon, 2003), the dmPFC may prove to be highly relevant structure for select aspects of creative thinking.

4.4. The issue of lateralization in creativity

Although this issue was not central to the objectives of this study, the results are telling and are therefore of relevance to creativity researchers. An interesting dissociation was uncovered in the lateralization of the findings such that activations related to divergent thinking were strongly lateralized to the left hemisphere whereas activations found when comparing working memory were more strongly lateralized to the right hemisphere. These results are, on one hand, unsurprising given that the divergent thinking tasks were language tasks and would therefore be expected to lead to a stronger left hemisphere response. On the other hand, even a comparison of the alternate uses task and the object location task showed a strong left lateralization as a function of conceptual expansion. This speaks against the ubiquitous idea the right brain is more "creative" than the left brain, a standpoint that has been discussed and criticized in the recent review by Dietrich & Kanso (2010). Furthermore, what these findings underscore is the necessity to carefully consider the parameters of the control or comparison task(s) when ascribing a particular function to any brain region.

4.5. Caveats and limitations in relation to the current experimental design

4.5.1. Deliberate versus spontaneous modes of creative idea generation

Creative thinking is among the most complex of human abilities and, in the current study, we have explored the deliberate problem solving mode of creative thinking under time constraints. There is, however, another vast dimension of creative thinking where idea generation occurs spontaneously, effortlessly, and/or in a state of defocused attention (Dietrich, 2004). In fact, creative idea generation is far less likely to result from deliberate cogitation during real everyday problem solving, but instead, it occurs spontaneously and unpredictably. This unconscious non-deliberate spectrum of creative thinking has received some attention in behavioral investigations (Cai, Mednick, Harrison, Kanady, & Mednick, 2009; Dijksterhuis & Meurs, 2006; Zhong, Dijksterhuis, & Galinsky, 2008). It is, however, less amenable to well-controlled investigation using current functional neuroimaging methods as creative idea generation under such conditions cannot be reliably promptly on demand under time constraints. This also necessarily means that it is not possible as yet to generalize the current findings in a significant manner to gain insights about the neurocognitive mechanisms underlying alternate aspects of creative thinking that occur as a function of implicit, unconsious, bottom-up driven or spontaneous modes of cognition. This as such constitutes the chief limitation of the current study.

4.5.2. Variations between high and low demand conditions

Another issue that is of note is that of the comparability between the conditions. While a great deal of care was taken to ensure the comparability of the low demand conditions to the high demand conditions, it must be noted that the difference between the low (object-location) and high (alternate uses) divergent tasks is not as optimally varied as between the low (1-back) and high (2-back) control tasks. Control or contrast conditions to creative tasks in the neuroimaging literature can be roughly divided into two kinds. The first approach is to instruct the participants to be either creative or uncreative when generating uses (Howard-Jones et al., 2005) or to generate uncommon as opposed to common uses of the task (Chrysikou & Thompson-Schill, 2011). The strength of this approach is that because both the experimental and control conditions involve use generation, the parameters are more comparable between the creative/ uncommon response generation condition and the uncreative/ common response generation condition. The weaknesses of this approach though, are that (a) it is cognitively far more demanding to generate uncommon uses than common uses, (b) even when explicitly told to generate uncommon uses, it is highly likely that the subjects will also think about common uses while doing so,

and vice versa. This latter point is especially problematic because it raises the question as to how qualitatively different the creative/uncommon and uncreative/common conditions really are within such a scenario and, consequently, how effective the comparisons between these conditions can be.

The second aproach, which is the approach adopted in the current study, involves contrasting the divergent alternate uses task with other divergent thinking tasks such as Object Characteristics Task, where participants are required to think of typical characteristics of everyday objects (Fink, Benedek, Grabner, Staudt, & Neubauer 2007; Fink et al., 2009). One limitation of this approach is shared with that of the previous approach in that the comparison divergent thinking task is usually cognitively less demanding than the alternate uses task. We have attempted to overule this latter point by including the low and high difficulty *n*-back control tasks and carrying out masked analyses of the data. The second limitation is specific to this approach and refers to the fact that the two divergent thinking tasks are qualitatively different from one another in terms of task requirements, cognitive demands, and pressure to generate original responses. Such qualitative differences render it impossible to, for instance, meaningfully compare the degree of originality of the responses in the Alternate Uses task by contrasting it with the responses of the Object Location task. The advantage of this approach though is that the divergent comparison condition is not confounded with the divergent creative condition. The choice to adopt this latter approach was because it has been successfully used in the past (Fink et al., 2009, 2010) and because, in our view, it was especially vital to overule any claim that the creative and comparison tasks were fundamentally confounded with one another.

4.5.3. Selection of response mode

Another issue to be discussed is the mode of response selected for the present divergent thinking tasks. As in the case of the current study, some functional neuroimaging studies of creativity have relied on participants carry out the task silently in the scanner during the fMRI testing session and later report their responses in a post-fMRI behavioral session (Bechtereva et al., 2004; Howard-Jones et al., 2005). Others have participants give vocal responses within the scanner (Chrysikou & Thompson-Schill, 2011; Fink et al., 2010; Jung-Beeman et al., 2004) with varying degrees of success (Fink et al., 2009). Within the latter approach, most investigators have subjects silently carry out the task during each trial and are then provided a cue at the end of the trial which indicate that they can now record their verbal responses (Fink et al., 2009, 2010; Jung-Beeman et al., 2004) as this allows one to overule the influence of complex motor movements in the period of interest within a trial. Others have had participants call aloud their responses within the trial itself upon generating a new use (Chrysikou & Thompson-Schill, 2011). There are advantages and disadvantages associated with both the post-fMRI and online-fMRI response generation approaches.

The chief disadvantage of the post-fMRI generation approach is that one cannot fully rule out forgetting or elaboration effects that can impact recall in the feedback session, and one cannot claim with absolute certainty that the participants were following task instructions during the fMRI experimental session. To reduce the likelihood of such eventualities, we instructed and trained subjects thoroughly beforehand in all of the tasks during the practice session. Also, unlike in previous investigations (e.g., Howard-Jones et al., 2005), we had subjects indicate with a button press every time they generated a new use or object during the fMRI experimental session. We were thus able to record precisely how many uses/objects were generated per trial across all subjects. After the subjects finished generating their

responses in the post-fMRI session, we also checked whether the number of responses in the feedback session corresponded to that of the fMRI experimental session as well as controlled whether any unacceptable responses were generated for either of the divergent thinking tasks. The correlations between the number of uses and objects generated during the imaging and feedback sessions were highly significant.

While this finding does not completely overrule the possibility of elaboration effects in the feedback session nor the possibility of low task involvement during the experimental session, the results that support the supposition that the subjects followed task instructions and were unlikely to have responded in a trivial manner on the divergent thinking conditions during both the fMRI and post-fMRI sessions are as follows. The subjects as a whole (a) generated meaningful as opposed to nonsense responses in both divergent thinking conditions, (b) generated slightly fewer responses as opposed to more responses in the feedback session compared to within the fMRI session (the opposite would have been a clear case for elaboration effects), (c) rated the D-H condition to be more difficult than both the low demand conditions (C-L, D-L), which speaks for their genuine engagement in the tasks, (d) responded on average with 4 uses per trial for the D-H condition as opposed to 8 objects per trial for the D-L condition, which speaks for the non-randomness of their performance, (e) showed consistent behavioral findings to those of other groups of subjects who participated in behavioral pilot studies (unpublished data), (f) took between 10–15 min to report the uses and objects in the post-fMRI session, which is too brief a time to generate wholly novel responses for each trial, and (g) included only good performers on the control tasks (reaching 75% accuracy criterion), which speaks for their generally high motivation to take the experiment seriously and to perform well. These key factors together with the findings that the brain activation patterns were in line with predictions and were highly significant in spite of stringent correction criteria, indicate that subjects were not carrying out the divergent tasks during either the fMRI experimental or feedback sessions in an manner that could be considered easy, trivial or random.

The decision to not adopt an online-fMRI response generation approach was mainly based on two grounds. The chief disadvantage of the vocal response generation approach during fMRI is that verbal responses involve jaw and head movements which are extremely difficult to control or correct during BOLD image analyses and can easily result in movement artefacts (e.g., Birn, Bandettini, Cox, Jesmanowicz, & Shaker, 1998). Some suggestions are available in the literature about how to optimally circumvent this issue in experimental designs (Birn, Bandettini, Cox, & Shaker, 1999; Diedrichsen & Shadmehr, 2005; Gracco, Tremblay, & Pike, 2005; Huang, Francis, & Carr, 2008), such as block designs with task and control durations of 10 s (Birn, Cox, & Bandettini, 2004). It is important to note though that none of these proposals were made with open-ended divergent thinking tasks in mind, which usually require much longer task durations and involve multiple verbal responses. Moreover, as only a bare few functional neuroimaging articles on creative thinking explicitly indicate how they deal with this critical issue in their reports (e.g., Fink et al., 2010) there are few means by which a consensus can be reached about which parameters would be considered optimal to circumvent this problem.

Another disadvantage of employing an online-fMRI vocal response generation approach is that having to include a lengthy response duration for each trial, during which time the vocal response can be made (the customary approach when using block designs), increases the total trial duration and consequently leads to a lower number of trials per condition as one cannot carry out effective fMRI testing for vey lengthy periods of time.

For instance, in the study by Fink et al. (2009) the trial was comprised of the following events—fixation duration of 20 s, task duration of 20 s, and response duration of 8 s, which makes a trial duration of 48 s. This in turn influences how many trials (eight) can be allotted per condition (four). A low number of trials can severely compromise the quality of the associated average HRF response because of poor signal-to-noise-ratio[2].

The current study was designed with a view to avoid these two limitations that have been associated with most of the studies that have adopted the online-fMRI response generation approach while also controlling for the limitations associated with the post-fMRI response generation approach.

4.5.4. Comparability of divergent and control tasks

The current study was devised in an attempt to overcome some of the problems that customarily accompany neuroscientific investigations of creative thinking. A severe shortcoming of most experimental designs, as detailed in the Introduction, is that the creative task (e.g., generate a story from semantically unrelated words) is usually more difficult or cognitively demanding than the comparison control task (e.g., generate a story from semantically related words). This makes it impossible to tease apart which parts of the resulting brain activations are specific to greater demands on creative idea generation from those that are generally involved in greater demands on cognitive control. Ensuring the comparability between conditions is an especially difficult issue as it is extremely challenging to devise an optimal control task that is similar in every possible way (such as in terms of involving high cognitive demand, divergent thinking, generation of equivalent number of responses, etc.) to the creative task except that it does not involve creative idea generation. This is almost certainly why the match between control tasks versus creative tasks in the past has been mostly suboptimal.

We attempted to deal with this particular issue of less cognitively demanding control tasks relative to creative tasks by employing divergent and control tasks that differed in the degree of cognitive demand, and conducted masked analysis of the fMRI data. Conceptual expansion was assessed by using the contrast of the alternate uses task (D-H) relative to 2-back control task (C-H) as a mask when interpreting the differences between the alternate uses (D-H) and the object location task (D-L). The findings that resulted from this analysis indicated which brain areas were significantly activated while performing the alternate uses task compared to the object location task, but only in those regions that were also more strongly activated during alternate uses task relative to 2-back control task. So the argument that the brain activations generated during creative thinking can be ascribed merely to high demands on cognitive control could be overruled as the brain regions in question were more strongly activated when performing the alternate uses task relative to both the object location task and the 2-back control task.

Our novel approach has several merits in that it avoids many of the pitfalls of previous studies. Nonetheless it is important to note that our approach is certainly not the perfect solution to the problem of lack of comparability between creative and control tasks within neuroscientific studies as there were several qualitative differences between the divergent and control tasks used within the design. As mentioned earlier in the interpretations of the results, the control tasks (1-back, 2-back) and divergent tasks (object location, alternate uses) used in the study differed greatly from one another in several ways, including stimulus type (letters versus words) and stimulus presentation (number of presented stimuli within one trial). Such differences are likely to have an impact on the pattern of results, particularly those associated with the contrasts that assessed divergent thinking in general relative to the working memory (D-H & D-L > C-H & C-L) as well as working memory relative to divergent thinking (C-H & C-L > D-H & D-L). Such issues need to be kept in mind when interpreting the findings associated with these contrasts.

5. Conclusions

A novel fMRI experimental design was developed that enabled the event-related investigation of select creative processes while overcoming many of the usual problems that beset this line of research, including differences in cognitive demand or response preparation. Brain regions that were selectively assessed as a function of conceptual expansion included the left anterior inferior frontal gyrus, the temporal poles and the lateral fronto-polar cortex, areas that are known to play a critical role in the retention, retrieval and integration of semantic information. This study represents the adoption of a novel approach in the neuro-physiological study of creative thinking (Kroger et al., 2012; Rutter et al., 2012) where the focus is on outlining and investigating different mental operations that underlie this singularly multifaceted ability. Future research will be required to fully unravel how the current findings on general creative thinking can be more specifically linked to findings on individual differences in creative ability and anatomical variables (Jung et al., 2010b; Shamay-Tsoory, Adler, haron-Peretz, Perry, & Mayseless, 2011), such as inverse correlations between white matter integrity in inferior frontal regions and creative ability (Jung, Grazioplene, Caprihan, Chavez, & Haier, 2010a).

The process of conceptual expansion was the subject of the current paper and further efforts will be necessary to explore the dynamics of conceptual expansion as well as examine other relevant mental operations in creativity such as creative imagery and constraints posed by recently activated knowledge in the generation of original responses (Abraham & Windmann, 2007). Such an undertaking is imperative to ensure that the field of creativity garners the same degree of rigorous scientific investigation and discourse as other research areas of higher-order cognition.

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[2] (a) http://mindhive.mit.edu/node/66, (b) http://imaging.mrc-cbu.cam.ac.uk/imaging/DesignEfficiency, (c) http://afni.nimh.nih.gov/pub/dist/HOWTO//howto/ht03_stim/html/stim_ background.shtml.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.neuropsychologia.2012.04.015.

References

Abraham, A., Schubotz, R. I., & von Cramon, D. Y. (2008). Thinking about the future versus the past in personal and non-personal contexts. *Brain Research*, *1233*, 106–119.

Abraham, A., & Windmann, S. (2007). Creative cognition: the diverse operations and the prospect of applying a cognitive neuroscience perspective. *Methods*, *42*, 38–48.

Aziz-Zadeh, L., Kaplan, J. T., & Iacoboni, M. (2009). "Aha!": The neural correlates of verbal insight solutions. *HumanBrain Mapping*, *30*, 908–916.

Baddeley, A. (2010). Working memory. *CurrentBiology*, *20*, R136–R140.

Badre, D. (2008). Cognitive control, hierarchy, and the rostro-caudal organization of the frontal lobes. *Trends in Cognitive Sciences*, *12*, 193–200.

Badre, D., Poldrack, R. A., Pare-Blagoev, E. J., Insler, R. Z., & Wagner, A. D. (2005). Dissociable controlled retrieval and generalized selection mechanisms in ventrolateral prefrontal cortex. *Neuron*, *47*, 907–918.

Badre, D., & Wagner, A. D. (2004). Selection, integration, and conflict monitoring; assessing the nature and generality of prefrontal cognitive control mechanisms. *Neuron*, *41*, 473–487.

Badre, D., & Wagner, A. D. (2007). Left ventrolateral prefrontal cortex and the cognitive control of memory. *Neuropsychologia*, *45*, 2883–2901.

Bechtereva, N. P., Korotkov, A. D., Pakhomov, S. V., Roudas, M. S., Starchenko, M. G., & Medvedev, S. V. (2004). PET study of brain maintenance of verbal creative activity. *International Journal of Psychophysiology*, *53*, 11–20.

Binder, J. R., Desai, R. H., Graves, W. W., & Conant, L. L. (2009). Where is the semantic system? A critical review and meta-analysis of 120 functional neuroimaging studies. *Cerebral Cortex*, *19*, 2767–2796.

Birn, R. M., Bandettini, P. A., Cox, R. W., Jesmanowicz, A., & Shaker, R. (1998). Magnetic field changes in the human brain due to swallowing or speaking. *Magnetic Resonance in Medicine*, *40*, 55–60.

Birn, R. M., Bandettini, P. A., Cox, R. W., & Shaker, R. (1999). Event-related fMRI of tasks involving brief motion. *HumanBrain Mapping*, *7*, 106–114.

Birn, R. M., Cox, R. W., & Bandettini, P. A. (2004). Experimental designs and processing strategies for fMRI studies involving overt verbal responses. *Neuroimage*, *23*, 1046–1058.

Bookheimer, S. (2002). Functional MRI of language: New approaches to understanding the cortical organization of semantic processing. *Annual Review of Neuroscience*, *25*, 151–188.

Botvinick, M. M. (2007). Conflict monitoring and decision making: reconciling two perspectives on anterior cingulate function. *Cognitive Affective and Behavioural Neuroscience*, *7*, 356–366.

Bowden, E. M., Jung-Beeman, M., Fleck, J., & Kounios, J. (2005). New approaches to demystifying insight. *Trends in Cognitive Sciences*, *9*, 322–328.

Bunge, S. A., Helskog, E. H., & Wendelken, C. (2009). Left, but not right, rostrolateral prefrontal cortex meets a stringent test of the relational integration hypothesis. *Neuroimage*, *46*, 338–342.

Bunge, S. A., Wendelken, C., Badre, D., & Wagner, A. D. (2005). Analogical reasoning and prefrontal cortex: Evidence for separable retrieval and integration mechanisms. *Cerebral Cortex*, *15*, 239–249.

Cai, D. J., Mednick, S. A., Harrison, E. M., Kanady, J. C., & Mednick, S. C. (2009). REM, not incubation, improves creativity by priming associative networks. *Proceedings of the National Academy of Sciences of United States of America*, *106*, 10130–10134.

Cappa, S. F. (2008). Imaging studies of semantic memory. *Current Opinion in Neurology*, *21*, 669–675.

Carlsson, I., Wendt, P. E., & Risberg, J. (2000). On the neurobiology of creativity. Differences in frontal activity between high and low creative subjects. *Neuropsychologia*, *38*, 873–885.

Chavez-Eakle, R. A., Graff-Guerrero, A., Garcia-Reyna, J. C., Vaugier, V., & Cruz-Fuentes, C. (2007). Cerebral blood flow associated with creative performance: A comparative study. *Neuroimage*, *38*, 519–528.

Christoff, K., Prabhakaran, V., Dorfman, J., Zhao, Z., Kroger, J. K., Holyoak, K. J., et al. (2001). Rostrolateral prefrontal cortex involvement in relational integration during reasoning. *Neuroimage*, *14*, 1136–1149.

Christoff, K., Ream, J. M., Geddes, L. P., & Gabrieli, J. D. (2003). Evaluating self-generated information: anterior prefrontal contributions to human cognition. *Behavioral Neuroscience*, *117*, 1161–1168.

Chrysikou, E. G., & Thompson-Schill, S. L. (2011). Dissociable brain states linked to common and creative object use. *HumanBrain Mapping*, *32*, 665–675.

Cohen, J. D., Perlstein, W. M., Braver, T. S., Nystrom, L. E., Noll, D. C., Jonides, J., et al. (1997). Temporal dynamics of brain activation during a working memory task. *Nature*, *386*, 604–608.

Diedrichsen, J., & Shadmehr, R. (2005). Detecting and adjusting for artifacts in fMRI time series data. *Neuroimage*, *27*, 624–634.

Dietrich, A. (2004). The cognitive neuroscience of creativity. *Psychonomic Bulletin and Review*, *11*, 1011–1026.

Dietrich, A. (2007). Who's afraid of a cognitive neuroscience of creativity?. *Methods*, *42*, 22–27.

Dietrich, A., & Kanso, R. (2010). A review of EEG, ERP, and neuroimaging studies of creativity and insight. *Psychological Bulletin*, *136*, 822–848.

Dijksterhuis, A., & Meurs, T. (2006). Where creativity resides: The generative power of unconscious thought. *Consciousness and Cognition*, *15*, 135–146.

Fiebach, C. J., Friederici, A. D., Smith, E. E., & Swinney, D. (2007). Lateral inferotemporal cortex maintains conceptual-semantic representations in verbal working memory. *Journal of Cognitive Neuroscience*, *19*, 2035–2049.

Fink, A., Benedek, M., Grabner, R. H., Staudt, B., & Neubauer, A. C. (2007). Creativity meets neuroscience: experimental tasks for the neuroscientific study of creative thinking. *Methods*, *42*, 68–76.

Fink, A., Grabner, R. H., Benedek, M., Reishofer, G., Hauswirth, V., Fally, M., et al. (2009). The creative brain: Investigation of brain activity during creative problem solving by means of EEG and FMRI. *HumanBrain Mapping*, *30*, 734–748.

Fink, A., Grabner, R. H., Gebauer, D., Reishofer, G., Koschutnig, K., & Ebner, F. (2010). Enhancing creativity by means of cognitive stimulation: evidence from an fMRI study. *Neuroimage*, *52*, 1687–1695.

Finke, R. A., Ward, T. B., & Smith, S. M. (1992). *Creative cognition: Theory, research and applications*. Cambridge, MA: MIT Press.

Friston, K. J., Holmes, A. P., Worsley, K. J., Poline, J. B., Frith, C., & Frackowiak, R. S. (1995). Statistical parametric maps in functional imaging: A general linear approach. *Human Brain Mapping*, *2*, 189–210.

Gracco, V. L., Tremblay, P., & Pike, B. (2005). Imaging speech production using fMRI. *Neuroimage*, *26*, 294–301.

Graybiel, A. M. (2005). The basal ganglia: Learning new tricks and loving it. *Current Opinion in Neurobiology*, *15*, 638–644.

Green, A. E., Fugelsang, J. A., Kraemer, D. J., Shamosh, N. A., & Dunbar, K. N. (2006). Frontopolar cortex mediates abstract integration in analogy. *Brain Research*, *1096*, 125–137.

Green, A. E., Kraemer, D. J., Fugelsang, J. A., Gray, J. R., & Dunbar, K. N. (2010). Connecting long distance: semantic distance in analogical reasoning modulates frontopolar cortex activity. *Cerebral Cortex*, *20*, 70–76.

Guilford, J. P. (1967). *The nature of human intelligence*. New York: McGraw-Hill.

Howard-Jones, P. A., Blakemore, S. J., Samuel, E. A., Summers, I. R., & Claxton, G. (2005). Semantic divergence and creative story generation: an fMRI investigation. *Brain Research:Cognitive Brain Research*, *25*, 240–250.

Huang, J., Francis, A. P., & Carr, T. H. (2008). Studying overt word reading and speech production with event-related fMRI: A method for detecting, assessing, and correcting articulation-induced signal changes and for measuring onset time and duration of articulation. *Brain and Language*, *104*, 10–23.

Jung, R. E., Grazioplene, R., Caprihan, A., Chavez, R. S., & Haier, R. J. (2010a). White matter integrity, creativity, and psychopathology: Disentangling constructs with diffusion tensor imaging. *PLoS One*, *5*, e9818.

Jung, R. E., Segall, J. M., Jeremy, B. H., Flores, R. A., Smith, S. M., Chavez, R. S., et al. (2010b). Neuroanatomy of creativity. *HumanBrain Mapping*, *31*, 398–409.

Jung-Beeman, M., Bowden, E. M., Haberman, J., Frymiare, J. L., rambel-Liu, S., Greenblatt, R., et al. (2004). Neural activity when people solve verbal problems with insight. *PLoS Biology*, *2*, E97.

Kroger, J. K., Sabb, F. W., Fales, C. L., Bookheimer, S. Y., Cohen, M. S., & Holyoak, K. J. (2002a). Recruitment of anterior dorsolateral prefrontal cortex in human reasoning: a parametric study of relational complexity. *Cerebral Cortex*, *12*, 477–485.

Kroger, J. K., Sabb, F. W., Fales, C. L., Bookheimer, S. Y., Cohen, M. S., & Holyoak, K. J. (2002b). Recruitment of anterior dorsolateral prefrontal cortex in human reasoning: a parametric study of relational complexity. *Cerebral Cortex*, *12*, 477–485.

Kroger, S., Rutter, B., Stark, R., Windmann, S., Hermann, C., & Abraham, A. (2012). Using a shoe as a plant pot: neural correlates of passive conceptual expansion. *Brain Research*, *1430*, 52–61.

Lambon Ralph, M. A., Cipolotti, L., Manes, F., & Patterson, K. (2010). Taking both sides: do unilateral anterior temporal lobe lesions disrupt semantic memory?. *Brain*, *133*, 3243–3255.

Lambon Ralph, M. A., & Patterson, K. (2008). Generalization and differentiation in semantic memory: insights from semantic dementia. *Annals of the New York Academy of Sciences*, *1124*, 61–76.

Lambon Ralph, M. A., Pobric, G., & Jefferies, E. (2009). Conceptual knowledge is underpinned by the temporal pole bilaterally: convergent evidence from rTMS. *Cerebral Cortex*, *19*, 832–838.

Legrand, D., & Ruby, P. (2009). What is self-specific? Theoretical investigation and critical review of neuroimaging results. *Psychol Review*, *116*, 252–282.

Lohmann, G., Muller, K., Bosch, V., Mentzel, H., Hessler, S., Chen, L., et al. (2001). LIPSIA—A new software system for the evaluation of functional magnetic resonance images of the human brain. *Computerised Medical Imaging and Graphics*, *25*, 449–457.

Lohmann, G., Neumann, J., Muller, K., Lepsien, J., & Turner, R. (2008). The multiple comparison problem in fMRI: A new method based on anatomical priors. In *Proceedings of MICCAI 2008*, New York.

Mansouri, F. A., Tanaka, K., & Buckley, M. J. (2009). Conflict-induced behavioural adjustment: A clue to the executive functions of the prefrontal cortex. *Nat.Rev.Neurosci*, *10*, 141–152.

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, *9*, 97–113.

Olson, I. R., & Berryhill, M. (2009). Some surprising findings on the involvement of the parietal lobe in human memory. *Neurobiology of Learning and Memory*, *91*, 155–165.

Patterson, K., Nestor, P. J., & Rogers, T. T. (2007). Where do you know what you know? The representation of semantic knowledge in the human brain. *Nature Reviews Neuroscience*, *8*, 976–987.

Pochon, J. B., Riis, J., Sanfey, A. G., Nystrom, L. E., & Cohen, J. D. (2008). Functional imaging of decision conflict. *Journal of Neuroscience*, *28*, 3468–3473.

Ramnani, N., & Owen, A. M. (2004). Anterior prefrontal cortex: insights into function from anatomy and neuroimaging. *Nature Reviews Neuroscience*, *5*, 184–194.

Rutter, B., Kroger, S., Stark, R., Schweckendiek, J., Windmann, S., Hermann, C., et al. (2012). Can clouds dance? Neural correlates of passive conceptual expansion using a metaphor processing task: Implications for creative cognition. *Brain and Cognition*, *78*, 114–122.

Schacter, D. L., Norman, K. A., & Koutsaal, W. (1998). The cognitive neuroscience of constructive memory. *Annual Review of Psychology*, *49*, 289–318.

Shamay-Tsoory, S. G., Adler, N., haron-Peretz, J., Perry, D., & Mayseless, N. (2011). The origins of originality: the neural bases of creative thinking and originality. *Neuropsychologia*, *49*, 178–185.

Simmons, W. K., & Martin, A. (2009). The anterior temporal lobes and the functional architecture of semantic memory. *Journal of the International Neuropsychological Society*, *15*, 645–649.

Simmons, W. K., Reddish, M., Bellgowan, P. S., & Martin, A. (2010). The selectivity and functional connectivity of the anterior temporal lobes. *Cerebral Cortex*, *20*, 813–825.

Smith, S. M., Ward, T. B., & Finke, R. A. (1992). A cognitive approach to creativity. *Bulletin of the Psychonomic Society*, *30*, 484.

Smith, S. M., Ward, T. B., & Finke, R. A. (1995). *The creative cognition approach*. Cambridge, MA: MIT Press.

Starchenko, M. G., Bekhtereva, N. P., Pakhomov, S. V., & Medvedev, S. V. (2003). [Study of the brain organization of creative thinking]. *Fiziol.Cheloveka*, *29*, 151–152.

Tewes, U. (1994). *HAWIE-R. Hamburg-Wechsler-Intelligenztest für Erwachsense, Revision 1991; Handbuch und Testanweisung*. Göttingen: Verlag Hans Huber.

Thompson-Schill, S. L., D'Esposito, M., Aguirre, G. K., & Farah, M. J. (1997). Role of left inferior prefrontal cortex in retrieval of semantic knowledge: A reevaluation. *Proceedings of the National Academy of Sciences of the United States of America*, *94*, 14792–14797.

Thompson-Schill, S. L., Jonides, J., Marshuetz, C., Smith, E. E., D'Esposito, M., Kan, I. P., et al. (2002). Effects of frontal lobe damage on interference effects in working memory. *Cognitive Affective and Behavioural Neuroscience*, *2*, 109–120.

Tse, C. S. (2009). The role of associative strength in the semantic relatedness effect on immediate serial recall. *Memory*, *17*, 874–891.

Wagner, A. D., Pare-Blagoev, E. J., Clark, J., & Poldrack, R. A. (2001). Recovering meaning: left prefrontal cortex guides controlled semantic retrieval. *Neuron*, *31*, 329–338.

Wallach, M. A., & Kogan, N. (1965). *Modes of thinking in young children: a study of the creativity–intelligence distinction*. New York: Holt, Rinehart & Winston.

Ward, T. B. (1994). Structured imagination—The role of category structure in exemplar generation. *Cognitive Psychology*, *27*, 1–40.

Ward, T. B., Patterson, M. J., Sifonis, C. M., Dodds, R. A., & Saunders, K. N. (2002). The role of graded category structure in imaginative thought. *Memory and Cognition*, *30*, 199–216.

Wixted, J. T. (2004). The psychology and neuroscience of forgetting. *Annual Review of Psychology*, *55*, 235–269.

Worsley, K. J., & Friston, K. J. (1995). Analysis of fMRI time-series revisited—Again. *Neuroimage*, *2*, 173–181.

Zhong, C. B., Dijksterhuis, A., & Galinsky, A. D. (2008). The merits of unconscious thought in creativity. *Psychological Science*, *19*, 912–918.

Zysset, S., Huber, O., Samson, A., Ferstl, E. C., & von Cramon, D. Y. (2003). Functional specialization within the anterior medial prefrontal cortex: A functional magnetic resonance imaging study with human subjects. *NeuroscienceLetters*, *335*, 183–186.