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Research Report

Semantic divergence and creative story generation: An fMRI investigation

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Abstract

The aim of this fMRI investigation was to identify those areas of the brain associated with approaching a story generation task creatively and to investigate the effects upon these correlates of incorporating a set of words that were unrelated to each other—a strategy considered to encourage semantic divergence. Preliminary experiments were undertaken to investigate the possible confounding effects of the scanner environment upon creativity and to reveal the effects of creative effort and word relatedness upon the creativity of those who would be participating in the fMRI scan. In the final part of the investigation, a factorial fMRI design was used to elucidate brain regions involved in increased creative effort and also the effect upon activity in these regions when participants incorporated words that bore little semantic relationship with each other. Results support the notion that areas of the right prefrontal cortex are critical to the types of divergent semantic processing involved with creativity in this context.

Theme: Neural basis for behavior
Topic: Cognition

Keywords: Semantic processing; Creativity; fMRI; Right prefrontal cortex

1. Introduction

Creativity is commonly agreed to involve "bringing something into being that is original (new, unusual, novel, unexpected) and also valuable (useful, good, adaptive, appropriate)" [34]. It has been argued that the construction of novel but appropriate concepts comes about through the combination of familiar but remotely associated components, possibly through a process of blind variation and selective retention [10]. Such ideas form the basis of some educational approaches that attempt to foster creativity through encouraging students to broaden their focus of attention and seek out more remote associations [22]. One well-known teaching technique encourages semantic divergence by asking students to incorporate elements into their solution that are unrelated to each other and/or the problem [20]. The present study uses such a strategy to shed light upon the neural correlates of creativity within the context of story generation. Insights, as well as some speculation, about the underlying neuropsychology of creativity have already arisen from studies of language. Language is considered, in most people, to be strongly lateralized to the left hemisphere. However, the semantic processing of distant associations may be an exception. For example, semantic priming was found to be greater in the right hemisphere when participants were presented with several distantly related primes but, when a single closely related prime was presented, it was found to be greater in the left hemisphere [4,5]. Abdullaev and Posner [1] measured event-related potentials when participants generated uses for stimulus nouns. They found that potentials were lateralized to the left hemisphere when uses and stimuli nouns were related but were bilateral when uses were

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generated that were related to the nouns in unusual ways. These studies tend to suggest that right-hemisphere representations are more suitable than left-hemisphere representations for the semantic processing of distant associates. It is the right inferior frontal gyrus that is most commonly implicated by imaging studies of right hemispheric language [7]. This area is thought to be involved with making decisions about making inferences and producing a complete representation of meaning and intent. However, in the fMRI study of Seger et al. [41], when participants generated unusual verbs for nouns, as opposed to the first verb that came into their head, there was increased activity in the right middle and superior frontal gyri and right medial frontal gyrus. Thus, it may be that prefrontal parts of the right hemisphere support the processing of distant associations and, as proposed by Seger et al. [41], creative thinking in some language-based contexts.

These results also concur with a PET study by Bekhterva et al., requiring the generation of a story from a set of 16 unrelated words presented simultaneously [6]. As in the present study, the effect upon activations when words within sets were related and unrelated was compared. This analysis revealed additional activity for unrelated words in prefrontal areas of the right hemisphere, in the superior frontal, mediofrontal and inferior frontal gyri. Some physiological studies have been made of individual differences using tasks more often used to assess creativity. For example, using PET, it has been shown that more creative individuals produce bilateral increases in anterior prefrontal regions during a “uses of object” test of divergent thinking, in contrast to increases restricted to the left frontotemporal areas shown by less creative individuals [11].

Here, we used fMRI to investigate the neural correlates of creativity in a story generation task by comparing brain activity when participants were producing creative and uncreative stories from sets of words. Following Bekhterva et al. [6], we also compared the effect upon activities when using related and unrelated words but employed a factorial design, which allowed comparison of creative and uncreative objectives, related and unrelated word sets and the interaction between relatedness and objective. Thus, from this interaction analysis, we were able to investigate the effect of using a semantically divergent word set upon those activities associated with approaching the task creatively. It was hypothesized that this interaction effect would include additional activity in the areas of the right frontal hemisphere identified by Seger et al. [41], investigating their suggestion that these areas are critically associated with divergent semantic processing. It is also an issue, in educational terms, whether the apparent positive effect of such strategies upon creative output is associated with additional brain activity or arises wholly from other more superficial issues. For example, it might be the inevitable salience of unrelated elements in the outcome that causes others to judge it as more creative, without any additional processing on behalf of the originator of the outcome.

Our investigation consisted of three experiments, all requiring participants to produce creative and uncreative stories from related and unrelated word sets. Experiment 1 investigated whether a simulation of the scanner environment influenced behavioral outcomes compared with a more naturalistic environment, as well as investigating the appropriateness of the stimuli to be used in Experiment 3. Experiment 2 investigated, under simulated scanning conditions, the behavioral responses of participants who would take part in Experiment 3. Finally, Experiment 3 involved a more realistic acclimatization to procedures inside the simulator followed by the actual scan. This experiment also allowed a comparison of a sample of the behavioral outcomes arising from the simulator and the actual scanning environment.

2. Experiment 1: effect of the environment on creativity

The primary objective of this first experiment was to compare behavioral outcomes under simulated scanning conditions with those generated in a more ecologically valid environment, in terms of its resemblance to a classroom. The educational orientation of the research, and the potential influence of a stressful environment upon creativity [44], made it advisable to check that the rated creativity of outcomes from the chosen task was not severely influenced by the unusual conditions associated with being scanned. Concerns have been raised that the perception and processing of stimuli can be influenced by the distractions of the scanning environment [30].

2.1. Method

2.1.1. Design

A 2 × 2 × 2 factorial block design was employed, all within-participant variables. The independent variables were objective (‘Be creative’, ‘Be uncreative’), relatedness of the words (related, unrelated) and environment (simulator, desk). The dependent variable was the creative value of the stories, as judged by an independent panel.

2.1.2. Participants

Eight native English speakers participated. All were following undergraduate and postgraduate courses to train as teachers, had normal vision and were aged 19–28 (mean age = 21.9, SD = 2.7). Seven were female, and one was male.

2.1.3. Stimuli

168 words, in sets of three, were used as stimuli. In 28 sets of words, the words belonging to each set bore some relation to each other, such as an association with a particular and common experience (e.g. magician, trick, rabbit). In the other 28 sets, the words bore no obvious relation to each other (e.g. flea, sing, sword). Word sets were

then divided to create 8 lists of word sets. There were four sets in which the words were related and four sets in which they were not related.

2.1.4. Apparatus and procedure

Participants were asked to generate a story from each set of 3 words. The set of words appeared on a computer screen for 1.5 s, together with an indication of the objective ("Be creative" or "Be uncreative"). The words (but not the indication of the objective) then disappeared for 10 s during which the participant was asked to generate the story. This was then followed by 20 s in which the participant reported their story. A blank screen for 1.5 s served as a warning that the next three words were about to appear.

Participants were told that they would be presented with sets of three words and that they were to generate the plot of a story that included these three words. They could change the form of the words as they wished. They were shown an example of the how the words would be presented, using words that would not appear in the word lists used for the experiment. Participants were told that they should generate a story that was as creative as possible when the objective "Be creative" appeared. When the objective "Be uncreative" appeared, they were to generate a story that was as uncreative as possible. They could introduce any other words they liked. When prompted on the screen to do so, they were to report their story, without further elaboration, exactly as they had been considering it.

Following the intended design for scanning, the independent variables of objective and the relatedness of the words were permutated to create initially four conditions, with 8 word sets in each condition. Participants were randomly assigned into pairs, and each pair was presented with the conditions in a sequence such that presentation order and the independent variables of objective and relatedness were balanced, although not all permutations of these could be represented (see Table 1). One of each pair was presented with their allotted sequence within a simulated scanning environment. After this, he/she was presented with the other unseen word lists, in the same sequence of conditions, while seated at a desk. The other member of the pair experienced the four conditions in the desk environment first followed by the simulated scanning environment. Thus, each participant experienced 8 conditions in total. As with all three experiments reported here, the presentation software randomized the order of presentation of word sets within each condition automatically for each participant.

Table 1
Participants

Participants $N = 8$	1st block	2nd block	3rd block	4th block
1, 2	R, C	R, UC	UR, C	UR, UC
3, 4	UR, UC	R, C	R, UC	UR, C
5, 6	UR, C	UR, UC	R, C	R, UC
7, 8	R, UC	UR, C	UR, UC	R, C

The sequence of conditions experienced by participants in Experiments 1, 2 and 3, based on permutation of presentation order and independent variables of objective (C = be creative, UC = be uncreative) and semantic relatedness (R = semantically related, UR = semantically unrelated).

The simulated scanning environment consisted of a dummy head-coil into which the head of the participant was strapped. A half pipe, the same diameter as the bore of the scanner magnet, was then drawn over the participant to enclose them. As with the actual scanner, a mirror system was used to present stimuli. Instead of ear protection, the participant wore closed-cup headphones through which a recording of a typical acoustic noise signal generated by EPI fMRI was reproduced. The level of this signal was set approximately 6 dB below the threshold of discomfort. As in an authentic scan, an intercom arrangement allowed communication with the participant inside the enclosure. Unlike the actual fMRI scan, a microphone was set just above the mouth of the participant to record their responses.

In the desk environment, participants viewed the stimuli in a quiet room directly from a computer screen, reporting their stories through a microphone mounted on the desk.

Stories were recorded, transcribed and then judged by an independent panel according to the Consensual Assessment Technique [2] for assessing creative quality. This technique provides a general measure of creative value by gaining a measurement of the creativity of an outcome according to a panel of individuals using their own independent criteria. For each judge, the order of the stories was randomized. The word set from which the story had been produced was presented with each story. Each judge was asked to rank the first 10 stories in order of creativity and then to ascribe to each story a score on a Likert scale (1: very uncreative, 2: uncreative, 3: undecided, 4: creative, 5: very creative). Having carried out this procedure for the first 10 stories and without any further ranking, the judge was then asked to rate the remaining stories. All judges were blind to experimental condition but were made aware of the task given to the participants. The judging panel consisted of 5 adults: a retired English teacher, 3 trainers of teachers (in English and Drama) and a primary school teacher. The judges were generally familiar with the domain of creative story generation, and thus their background met the criteria suggested by Amabile [2] for identifying appropriate judges.

It was hypothesized that both the relatedness of the words and the objective would influence the rated creativity of the stories.

2.2. Results

The inter-judge reliability among the panel of 5 judges was good (Cronbach's alpha = 0.86). The mean creativity ratings of stories (with mean standard errors) produced by individuals in the desk and simulator conditions are provided in Table 2. A within-participants ANOVA was carried out with factors of environment, relatedness and objective. This confirmed main effects of relatedness

Table 2
The mean creativity ratings of stories (with mean standard errors) produced by individuals in the desk and simulator conditions of Experiment 1, according to the independent variables of relatedness and objective

Environment	Objective	Relatedness	Mean	MSE
Desk	Be creative	Related	2.79	0.27
		Unrelated	3.14	0.29
	Be uncreative	Related	1.83	0.23
		Unrelated	2.78	0.19
Simulator	Be creative	Related	2.99	0.19
		Unrelated	3.41	0.17
	Be uncreative	Related	1.70	0.25
		Unrelated	2.68	0.23

(F(1,7) = 61.67, $P < 0.001$) and objective (F(1,7) = 9.31, $P = 0.019$) and no significant effect of environment. There were no significant interaction effects except for relatedness with objective (F(1,7) = 7.70, $P = 0.027$).

2.3. Discussion

As predicted, the inclusion of unrelated words in the stories improved the rated creativity of the outcomes. It was also evident, as predicted, that the rated creativity of the outcomes of the stories was influenced by providing a "Be creative" or "Be uncreative" objective. Mean values of creativity were very similar for stories produced inside the simulator and when seated at a desk, and this similarity of results was reassuring in terms of concerns about distraction effects.

Participants appeared to generate stories from stimulus words in a process resembling blind variation and selection [10] through the determination of links between retrieved contextual associations. Indeed, the stories produced when following a creative objective contained carefully selected and divergent connections between contextual elements that operated on more than one level. For example, in this story from the unrelated–creative condition, the cow has been connected to the star through a space-related nursery rhyme. This also allowed the introduction of the word "zip" (original stimulus words in bold, rated creative score in parentheses):

"This **cow** got so fed up with people doubting that cows could jump over the moon that it decided to jump over a star. To do this, it wore a special rocket suit. The cow **zip**ped up the space suit, lit the blue touch paper and flew up over the **star**" (4.0).

In another story, from the related–creative condition, the participant introduced their own unrelated context of being marooned on a desert island. Through this device, additional connections could be made between the original three words that were related through a football theme:

"Marooned on a desert island with nothing to do I **kick**ed around watermelons. I became so good at it that, when I was finally picked up by a passing boat, I was encouraged to join the local **football** team—I scored lots of **goal**s and was soon recognized for the amazing talent that I'd become" (3.6).

In contrast, participants in the uncreative conditions tended to stay focused upon a single and unelaborate connection between the words, thus minimizing the introduction of any additional contextual material. Often, as in this story from the uncreative–related condition, the participants achieved this by simply restructuring the same connection in a somewhat repetitive way:

"The children were told that they must **brush** their **teeth** when they are young in order to make them **shine** and that they wouldn't have any friends if their teeth weren't shiny. So every single night, the children brushed their teeth to make them shine" (2.4).

In the unrelated–uncreative condition, as in the following example, some additional contextual retrieval and divergent association was necessary, but at least one of the words was often linked in a superficial manner:

"I looked at the sky on a really dark day not so long ago—it was really black and one particular **cloud** looked as though there was lightning going to come out of it. The **strike** just happened then and it hit the bunch of **grape**s I was eating at the same time—not me" (2.6).

From the observed interaction of objective and relatedness, it would appear that the rated creativity of stories was influenced more by objective in the related conditions than in the unrelated conditions. This may have been related to the informal comments made by some participants that they found being uncreative with unrelated words quite difficult. Indeed, according to our model above, some remote association must be found between the words, and some participants were clearly aware of this.

Although judges used the full range of the scale, scores were generally conservative, with very few instances of stories receiving the highest score. Indeed, two of the judges made unsolicited comments after evaluating the stories about their unwillingness to apply judgments of "very creative" when dealing with such brief samples of writing. It is entirely possible that another panel of judges, perhaps with more or less experience with creative story writing, might have judged the outcomes differently to our selected panel, at least in absolute terms. However, the influence of expertise has only been found to influence judgments of "high-level" products, with generally good correlation between experts and non-experts when comparing the relative merits of outcomes arising from a non-specialist task, provided that the latter have some experience of the domain [2]. It is likely, then, that employing another panel of judges would only have produced a different relationship between the conditions if the judges had possessed no experience at all with creative writing.

3. Experiment 2: behavioral response of fMRI participants

A prior investigation, using the simulator, of the behavioral responses of participants selected for scanning was considered important since it would not be practical to record immediate reports of stories within the scanner itself.

3.1. Method

3.1.1. Design

A 2 × 2 factorial block within-participants design was employed. The independent variables were objective ('Be creative', 'Be uncreative') and relatedness of the words (related, unrelated). The dependent variable was the creative value of the stories, as judged by an independent panel.

3.1.2. Participants

A new set of eight native English speakers participated. All were following undergraduate and postgraduate courses to train as teachers, had normal vision, were aged 19–28 (mean age = 20.3, SD = 1.3) and were right-handed as assessed by the Edinburgh test [33]. Seven were female, and one was male. The medical history of these 8 participants was also checked in order to ascertain their suitability for subsequent MRI scanning.

3.1.3. Stimuli

A new corpus of words was used to produce another 8 lists of word sets consisting of 4 lists of related word sets and 4 lists of unrelated word sets.

3.1.4. Apparatus and procedure

The procedure for the first experiment was repeated except that the stimuli were only presented in the simulation environment. One of each pair of participants was presented with the two related word lists (one list with each objective) and two unrelated word lists (one list with each objective), the other participant experienced the same four conditions but using the other four sets of words. Again, stories were verbalized immediately, recorded, transcribed and judged by the same panel of judges in the manner previously described.

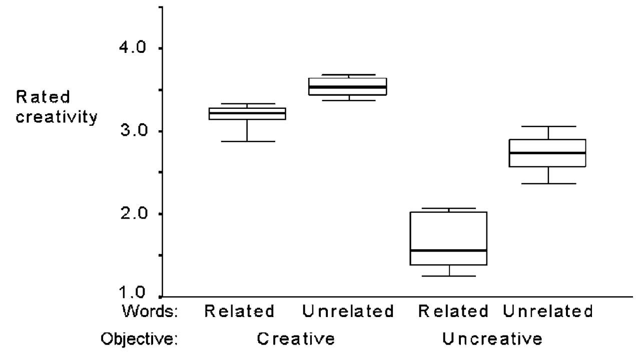

Fig. 1. Box plot of scores for the rated creativity of stories generated and reported immediately in the simulated scanning environment by the eight participants in Experiment 2, who later took part in the fMRI scanning procedures of Experiment 3.

3.2. Results

The inter-judge reliability among the panel of 5 judges was good (Cronbach's alpha = 0.87). The mean creativity ratings of stories (with mean standard errors) produced by individuals in the four conditions are provided in Table 3, and Fig. 1 shows a box plot of the scores achieved by the participants in these four conditions.

A within-participants ANOVA was carried out with factors of environment, relatedness and objective. This confirmed main effects of relatedness ($F(1,7) = 58.64$, $P < 0.001$) and objective ($F(1,7) = 49.45$ $P < 0.001$) and a significant interaction effect for relatedness with objective ($F(1,7) = 32.51$, $P = 0.001$).

Table 3
The mean creativity ratings of stories (with mean standard errors) produced by participants in Experiment 2 under simulated scanning conditions according to independent variables of relatedness and objective

Objective	Relatedness	Mean	Mean standard errors
Be creative	Related	3.23	0.22
	Unrelated	3.51	0.38
Be uncreative	Related	1.66	0.35
	Unrelated	2.8	0.38

The same participants would later take part in Experiment 3 involving the fMRI scan.

3.3. Discussion

As in Experiment 1, both the objective followed by participants and the relatedness of the word set that was used significantly influenced the rated creativity of the stories generated. The box plot in Fig. 1 reflects the approximately normal distribution of scores recorded in all 4 conditions. Inspection of the stories revealed that the participants were employing similar strategies in response to the four conditions as identified in Experiment 1.

4. Experiment 3: fMRI scan

4.1. Method

4.1.1. Design

A 2 × 2 factorial block design was employed, all within-participant variables. The independent variables were objective ('Be creative', 'Be uncreative') and relatedness of the words (related, unrelated), with permutations of these variables again producing four conditions.

4.1.2. Stimuli

The stimuli from Experiment 1 were also used again here in Experiment 3.

4.1.3. Procedure

The reporting of stories during scanning was considered problematic in terms of the motor activity produced. For this reason, the procedure was modified. After each set of words and the objective had appeared on the computer screen for 1.5 s, the participant was provided with 22 s to generate the story (with the objective remaining on the screen as before) followed by a blank screen for 1.5 s that served as a warning that the next word set was about to be presented. Instead of reporting during scanning, participants were asked, immediately after leaving the scanner, to identify (from a list of 24 word sets) the 12 sets presented during the test. They were also asked to recall their stories for a random selection of 20 word sets (5 from each of the four conditions). These two tasks were designed to check the attention of the participants during scanning and to collect retrospectively a sample of the stories they produced. Once again, an attempt was made to minimize the effects of presentation order using the sequence of conditions illustrated in Table 1.

To acclimatize the participants, this procedure was first rehearsed in the simulator, where participants were presented with those four lists of word sets from Experiment 2 that they had not seen previously.

Imaging was performed with a 1.5 T whole-body magnetic-resonance imager (Phillips Gyroscan Intera with quadrature head coil). The head of the participant was strapped firmly but comfortably in the head coil. Attached to the head coil was a mirror through which could be viewed the projection of a computer screen, positioned beyond the bore of the imager. A T2* sensitive (BOLD) echo-planar imaging sequence was used for functional imaging with TR = 3000 ms, TE = 50 ms. For each participant, 512 3D volume acquisitions were obtained (128 acquisitions over a period of 6.4 min for each of the four conditions in immediate succession, giving a total imaging time of around 26 min). Each 3D volume acquisition consisted of 32 contiguous slices of 4 mm thickness, 64×64 matrix, with a voxel size of $4 \times 3.6 \times 3.6$ mm^3, in an oblique axial plane that was rotated 20° (clockwise with nose to left) with respect to the anterior commisure–posterior commisure line. This angle optimized acquisition of cerebellar and frontal lobe structures. For each condition, the beginning of the 6.4 min of imaging time was automatically initiated 6 s before the presentation of the first stimulus.

Processing of data was performed off-line using SPM2 (Wellcome Department of Cognitive Neurology, UCL, London). After discarding the first 3 volumes in each condition, data from each individual were realigned to the first scan and "unwarped" using a model for susceptibility-by-movement interactions to remove the residual movement related variance [3]. The data for each participant were then spatially normalized to the Montreal Neurological Institute template. Images were smoothed with a (12 mm FWHM) Gaussian kernel filter. The analysis of the functional imaging data entailed the creation of parametric maps representing a statistical assessment of hypothesized condition-specific activity using the general linear model approach [16]. A within-participants analysis was performed with identical models across participants. For model estimation, individual data were temporally smoothed using a convolution with the hemodynamic response function. A temporal high-pass filter (128 s) was applied to remove low-frequency extraneous effects, such as cardiac and respiratory artifacts. For each participant, the four conditions were all included in the same design matrix. Each condition was identically modeled using a boxcar to create regressors of interest. We report regions arising from a fixed effects analysis of main effects that survived correction for multiple comparisons at $P > 0.05$.

For the interaction of the variables of relatedness and objective, representing the special demands of working creatively with unrelated stimuli, it was hypothesized that additional activity would occur in those areas of the right hemisphere that Seger et al. [41] suggested may be critical to creative thinking. Thus, for this analysis, we report those regions surviving an uncorrected threshold of $P < 0.001$ for which we had the a priori hypothesis. We acknowledge that the results reported with this fixed effect model concern the specific group of participants that we tested and may not be applicable to the general population, as would have been the case with a random effects model.

4.2. Results

4.2.1. fMRI

The main effects of objective were calculated statistically using a conjunction analysis [39]. Conjunction analyses are generally more suited to factorial designs of the type used here since, unlike cognitive subtraction, cognitive conjunction does not depend on "pure insertion"—the assumption that the addition of an extra processing component in the activation task has no effect on the implementation of the processes that are also engaged in the baseline task. Thus, by conjointly testing the hypotheses relating to the (creative–uncreative) contrasts in both the related and unrelated conditions, this analysis was able to reveal the main effect of objective in the absence of interaction—i.e. those regions of the brain that were significantly more active in the creative conditions than in the uncreative conditions (see Fig. 2A). Reverse contrasts, showing regions that were more active when being uncreative, are also indicated (Fig. 2B).

Similarly, the main effect of word relatedness in the absence of interaction with objective was calculated by conjointly testing the hypotheses relating to the (unrelated–related) contrasts in both the creative and uncreative conditions. Regions of the brain that were significantly

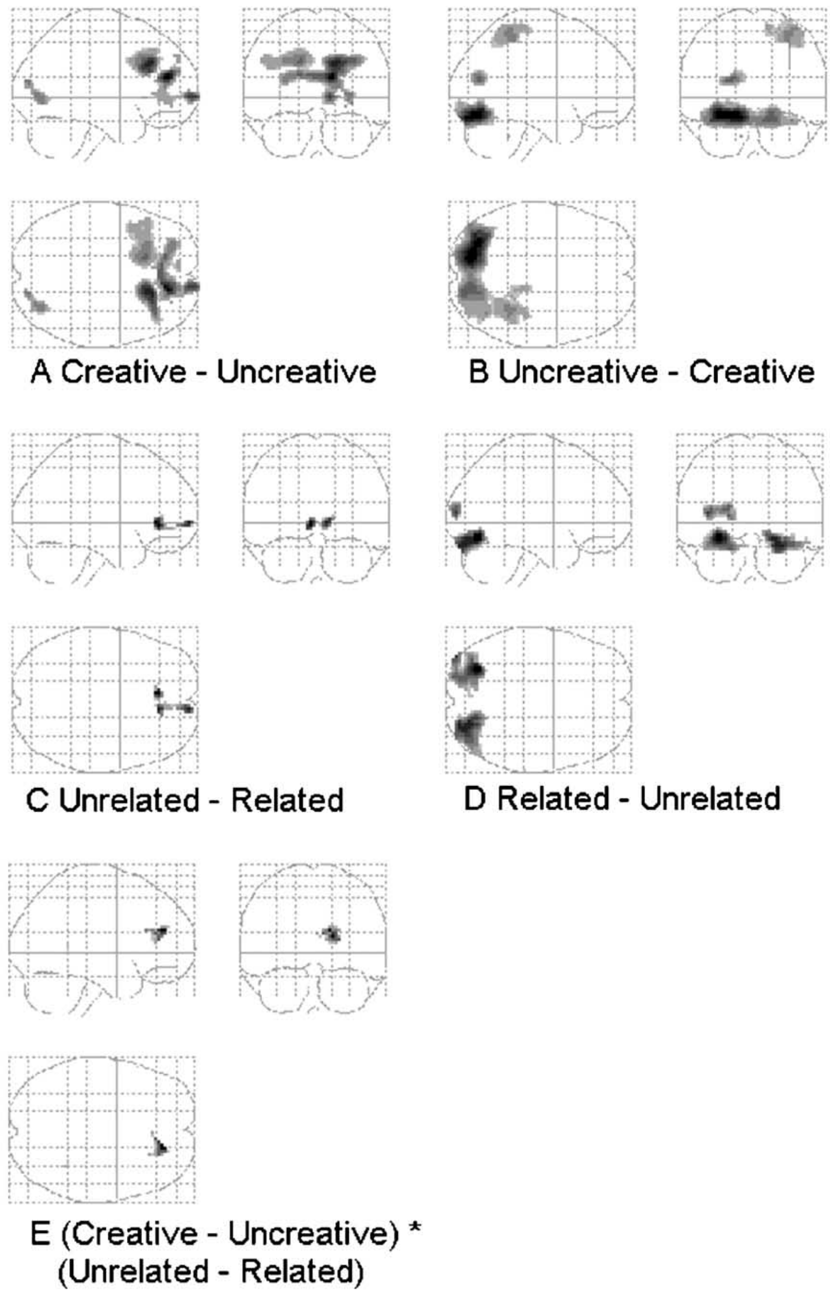

Fig. 2. Statistical parametric maps, as glass brain images, of (A) conjunction of creative–uncreative contrasts, (B) conjunction of uncreative–creative contrasts, (C) conjunction of unrelated–related contrasts, (D) conjunction of related–unrelated contrasts, (E) interaction of objective with relatedness, masked inclusively by the conjunction of creative–uncreative contrasts. (For the contrast matrices used in each analysis, see Table 4).

more active in the unrelated conditions than in the related conditions are shown in Fig. 2C. Regions that were more active in the related conditions, compared with unrelated conditions, are shown in Fig. 2D.

To identify how using unrelated words interacted with the correlates of approaching the task creatively, the interaction contrast was derived by means of subtraction and by then inclusively masking the outcome with the conjunction of the pair (related and unrelated) of creative–uncreative contrasts. In this way, those regions of the brain could be identified where the unrelatedness of words increased activity in the creative condition relative to the uncreative condition. Statistically significant activity was identified in only one region, and this was in the right medial frontal gyrus (see Fig. 2E). Co-ordinates, z scores and sizes of the activations arising from these analyses are given in Table 4.

4.2.2. Ratings of retrospective stories

Analysis of the rated creativity of stories reported retrospectively after scanning and simulation of scanning is provided in Table 5.

Table 4
Brain regions of significant activation identified in Experiment 3

Analysis	Region size cm^3	Anatomical location of voxel maxima	Coordinates	Brodmann area	*Z*
Creative–uncreative contrasts (1−100) conjoined with (001−1)—see Fig. 2:A	11.0	Right medial frontal gyrus	15, 43, 14	10	Infinite
	8.1	Right medial frontal gyrus	18, 28, 29	9	Infinite
	9.9	Left middle frontal/limbic cingulate	−15, 22, 29	9/32	6.79
	1.7	Right middle occipital (primary visual cortex)	21, −82, 15	17	6.61
Uncreative–creative contrasts (−1 1 0 0) conjoined with (0 0 −1 1)—see Fig. 2:B	28.4	Left occipital lingual gyrus	−18, −76, −11		Infinite
	2.24	Left occipital cuneus	−21, −69, 17	18	7.78
	6.79	Right inferior parietal lobule	33, −38, 54	40	6.79
Unrelated–related contrasts (1 0 −1 0) conjoined with (0 1 0 −1)—see Fig. 2:C	0.7	Left anterior cingulate	−6, 35, −4	32	5.98
	1.1	Right anterior cingulate/medial frontal gyrus	9, 35, −2	24	5.71
Related–unrelated (−1 0 1 0) conjoined with (0 −1 0 1)—see Fig. 2:D	5.7	Left occipital lingual gyrus	−30, −70, −9	18	Infinite
	6.3	Right inferior occipital gyrus	27, −85, −13	18	Infinite
	2.2	Left middle occipital gyrus	−39, −87, 13	18	7.55
Interaction (1 −1 −1 1) masked by conjunction of (1 −1 0 0) and (0 0 1 −1)—see Fig. 2:E	0.8	Right medial frontal gyrus	15, 39, 15	9/10	5.98 *

All activations are shown that survived correction for multiple comparisons at $P > 0.05$, except for * which survived an uncorrected threshold of $P < 0.001$. Contrast matrices map to conditions as (UR/C UR/UC R/C R/UC) where each element is defined by relatedness/objective: C = be creative, UC = be uncreative, R = semantically related, UR = semantically unrelated).

A within-participants ANOVA was carried out with factors of environment, relatedness and objective. This confirmed main effects of relatedness ($F(1,7) = 68.82$, $P < 0.001$) and objective ($F(1,7) = 26.95$ $P = 0.001$) and no significant effect of environment. There were no significant interaction effects except for relatedness with objective ($F(1,7) = 21.71$, $P = 0.002$). Again, there was no evidence that the environment was influencing the creativity of the participants. Differences in mean scores for relatedness and objective for the sample of stories retrospectively reported after both simulated and actual scanning procedures were also in the same direction as when these participants immediately reported all their stories in the simulated scanning conditions of Experiment 2.

4.3. Discussion

From the analysis of stories in Experiments 1 and 2, it was expected that participants would be creating stories by retrieving contextual elements associated with the given stimuli words and finding additional links through combining and selecting combinations that contributed to the given objective. Inspection of the retrospective stories collected after scanning supported these assumptions. Moreover, when words were unrelated rather than related, or the objective was creative rather than uncreative, these processes of combination and selection again appeared to have been modified to support more divergent links between words and/or retrieved contextual elements. On the basis of blind variation and selection, the making of more divergent links will use essentially the same processes of combination and selection, but with increased selectivity with respect to outcomes and supported by an increase in the number of combinations made. This could be expected to make greater demands on episodic retrieval, working memory, monitoring and higher cognitive control.

Table 5
Means (with mean standard errors) of rated creativity of stories reported retrospectively in Experiment 3 after scanning and simulation of scanning

Environment			Mean	Standard error
Scanner	Be creative	Related	3.49	0.20
		Unrelated	3.88	0.22
	Be uncreative	Related	1.71	0.26
		Unrelated	2.81	0.16
Simulator	Be creative	Related	3.15	0.20
		Unrelated	3.63	0.20
	Be uncreative	Related	1.88	0.19
		Unrelated	2.79	0.21

4.3.1. Creative–uncreative contrasts

Fig. 2A shows that, when participants were being creative, as opposed to uncreative, there was an increase in activity in the prefrontal areas, including bilateral medial frontal gyri and left anterior cingulate cortex (ACC). While left prefrontal activation occurs over a range of tasks including word association [36] and sentence completion [31], a number of studies [4,5,11] also suggest a role for the right hemisphere in the processing of the types of distant associations required for the generation of a creative story. In the fMRI study of Seger et al. [41], analysis of conditions when participants generated novel verbs to nouns, rather than the first that came into their head, produced similarly extensive patterns of bilateral prefrontal activity. In addition to left middle frontal activation, Seger et al.[41] also identified right activations in the superior and middle frontal gyri, and the medial frontal gyrus extending into the anterior cingulate, and explained these results in terms of differences in hemispherical contributions to semantic processing.

According to our cognitive analysis of divergent semantic processing, some of the right prefrontal activations observed here, and in the study of Seger et al., may be explained by additional retrieval of episodic details and the working memory demands of combining these creatively. In a study of telling lies [17], activity in the right middle frontal gyrus BA8/9 was linked to extra working memory load due to keeping in mind the many possibilities while selecting ones that were untruthful but consistent with other details. This same study of lies also identified activity in the right middle frontal gyrus (BA10), even where the lies were well-rehearsed, suggesting that activation here may be due to increased demands on episodic memory retrieval.

Additional activity in the anterior cingulate cortex has been linked to increased information processing demands in a wide range of different tasks. When participants were being creative, rather than uncreative, additional activity in the ACC may have resulted from extra episodic retrieval of contextual material and/or the additional conflict monitoring required when applying more appropriate and novel criteria in the combination of contextual elements. A number of other studies have linked the ACC to selection of items from episodic memory. Activity has also been found in the left ACC for the auditory retrieval of previously studied, as opposed to new, sentence material [42]. Extra activity in the ACC during creative conditions, as opposed to uncreative conditions, may also be explained by the increased working memory load when seeking associations [9]. The likely need for increased conflict monitoring in this process of making divergent associations extends further the range of possible interpretations of the role of the ACC in creative effort. Both the ACC and prefrontal structures have been implicated in additional monitoring. While some workers have suggested that the ACC itself detects problems, errors and conflict in the action system [12,40,8], others emphasize the role of prefrontal structures in evaluating the need for executive control and imply that the ACC is more involved with implementing this control [37,43,19]. Recent successes in dissociating activity in these two regions have supported the latter view [15,18].

Extra activity was also observed in regions of the visual cortex, and this may be explained by visual imagery [26]. Controversy persists about such activation of the primary visual area during visual mental imagery. Some studies [13,24,25] have reported activation during tasks requiring visual mental imagery of objects, while others [28] have not found such evidence. However, a recent study [29] has highlighted the influence of learning modality upon these effects, with visually learnt images producing less activation in the early visual cortex than images produced by verbal description, as in the present investigation.

4.3.2. Unrelated–related contrasts

Since stimuli consisted of a sequence of three words, episodic retrieval processes associated with reading one word may be expected to prime processes involved with the next. Unlike the related word conditions, where two or three of the words in each trial may even be expected to lead to some similar outcomes of retrieval, forming unrelated words into a story would have required greater retrieval effort than if the words were semantically related. The regions of the ACC activated here are unusually ventral but correspond to similar areas attributed to retrieval effort when participants recalled previously presented words [38]. Furthermore, some semantic link between these remotely associated words must also occur in order to form any story, requiring additional monitoring, control and load upon working memory. Thus, irrespective of whether participants were trying to be creative or uncreative and following the discussion above, this extra processing could be expected to produce the types of additional activity in the ACC and frontal medial gyrus shown in Fig. 2C.

4.3.3. Reverse contrasts (uncreative–creative, related–unrelated)

The uncreative–creative contrasts in Fig. 2B show large bilateral activations of the visual cortex and also the right inferior parietal cortex. Imagery is typically used less when the response can be more easily inferred from the associated information [23], so it is difficult to explain why these activities should be more active in uncreative, rather than creative, conditions. Some explanation may be derived from considering the strategies used by participants to avoid being creative. As illustrated by both the examples above, participants tended to make connections that reflected a less careful and probably briefer experimentation and selection of alternative ways to combine the 3 words. After solving this problem, they then refrained from elaborating discursively, sometimes offering only limited reorganizations of the original idea. The activation of the visual cortex may be due to focusing attention upon this redescription of the visualized scenario in order to prevent further creativity. An alternative and simpler explanation may be that such an uncreative strategy was completed quickly, giving participants more opportunities to look around their field of view than when they were trying to be creative. Similar occipital activations are observed in the related–unrelated contrasts (Fig. 2D), possibly because there was still some tendency to respond uncreatively to the words when they were from the same semantic field, even when given the objective to be creative. In the uncreative–creative contrasts, there is also activation of the right inferior parietal cortex. This area has previously been implicated in the types of semantic similarity judgments that would support the conscious application of such an uncreative repetitive strategy [21].

4.3.4. Interaction (creative–uncreative with unrelated–related)

The interaction analysis displayed in Fig. 2E reveals additional activity in the right medial gyrus (BA9/10) when using unrelated, as opposed to related, words with the objective of being creative rather than uncreative. This activity can be associated with the apparent increase in creative ability participants achieved in the prior behavioral studies that was beyond that of following a creative objective with unrelated words or of working uncreatively with unrelated words. Such increased creativity, as in the creative–unrelated example above, seems to involve making additional associations between the contextual elements that compliment, or at least do not contradict, the preliminary connection found between them. Elaborating further upon the simple narrative in this way might arise from additional episodic memory retrieval in the search for contextual details that might link together. However, such an interpretation should be made with caution. In a multi-study analysis of the areas involved with episodic memory retrieval, 3 right prefrontal sights have been identified that are in accordance (to 16 mm or less) with the results of 17 other studies [27]. The center of our activity is more than 17 mm from the closest of these—the right polar frontal site. However, the area of activity indicated by this interaction analysis is one of those identified by Seger et al. [41] when participants were producing unusual word associations. Seger et al. explained this right hemispheric activation in terms of increased monitoring and, indeed, activity in this area has arisen in Stroop tasks that place particularly strong demands on attentional systems [35]. Our results support the suggestion of Seger et al. that this is an area involved with approaching language-based tasks creatively, and our present understanding suggests that this arises from increases in the type of higher cognitive control required for stringent monitoring. However, as outlined above, the contribution of prefrontal regions and others, such as the ACC, to the monitoring of performance and the allocation of attention is complex and may involve more than one pathway [14]. Recent experiments have sought to dissociate activity in these two regions [15,12]. These studies would favor an interpretation of the activity in BA10 based upon increased higher level control, rather than just monitoring, brought on by more stringent and challenging criteria when attempting to be creative. In a recent study, intentional false responding was found to share neural substrates with response conflict and cognitive control, and a similar cluster of activity to ours (centers 11 mm apart) was identified in BA10 when participants falsified responses to autobiographical questions [32]. As with the falsification of information, effortful creativity requires the inhibition of responses that are unconvincing (be it in terms of likelihood or novelty) or self-conflicting. Additional effort to creatively combine words and contexts from different semantic fields may result in combinations that are greater in number and diversity, consequently demanding increased inhibition of inappropriate outcomes.

5. Conclusion

In a story generation task, the pursuit of a creative objective has produced additional bilateral activity, associating a number of left and right prefrontal regions with increased creative effort in this context. Requiring participants to incorporate semantically unrelated material, another means by which to increase the rated creativity of outcomes, produces additional activity in one of these regions (in BA9/10). Our findings support the suggestion that some prefrontal areas of the right hemisphere are involved with the types of divergent semantic processing associated with creativity in a story generation task. Our explanation for this involvement includes the need for additional episodic retrieval, monitoring and higher cognitive control. However, we expect that more research into the apparently complex and interrelating roles of the ACC and prefrontal cortex in cognitive control will further illuminate our understanding of our higher mental reasoning skills, including what is commonly referred to as creative thinking.

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