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The origins of originality: The neural bases of creative thinking and originality

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ABSTRACT

Although creativity has been related to prefrontal activity, recent neurological case studies postulate that patients who have left frontal and temporal degeneration involving deterioration of language abilities may actually develop de novo artistic abilities. In this study, we propose a neural and cognitive model according to which a balance between the two hemispheres affects a major aspect of creative cognition, namely, originality. In order to examine the neural basis of originality, that is, the ability to produce statistically infrequent ideas, patients with localized lesions in the medial prefrontal cortex (mPFC), inferior frontal gyrus (IFG), and posterior parietal and temporal cortex (PC), were assessed by two tasks involving divergent thinking and originality. Results indicate that lesions in the mPFC involved the most profound impairment in originality. Furthermore, precise anatomical mapping of lesions indicated that while the extent of lesion in the right mPFC was associated with impaired originality, lesions in the left PC were associated with somewhat elevated levels of originality. A positive correlation between creativity scores and left PC lesions indicated that the larger the lesion is in this area the greater the originality. On the other hand, a negative correlation was observed between originality scores and lesions in the right mPFC. It is concluded that the right mPFC is part of a right fronto-parietal network which is responsible for producing original ideas. It is possible that more linear cognitive processing such as language, mediated by left hemisphere structures interferes with creative cognition. Therefore, lesions in the left hemisphere may be associated with elevated levels of originality.

1. Introduction

Although creativity is a central cognitive component which allows everyday flexible and adaptive behavior, there are few neurocognitive models of creative cognition. Creativity has been defined as the ability to produce responses which are both novel (i.e., original, rare and unexpected) and appropriate (i.e., adaptive and useful according to the task constrains) (Sternberg & Lubart, 1999). As opposed to convergent thinking, which is directed towards finding a single correct solution to a problem, creativity or divergent thinking involves the ability to consciously generate new ideas that branch out and allow for many possible solutions to a given problem. Several cognitive tests of divergent thinking have been used to assess levels of creative cognition (Guilford, 1956). Divergent thinking tests are instruments that have been designed to be open-ended and afford multiple appropriate responses such as 'list as many alternate uses as possible for a shoe' (Guilford, 1986). These tests provide structured and objective measurements of creativity and its components. One central component of creative cognition and divergent thinking is originality (Sternberg & Lubart, 1999). An idea is considered to be original when it is statistically rare and represents an uncommon unique response (Guilford, 1956, 1959, 1960, 1986). It is important to note here, that rare and unexpected ideas which are inappropriate are not considered original in divergent thinking tasks (Mackinnon, 1965; Runco & Charles, 1993). While recent experimental reports of creative cognition have included neuroanatomical measurements, originality has been investigated only in a handful of studies.

Traditionally, impairments in divergent thinking and creative cognition have been linked to frontal lobe damage (Damasio, 2001; Heilman, 2005). Supporting this view, recent neuroimaging studies have been increasingly capable of demonstrating frontal activation during the performance of tasks that require creativity (e.g., Carlsson, Wendt, & Risberg, 2000; Folley & Park, 2005). Specifically, it has been shown that a network comprised of the medial prefrontal cortex (mPFC) and the inferior frontal gyrus is activated during the performance of tasks requiring creativity (Neubauer & Fink, 2009). For example, Limb and Braun (2008) found that musical improvisation (as compared to the production of over-learned musical sequences) was consistently characterized by a dissociated pattern of activity in bilateral PFC structures, with extensive deactivation of the dorsolateral prefrontal and orbitofrontal regions and focal activation of the mPFC. In line with this study, Gibson, Folley, and Park (2009) recently suggested that creative musicians are

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Table 1
Mean and SD of neuropsychological assessment including the Raven's Progressive Matrices test (RAVEN), the Beck Depression Inventory (BDI), the Wisconsin Card Sorting Test (WCST), Trails making test B/A and verbal fluency [category (animals, fruits, and vegetables) and letter fluency].

	mPFC	IFG	mPFC/IFG	PC	Controls	Sig
Age	36.25 (14.31)	36.14 (16.79)	30.5 (14.05)	42.13 (16.06)	33.55 (14.75)	ns
Education	12.08 (2.5)	13.42 (1.8)	12.66 (1.03)	13.46 (2.3)	13.88 (3.2)	ns
BDI	15.58 (10.94)	10.28 (10.29)	12.66 (9.1)	12 (11.87)	4.92 (6.49)	ns
RAVEN percentile	37.41 (19.37)	38 (27.82)	36.8 (29.9)	42.7 (34.4)	56.64 (28.66)	ns
Fluency semantic	17.62 (6.16)	20.28 (4.54)	19.33 (5.18)	16.56 (3.69)	21.79 (4.89)	*
Fluency phonemic	9.16 (3.1)	9.21 (2.54)	10.91 (3.84)	11.86 (4.7)	14.16 (4.53)	*
Fluency design	25.16 (17.01)	22.85 (7.35)	21.83 (15.36)	18.4 (10.85)	38.88 (17.68)	**
WCST Preservative errors	14.83 (8.98)	12.57 (4.19)	12.16 (4.35)	15.26 (8.72)	9.41 (2.67)	ns
Trails making test B/A	2.26 (0.87)	2.68 (0.78)	1.9 (0.43)	2.12 (0.57)	1.96 (0.49)	ns

* $p < 0.05$.
** $p < 0.01$.

characterized by enhanced divergent thinking, which is supported by increased bilateral PFC activity, as measured by near-infrared spectroscopy.

Other studies have stressed the importance of brain asymmetry in creativity. Fink et al. (2009) reported left inferior frontal and left precentral gyrus involvement in creativity tasks such as the Alternate Uses (AU) task. In an EEG event-related study, Neubauer, Fink, and Grabner (2006) demonstrated that creativity elicited a stronger synchronization of alpha activity and higher phase coupling in the right hemisphere, particularly in the PFC regions. These reports maintain that the generation of novel and creative ideas is accompanied by a low arousal of brain activity (Martindale, 1999) and is mediated by inhibition or top-down control (Sauseng et al., 2005). Additional evidence for the involvement of right frontal regions in creativity is reported in studies of musicians. Bengtsson, Csíkszentmihályi, and Ullén (2007) have demonstrated that the right dorsolateral PFC participates in a network involved in musical creation. On the other hand, Howard-Jones, Blakemore, Samuel, Summers, and Claxton (2005) found that creative story generation was associated with stronger bilateral mPFC and right middle occipital activation and lower activity in the right inferior parietal lobe.

Taken together, it appears that while most of these studies report an association between mPFC activity and creativity, there are conflicting reports regarding the exact location of activations and deactivations within a fronto-parietal network. Additionally, there is an ongoing debate regarding the role of brain asymmetry in creativity.

In contrast with the widely agreed-upon role of the PFC in creative thinking, recent neurological case studies postulate that patients with frontotemporal degeneration may actually develop new visual or artistic abilities. Studies with patients with semantic dementia demonstrate that focal degeneration in the left anterior temporal lobe involving impaired language abilities may be associated with enhanced artistic creativity (Miller, Ponton, Benson, Cummings, & Mena, 1996; Miller et al., 1998; Miller, Boone, Cummings, Read, & Mishkin, 2000). Furthermore, progressive aphasia, a neurodegenerative condition that involves the degeneration of speech, grammar, articulation, and syntax (Mesulam, 1982), resulting from atrophy of the left inferior frontal gyrus (Gorno-Tempini et al., 2004) has been also associated with creativity (e.g., Finney & Heilman, 2007). Recently, Seeley et al. (2008) demonstrated preserved and even increased visual and artistic creativity in one patient, despite severe degeneration of the left inferior frontal-insular, temporal, and striatal regions. The authors suggest that the left inferior frontal injury actually had a releasing effect on the non-dominant posterior neocortex, thereby improving the creative abilities of the patient. Although the latter case studies characterized artistic and visual forms of creativity, it is possible that other forms of creativity, including verbal creativity are mediated by right hemisphere structures.

Thus, while neuroimaging studies point to an active role of the right mPFC in creativity, contradictory evidence from neurological studies suggests that creativity may be the outcome of left frontal, parietal and temporal degeneration resulting in the deterioration of language abilities. One possibility is that the right mPFC is part of a neural network that mediates creativity, while the left hemisphere language areas, such as the left inferior frontal and temporoparietal regions, may compete or interfere with creative cognition. Therefore, damage to the right mPFC would be expected to diminish the level of creativity, while lesions in the language areas, such as the left inferior frontal and the left temporoparietal regions, may actually improve creative abilities.

While neuroimaging studies to date have been increasingly capable of characterizing the neural networks involved in creativity, only lesion studies can directly demonstrate whether the mPFC is *necessary* for creativity and originality. No study to date has examined originality in patients with acquired lesions. Therefore, the aim of the present study was to characterize originality following localized lesions.

2. Method

2.1. Subjects

Forty patients with localized brain damage and seventeen age-matched healthy volunteer controls participated in the study (see Table 1 for demographic details). All participants were fluent in Hebrew. Patients suffering from visual impairment, severe language deficits, or motor limitations that might interfere with performance of the neuropsychological tasks were excluded. For the control group, exclusion criteria included a history of psychiatric illness, developmental disorders, or any neurological disease or systemic disease with CNS complications.

Etiologies of the lesions included stroke ($N = 4$), meningioma (resected) ($N = 7$), and head injury ($N = 29$). The distribution of etiologies was balanced between the experimental groups.

2.2. Procedure

All participants signed an informed consent form before testing, and ethical approval was granted by the hospital ethics committee. Prior to the experiment, all patients were examined neurologically. Based on screening and imaging data from this examination, suitable candidates were identified and contacted. Each participant was assessed individually during at least one session, with about a week between sessions when more than one was required. Testing was conducted during the chronic phase of recovery that is, at least six months following trauma or surgery.

2.3. Anatomical mapping of lesions

Two expert neuroradiologists, blind to the study's hypotheses and the neuropsychological data, carried out a detailed anatomical rating of lesions based on acute and recent CTs or MRIs. The final rating was based on two evaluations of the same imaging data for each subject, which were performed during different sessions. Only cases where the scoring obtained in the two sessions was identical were included in

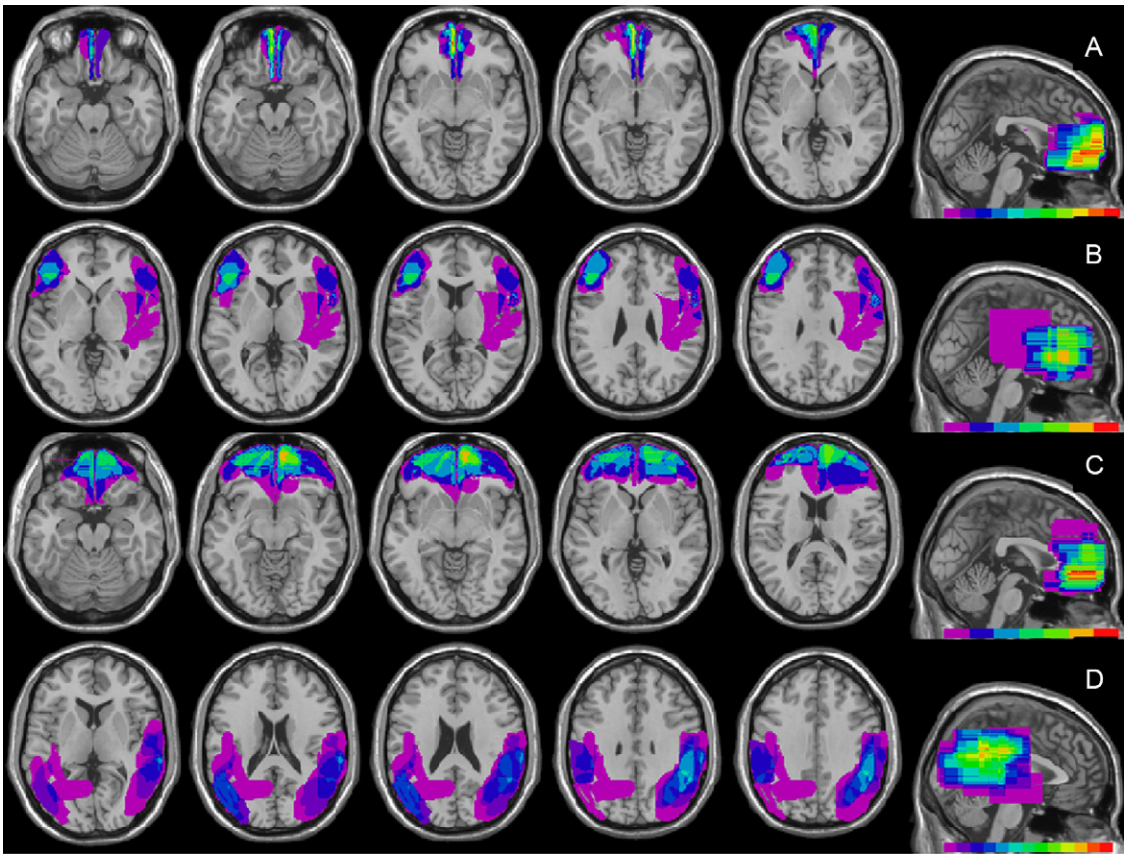

Fig. 1. Location and overlap of brain lesions. (A) Lesions of the 12 subjects with mPFC damage; (B) lesions of the 7 subjects with IFG damage; (C) lesions of the 6 subjects with mPFC and IFG damage; and (D) lesions of the 15 subjects with damage outside the frontal lobes (PC). Lesions are projected on three axial slices of the standard Montreal Neurological Institute brain, oriented according to radiological convention (i.e., left is right). Areas damaged in one subject are shown in pink; brighter shades denote the degree to which lesions involve the same structures in two or more individuals, as indicated by the color strip at the right-hand corner.

the statistical analysis. To be included, lesions had to be localized to either frontal, parietal or temporal regions. Cases with both gray and white matter lesions were included.

For patients with head injury, both the acute neuroradiological studies, which were performed within the first 24–48 h post-injury, and the chronic-phase recent scans were examined. Particular attention was given to diagnosing diffuse axonal injury (DAI) following head trauma, and patients with signs of DAI in the MRI were excluded from the study.

To assess the extent of each lesion in each Brodmann area, a semi-quantitative 15-point scale (0 indicates no lesion, 1 indicates a 1 mm lesion; 2 indicates a 2 mm lesion, etc.) was used. The size of the lesion was quantified for each axial slice in which the lesion was evident, and an overall score for the lesion size in each Brodmann area (BA) involved in each lesion was obtained by summing up the scores for the separate slices. For each slice, separate scores were derived for the left and right hemispheres.

Following the anatomical mapping procedure, subjects were divided into four groups according to (Damasio, 2001): the mPFC group ($N = 12$), if damage involved mostly the medial wall of the frontal lobe (Brodmann areas: mesial 8 and 9, 10, 24 and 32, 10 and 11); the IFG group ($N = 7$), if damage involved mostly the pars opercularis and the pars triangularis (Brodmann areas 44, 45); the mPFC/IFG ($N = 6$), if damage involved approximately the same amount of mPFC and IFG cortices; and a group of patients with posterior lesions (PC group, $N = 15$) involving damage in the temporoparietal, inferior parietal, or superior parietal lobule.

Additionally, lesions were transcribed from CT and MRI images to appropriate slices of the MRIcro program, for further lesion superimposition analysis. Two patients did not have recent MRIs, and their lesions were not transcribed into the MRIcro. Lesions were independently drawn twice by two neuropsychologists with experience in neuroimaging and were independently verified by the primary author. The volume of lesions ranged from 12.02 cm^3 to 108.709 cm^3 (mean = 34.34 cm^3, SD = 21.55 cm^3). In order to examine the reproducibility of this transcription method, correlation analyses of lesion volumes, as determined by the two experimenters, were conducted. The analyses yielded highly significant results ($r = 0.894$, $p = 0.0001$), indicating the high reliability of this method.

Fig. 1 presents lesion superimposition for the mPFC, IFG, mPFC/IFG, and PC groups. Two patients assigned to the IFG group also had some minor damage to an additional area, extending to the mPFC in one case and including temporoparietal cortices in the other. In four cases, patients assigned to the mPFC group also had lesions extending to BA 46, 47, and in one patient the lesion reached BA 25.

2.4. Instruments

Neuropsychological assessment and creativity testing were administered in random order, using the following tests and tasks.

2.5. Neuropsychological assessment

All subjects completed the Raven's Progressive Matrices test in order to assess reasoning abilities and to obtain an estimate of general intellectual functioning (Beaumont & Davidoff, 1992). In addition, the Beck Depression Inventory (Beck, Brown, Steer, Eidelson, & Riskind, 1987) was administered in order to obtain a measure of depression among participants. Executive functions were assessed using the Wisconsin Card Sorting Test (WCST; administration and scoring following (Heaton, Chelune, & Talley, 1993), the Trails Making Test A and B (Corrigan & Hinkeldey, 1987), verbal fluency [semantic/category (animals, fruits, and vegetables) and phonemic/letter fluency], and design fluency.

2.6. Assessment of originality

2.6.1. Torrance test of creative thinking (circles sub-scale) (Torrance, 1974)

Subjects were presented with a page on which 30 identical circles were drawn. They were asked to draw as many different drawings of meaningful objects as possible, each of which must include at least one circle. As originality involves the ability to produce different and original categories, the scoring of originality was based on the number of categories and the rarity of the response. This was calculated according to the scoring of original responses, as detailed in the Torrance Tests of Creative Thinking scoring guide (Torrance, 1974). Scoring included also a measurement of number of rule breaks (RBs) and number of preservative responses. While RBs represented an inappropriate response (i.e., turning the circle into a square), preservative scores represented a repetition of the same response in a slight change (i.e., smiling face, frowning face, etc).

2.6.2. Alternate uses (AU) task (Guilford, Christensen, Merrifield, & Wilson, 1978)

Subjects were presented with a list of six common objects and were asked to list as many alternate uses as possible for each object, with no time limit imposed. The most common everyday use was indicated in parenthesis. The objects were: can (common use: keep liquids); stapler (common use: attach papers); shoe (common use: wear on foot); cardboard box (common use: store objects); tire (common use: car wheel); and drinking glass (contain liquid). Only responses that did not repeat the common uses given were counted and included. As in the Torrance test, scoring included also a measurement of RBs (putting a shoe on the head) and number of preservative responses (using a can to contain pencils, using it to contain pens, using it to contain magic markers, etc.).

Since there are no guidelines for the scoring of original responses in the AU, original responses were defined as statistically infrequent responses according to a pretest conducted in our lab. As in the Torrance Test, the final scoring of originality was based on two measures: the number of categories and the rarity of the response.

2.6.3. Pretest

In order to create a valid criterion of response frequency, a group of 65 healthy participants who did not participate in this study completed the AU. For each object, a list of all possible uses was collected from all 65 participants. A statistical infrequency measure was calculated based on this list in order to evaluate the originality score for each answer and, subsequently, for each participant. Answers were given a score of zero if 5% or more of the participants listed a given use, a score of one if 2–4.99% of participants listed it, and a score of two if less than 1.99% listed the use. According to these statistical infrequency scores, an average originality score was calculated for each participant.

3. Results

As observed in Table 1, no significant group differences were observed in demographic variables such as age, estimated intellectual abilities, and years of education.

Overall, neuropsychological assessment indicated significant differences between groups only with respect to the phonemic fluency [$F(4, 52) = 3.429$, $p = 0.015$], the semantic fluency [$F(4, 52) = 2.66$, $p = 0.043$] and the design fluency tasks [$F(4, 52) = 4.38$, $p = 0.004$]. Post hoc analysis indicated that patients with mPFC ($p < 0.05$) and patients with IFG ($p < 0.05$) damage were significantly impaired as compared to controls on the phonemic fluency task, while the control group performed better than all patient groups ($p < 0.05$) on the design fluency task. Patients with PC lesions differed significantly from the controls with respect to performance on the semantic fluency task ($p < 0.05$).

3.1. General assessment of creativity

3.1.1. AU task

Separate ANOVAs with the total number of responses, number of categories, and response uniqueness/rarity as dependent variables and group membership as an independent variable indicated significant group effects for AU total scores [$F(4, 52) = 7.33$, $p = 0.0001$] and AU number of categories [$F(4, 52) = 6.424$, $p = 0.0001$] but not for the AU rarity scores [$F(4, 52) = 1.42$, $p = 0.221$]. As depicted in Fig. 2a, post hoc analysis (Duncan) indicated that for the AU total score, as well as for the number of categories, the mPFC group was significantly impaired as compared to the controls, IFG, and PC groups ($p < 0.05$). The mPFC/IFG group was significantly impaired as compared to the controls and the PC groups ($p < 0.05$). In addition, separate ANOVAs indicated no significant differences between groups in the RB scores [$F(4, 52) = 0.880$, $p = 0.823$] or in the number of preservative responses [$F(4, 52) = 1.344$, $p = 0.266$].

3.1.2. Torrance test

Separate ANOVAs with the total number of responses, number of categories, and response uniqueness/rarity as the dependent variables and group membership as the independent variable indicated significant group effects for the Torrance total scores [$F(4, 52) = 4.623$, $p = 0.003$] as well as the rarity scores [$F(4, 52) = 5.209$, $p = 0.002$] but not in the number of categories [$F(4, 52) = 1.61$, $p = 0.184$]. As depicted in Fig. 2b, post hoc analysis (Duncan) indicated that with respect to the total Torrance scores, as well as the rarity scores, the mPFC group was significantly impaired as compared to the controls and PC groups ($p < 0.05$) and the mPFC/IFG group was significantly impaired as compared to the controls and the PC groups ($p < 0.05$). The rest of the groups were not significantly different from one another. In addition, separate ANOVAs indicated no significant differences between groups in the RB scores [$F(4, 52) = 1.672$, $p = 0.171$] or in the number of preservative responses [$F(4, 52) = 0.749$, $p = 0.563$].

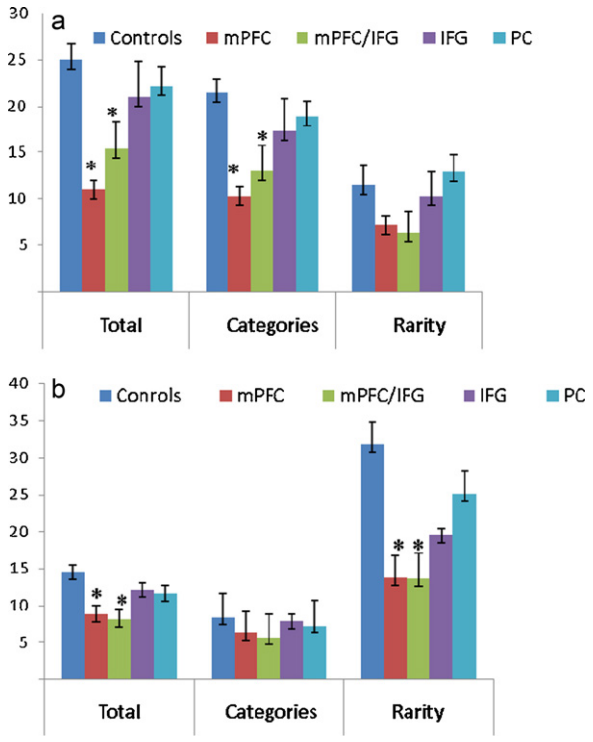

Fig. 2. Differences in creativity between groups. (a) Separate ANOVAs indicated significant group effects for AU total scores and AU number of categories, but not for AU rarity scores. For AU total score, and for number of categories scores, the mPFC group was significantly impaired as compared to the controls, IFG, and PC groups ($p < 0.05$). The mPFC/IFG group was significantly impaired as compared to the controls and the PC groups ($p < 0.05$). (b) Torrance test: separate ANOVAs indicated a significant group effect for the Torrance total scores as well as for the rarity scores, but not for the Torrance number of categories scores. For total Torrance scores and for rarity scores, the mPFC group was significantly impaired as compared to the controls and PC groups ($p < 0.05$). The mPFC/IFG group was significantly impaired as compared to the controls and the PC groups ($p < 0.05$).

The correlation between the Torrance and the AU tests was significant and high ($r = 0.53$, $p = 0.0001$). To examine the relationship between creativity and general fluency, correlation analyses were conducted between the AU task, verbal and design fluency. These analyses indicated that the AU correlated with phonemic fluency ($r = 0.385$, $p = 0.003$) and marginally with semantic fluency ($r = 0.254$, $p = 0.056$). The Torrance correlated with the design fluency task ($r = 0.311$, $p = 0.018$) but also with the phonemic ($r = 0.455$, $p = 0.0001$) and semantic fluency ($r = 0.513$, $p = 0.0001$) tasks.

To examine if the differences between groups in creativity scores could be accounted for by general difficulties in fluency separate ANCOVAs were performed with the verbal and design fluency as covariates. These analyses indicated that in the AU task, group differences remained highly significant even after controlling for phonemic fluency [$F(5, 51) = 5.155$, $p = 0.001$], semantic fluency [$F(5, 51) = 6.575$, $p = 0.0001$] and design fluency [$F(5, 51) = 6.580$, $p = 0.001$]. Likewise, in the Torrance task group differences remained even after controlling for phonemic fluency

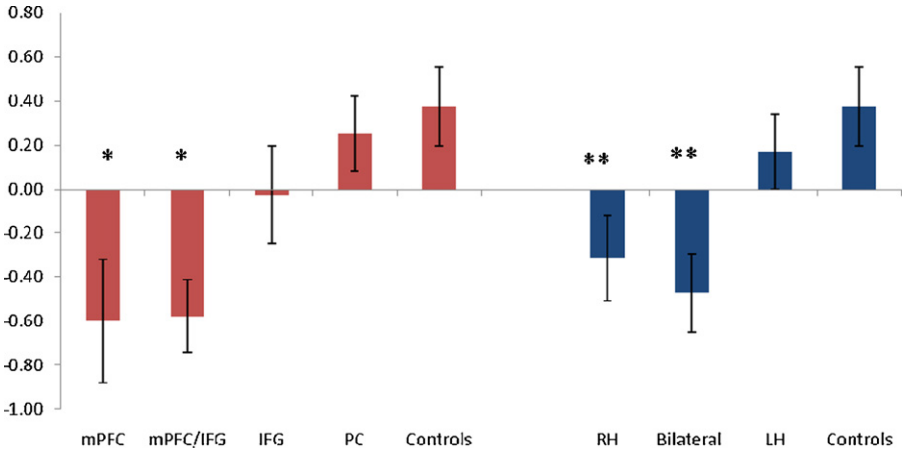

Fig. 3. Differences in originality indexes according to lesion location and lesion side. (a) An ANOVA with the originality index as the dependent variable and group membership as the independent variable indicated significant group effects for the originality index. Post hoc analysis indicated that the mPFC and the mPFC/IFG groups were significantly impaired in the originality index as compared to the controls and PC groups ($p < 0.05$). (b) An ANOVA with the originality index as the dependent variable and lesion side as the independent variable indicated significant side effects (right hemisphere lesion [RH], left hemisphere lesion [LHD], and bilateral lesion [Bilat]) for the originality index. Post hoc analysis indicated that patients in the Bilat and the RH groups were significantly impaired in the originality index as compared to the controls and the LH groups ($p < 0.05$).

[$F(5, 51) = = 2.791$, $p = 0.036$], semantic fluency [$F(5, 51) = 3.668$, $p = 0.011$] and design fluency [$F(5, 51) = 3.400$, $p = 0.015$].

3.2. Originality index

Scores from both tasks were transformed into *z*-scores such that the data could be collapsed. As described in Section 2, an overall originality index incorporating mean number of categories and number of infrequent/rare responses on the AU and the Torrance tasks was calculated.

3.2.1. Originality levels and lesion location

To examine the effect of lesion location on levels of originality, an ANOVA with the originality index as the dependent variable and group membership as the independent variable indicated significant group effects for the originality index [$F(4, 52) = 7.33$, $p = 0.0001$]. As shown in Fig. 3a, post hoc analysis (Duncan) indicated that the mPFC and the mPFC/IFG groups were significantly impaired in the originality index as compared to the controls and PC groups ($p < 0.05$). The rest of the groups were not significantly different from one another.

3.2.2. Originality levels and asymmetry of the lesion

In order to determine whether the asymmetry of the lesion was an important factor in the decline in originality, patients were re-divided according to lesion side (right hemisphere lesion [RH], left hemisphere lesion [LHD], bilateral lesion [Bilat]). An ANOVA with the originality index as the dependent variable and lesion side as the independent variable indicated significant group effects for the originality index [$F(3, 53) = 4.728$, $p = 0.006$]. As shown in Fig. 3b, post hoc analysis indicated that patients in the Bilat and the RH groups were significantly impaired in the originality index as compared to the controls and the LH groups ($p < 0.05$). The rest of the groups were not significantly different from one another.

It is important to note here that although it was impossible to divide patients according to lesion location as well as lesion side due to the small number of patients in each group, the left PC group (mean = 17.35, SD = 5.06) had slightly higher originality levels as compared to the control subjects (mean = 16.529, SD = 5.81). The left IFG group had similar levels of originality (mean = 16.50, SD = 5.13).

3.3. Precise anatomical mapping of originality

The originality index was further used to detect patients with impaired versus improved performance on both originality tasks. To identify the critical lesion locations associated with decreased and increased originality, patients were assigned to one of two subgroups: one standard deviations above or below the mean originality index of the control group. The "high originality" group included the 6 patients with the highest originality scores (1 patients with IFG damage, and 5 patients with PC lesions). The "low originality" group included the 14 patients with the lowest originality index (1 patient with IFG damage, 7 with mPFC, 2 with PC damage, and 4 with mPFC/IFG lesions).

We then examined whether the degree of deficit in originality was related to the extent of damage within the mPFC, IFG, and PC regions, and whether the lesion side within those regions was an important factor. Comparisons between the localization and extent of the lesions of the 14 "low originality" group patients and those of the 6 "high-originality" patients were examined using a repeated measures ANOVA, with side (right, left), location (mPFC, IFG, PC), and originality group (low/high) as independent variables and extent of lesion as a dependent variable. This analysis indicated a significant originality group by lesion location effect [$F(2, 36) = 5. 451$, $p = 0.027$] and a significant side by originality group effect [$F(1, 18) = 9.509$, $p = 0.06$], suggesting that the level of originality depends on the location and the side of the lesion. There was no significant main effect of side [$F(1, 18) = 0.429$, $p = 0.521$] or location [$F(2, 36) = 1.347$, $p = 0.2647$], indicating that overall, patients were equally impaired in both locations and both sides. The three-way interaction (location, side, originality group) was also not significant [$F(2, 36) = 0.741$, $p = 0.454$]. Finally, a test of between subject effects indicated no significant originality group effect [$F(1, 18) = 1.398$, $p = 0.252$], confirming that the two originality groups did not differ in lesion extent. To examine the basis of the group by lesion location interaction effect and the side by originality group interaction effect, follow-up independent *t*-tests (with Bonferroni corrections) were carried out. As observed in Fig. 4, these analyses indicated significant differences between the "high originality" and "low originality" groups with respect to lesion extent in the right mPFC [$t(18) = 3.308$, $p = 0.006$], indicating that the "low originality" group had larger lesions in the right mPFC than the "high originality" group. On the other hand, lesions in the left PC were larger [$t(18) = -2.646$, $p = 0.047$] in the "high originality" group than in the

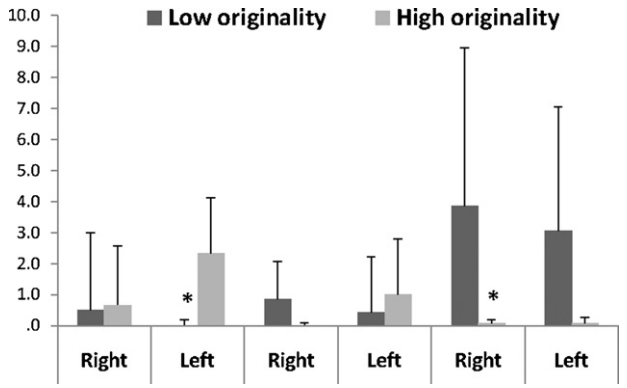

Fig. 4. Originality group, lesion location, and lesion side interactions. A significant originality group by lesion location effect and a significant side by originality group effect were shown, suggesting that the level of originality depends on the location and the side of the lesion. Significant differences in lesion extent between the "high originality" and "low originality" groups were observed in the right mPFC. Lesions in the left PC were larger in the "high originality" group as compared with the "low originality" group.

"low originality" group. These results indicated that patients in the "low originality" group had significantly larger lesions in the right mPFC, whereas patients in the "high originality" group had larger lesions in the left PC. No significant differences between the originality groups were observed with respect to lesions in the left IFG, left mPFC, right IFG, or right PC.

To examine the relationship between the extent of lesions in each location and originality scores a correlation analysis (with Bonferonni corrections) was conducted between originality scores and lesion extent in the right and the left IFG, mPFC, and PC. Results indicated a significant positive correlation between originality scores and left PC lesions ($r = 0.435$, $p = 0.005$), indicating that the larger the lesion in this area the greater the originality. A significant negative correlation was observed between originality scores and lesions in the right mPFC ($p = -0.421$, $p = 0.007$) indicating that the larger the lesion in the right mPFC the greater the impairment in originality. The rest of the correlations were not significant.

Finally, to examine if the patients from the "high originality" group (which included 1 patient with left IFG damage, 4 patients with left PC damage and 1 patient with right PC damage) indeed had higher originality scores than the healthy controls, an independent sample *t*-test was conducted. As shown in Fig. 5, this analysis indicated that patients in the "high originality" group had significantly [$t(21) = 2.515$, $p = 0.023$] higher originality scores as compared to the control subjects. Furthermore, analysis of the frequencies of patients in the "high originality" and "low originality" subjects and grouping of subjects according to location and lateralization using Chi-square, revealed significant different distributions of lesion groups and originality groups ($\chi^2[9] = 17.550$, $p = 0.041$). While 44.44% of the patients with left PC lesions were in the "high originality" (0% were in the "low originality" group and the rest did not belong to any group), only 23.5% of the healthy controls were in the "high originality" group (11.76% were in the "low originality" group and the rest did not belong to any group).

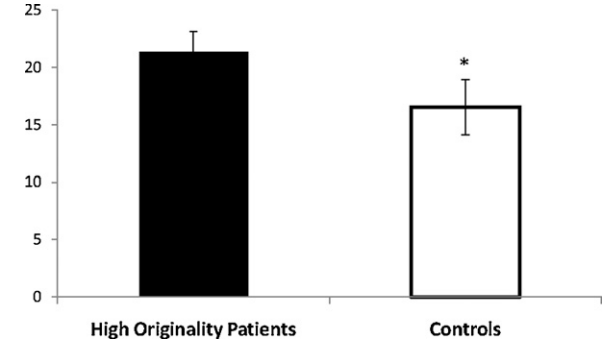

Fig. 5. Differences in the originality scores between the "high originality group" and the control subjects. The "high originality" group had significantly [$t(21) = 2.515$, $p = 0.023$] higher originality scores (mean = 21.33, SD = 3.16) as compared to the control subjects (mean = 16.529, SD = 5.81).

4. Discussion

An original response requires the ability to produce various new, unique, and infrequent ideas that branch out to many appropriate and possible solutions for a given problem. It appears that the crux of an original response is the interaction between generating unique new ideas and inhibiting stereotypical automatic thinking. Functional imaging data indicate that divergent thinking is associated with the activation of mPFC cortices, including the ACC (Limb & Braun, 2008; Neubauer & Fink, 2009). Here, we show that damage to the mPFC is indeed associated with profound impairment in several measures of creativity.

In comparison to controls, the patients with mPFC lesions were shown to be impaired on two measures of creativity and originality. Additionally, there was a general effect of lesion side, with lesions in the right hemisphere associated with more deficits in originality than lesions in the left hemisphere. Moreover, patients with right hemisphere damage, particularly those with right mPFC lesions, showed the most severe impairments in originality.

Several processes which are linked to creative cognition have been associated with the mPFC. The ACC has been reported to be involved in response selection and conflict processing (Crottaz-Herbette & Menon, 2006; Milham et al., 2001; van Veen & Carter, 2005). Additionally, the ACC may show increased activity when the probability of making an error increases, indicating that this area may be involved in response evaluation (Milham & Banich, 2005). This might suggest that the impaired originality observed in the mPFC group might be related to difficulties in response selection and evaluation in general as part of the creativity process which involves responding in a manner that is both appropriate and original. Nonetheless, the fact that the number of rule breaks (RBs) was not significantly different between groups suggests that impaired originality found in the mPFC group could not be entirely accounted for by difficulties in response selection.

In the current study, while right mPFC lesions were associated with impaired originality, the originality scores of patients with left PC lesions were somewhat higher than those of the other participants. Although, overall patients with LH lesions did not show improved originality, left inferior frontal and posterior lesions were associated with higher originality. It should be noted that although increased creativity was observed in patients with left PC and left IFG lesions several patients with left PC and IFG lesions showed an average performance in the tasks. In particular, patients with lesions in the left temporoparital region, including the inferior parietal lobule, and patients with left IFG lesions exhibited high originality scores. Furthermore, there was a significant correlation between lesions in the left PC and originality scores, indicating that the greater the impairment in this region, the higher the originality score. The left IFG is a key language processing region and is reported to be engaged in a wide range of cognitive tasks demanding verbal information processing (for a review see Gernsbacher & Kaschak, 2003). The left PC, particularly the left temporoparietal region and the left inferior parietal lobe are extremely important for language production (Metter et al., 1990; Stoeckel, Gough, Watkins, & Devlin, 2009). Indeed, there are a number of reports of de novo development of artistic behavior following brain injury specifically affecting the left IFG and left PC (Pollak, Mulvenna, & Lythgoe,

2007). Patients with progressive aphasia and semantic dementia have been known to show new creative abilities (Seeley et al., 2008) alongside with frontotemporal degeneration. Mell, Howard, and Miller (2003) reported on the case of a patient with progressive aphasia who displayed more originality as language abilities declined. The authors suggest that a release of the right PFC from language-dominant patterns of thinking, which are organized in the dominant frontal and anterior temporal regions, is a key factor in the emergence of artistic skills in such cases of progressive aphasia.

These case studies support the idea that creative cognition involves a right fronto-parietal neural network while more linear processing such as language abilities mediated by a left neural network may compete with the function of this right fronto-parietal network and diminish levels of creativity. Therefore, lesions in the right hemisphere are associated with impaired creativity, whereas damage to the left hemisphere may be associated with somewhat increased creativity. Indeed, Jausovec and Jausovec (2000) observed greater intra- and inter-hemispheric cooperation (in the form of greater coherence) between fronto-polar and parietal electrode position while participants were engaged in writing an essay, but not while reading. Razumnikova (2007) found that originality scores were positively correlated with increases of coherence in the $\beta 2$ band (20–30 Hz) in the fronto-parietal cortex (F3, C3, C4, P3, and P4 electrode sites). Finally, Kowatari et al. (2009) used structure equation modeling to analyze a possible brain network for imagining a novel design of a pen. The authors suggest that a right fronto-parietal network is involved in creativity and that creativity training may modulate the connection between the right PFC and the left PFC. The authors also noted that in novice as compared to expert subjects, there was a negative correlation between originality and left PC activity, indicating that originality involved decreased left PC activation (Kowatari et al., 2009).

Collectively, it is therefore possible that left language cortices are important for activating networks which store systematic, linear, logical, semantically similar, and automatic knowledge, whereas the right hemisphere is responsible for activating conceptual networks that have been only weakly activated or not activated at all. Activation of these remote networks might be important in producing an original idea and a competition between the two hemispheres may diminish levels of originality. If this is the case, then the higher originality score of the patients with left PC lesions might reflect the release of the right PFC from this competition, thus facilitating the expression of the original response.

The present study has certain limitations that need to be taken into account. The first limitation is that of patient variability in lesion etiology. Another related limitation is the large number of patients with traumatic injury. Although patients with MRI evidence of diffuse axonal injury were excluded from the study, one cannot be completely certain that none had diffuse damage which was not observed on MRI. Nonetheless, the fact that the patients with traumatic injury were equally distributed between the groups may reinforce the conclusions of the present study. It is also important to note that in the present study we used cognitive tests of divergent thinking to assess basic levels of originality. Although it has been reported that people with high visual artistic creativity also demonstrate superior performance in tasks of divergent thinking (Burch, Pavelis, Hemsley, & Corr, 2006), the study conclusions should be treated with caution as different lesion location may have differential effects on other forms of creativity which have not been directly evaluated in the present study.

Although fluency and originality are two related dimensions that constitute creativity (Plucker & Renzulli, 1999), in the present study we found that mPFC lesions were specifically associated with diminished levels of originality, but not with impairments in a more general fluency deficits. Group differences in creativity remained highly significant even after controlling for verbal and design fluency, indicating that although fluency is a major component in creative cognition, the creativity deficits observed in the mPFC group is not utterly due to a more general fluency deficit. In line with these findings, Chavez-Eakle, Graff-Guerrero, Garcia-Reyna, Vaugier, and Cruz-Fuentes (2007) have reported a functional anatomical dissociation between fluency and originality, suggesting that these abilities may be dissociable. Bazanova and Aftanas (2008) found that individuals with the lowest values for individual EEG baseline alpha activity were also the ones with the highest levels of originality, while fluency was found in individuals with the highest alpha-rhythm maximum peak frequency values. These findings suggest that despite their strong behavioral correlation, fluency and originality may be mediated by separate brain networks.

To conclude, an original response is one that is statistically infrequent in the context of the selected sample. It is possible that in order to produce an original response, as opposed to a more typical response, one would need to inhibit the typical, automatic responses most likely related to left hemisphere activation. Therefore, damage that involves the left hemisphere may result in increased originality, while damage to the right mPFC may be associated with impaired originality.

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