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Unleashing creativity: The role of left temporoparietal regions in evaluating and inhibiting the generation of creative ideas

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ABSTRACT

Human creativity is thought to entail two processes. One is idea generation, whereby ideas emerge in an associative manner, and the other is idea evaluation, whereby generated ideas are evaluated and screened. Thus far, neuroimaging studies have identified several brain regions as being involved in creativity, yet only a handful of studies have examined the neural basis underlying these two processes. We found that an individual with left temporoparietal hemorrhage who had no previous experience as an artist developed remarkable artistic creativity, which diminished as the hemorrhage receded. We thus hypothesized that damage to the evaluation network of creativity during the initial hematoma had a releasing effect on creativity by "freeing" the idea generation system. In line with this hypothesis, we conducted a subsequent fMRI study showing that decreased left temporal and parietal activations among healthy individuals as they evaluated creative ideas selectively predicted higher creativity. The current studies provide converging multi-method evidence suggesting that the left temporoparietal area is part of a neural network involved in evaluating creativity, and that as such may act as inhibitors of creativity. We propose an explanatory model of creativity centered upon the key role of the left temporoparietal regions in evaluating and inhibiting creativity.

1. Introduction

Creativity has been defined as the ability to produce responses that are both novel (i.e., original, rare and unexpected) and suitable (i.e., adaptive and useful according to task constraints) (Sternberg and Lubart, 1999). There are a number of cognitive processes that are important for creativity including insight, fluid intelligence, artistic visual perception and musical improvisation (Jung et al., 2010). Yet, one of the most essential thought processes that underlie creative cognition is divergent thinking (DT). DT is widely considered to be an important antecedent of creativity because it involves the ability to consciously generate new ideas that branch out and allow for many possible solutions to a given problem (Guilford, 1986). Although many attempts have been made to move beyond DT to assess creativity (Dietrich, 2007), it has been suggested that since DT tests provide structured, valid and objective measurement of creativity and its components, they are particularly valuable for neuroscientific investigation (Takeuchi et al., 2012). Furthermore, considering that DT tasks may also predict performance in tasks of artistic creativity (Hocevar, 1980; McCrae, 1987; Runco and Bahleda, 1986), it is possible that assessment of DT abilities may also apply to artistic abilities. High scores in DT tasks require the formation of novel associations based on using different types of information out of obvious confined context (Guilford, 1959) which can be viewed as a broadening of the contextual problem space. Artistically talented individuals have been suggested to be less "captured" by context and less restricted by one particular meaning and its close associations (Ryder et al., 2002), which would indicate that both artistic creativity and DT share context independent thinking. This view is in line with theoretical models that characterize creativity as domain general (Chen et al., 2006; Plucker, 1999). Indeed, although several reports view creativity as domain specific (Baer, 1998; Kaufman and Baer, 2004; Sternberg et al., 2004), others argue that creativity is domain general (Chen et al., 2006; Plucker, 1999) or has both domain-specific and domain-general aspects (Plucker, 2004, 2005; Sternberg, 2005).

One cognitive model proposed to explain the creative process is the twofold model or dual process model (Basadur et al., 1982; Finke et al., 1992; Sowden et al., in press). According to the model creativity can be seen as an interplay between two processes: the process of production and generation of ideas, perhaps in an associative

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manner, and the process of evaluation and exploration of these ideas (Basadur et al., 1982; Finke et al., 1992; Sowden et al., in press). These dual process models also follow the definition of creativity as producing new ideas but ideas that also have value (are meaningful and useful). Thus, creativity can be seen as entailing two processes. One is termed the idea generation process whereby through free association, the majority of ideas, including innovative ideas, are generated. The other is logical evaluative thinking (idea evaluation process), whereby the appropriateness and originality of generated ideas are evaluated (Martindale, 1999). According to this view, the creative process involves cycles of shifting between the process of generation and that of evaluation and verification. In the generation process ideas are accessed, retrieved and associated from memory (Benedek et al., 2014b), and in the evaluation process ideas are analyzed for their relevance and novelty. The current study focused on examining the neural underpinning of the evaluation system. According to this model, idea evaluation involves the assessment of ideas against a benchmark of standards and can range on a continuum between very lenient and very stringent evaluation. The idea evaluation process informs rejects and revises ideas generated in the generation process (Mumford et al., 2002). The role of the evaluation process is to ensure that generated ideas are developed and explored by informing generation and ideation processes. Balanced evaluation may allow the production of original ideas through the process of discarding trivial or useless ideas (Dailey and Mumford, 2006). Yet, a stringent evaluation may inhibit the generation of new ideas as it may lead to premature closure of ideas that can be further developed (Runco and Basadur, 1993). Likewise, lenient evaluation may lead to an increase in the amount of accepted ideas, even if some of them are inappropriate. In addition, inaccurate evaluation may constrain the individual from generating potential creative ideas (Runco and Acar, 2012). As such, the evaluation process can impose an inhibitory effect on the creative process, by restraining and hindering ideas and associative processing occurring in the generation process (Fig. 1).We suggest that as part of the neural network of creativity that involves idea generation, the evaluation system may have an important role, which in addition to a facilitating role allowing potential ideas to be further explored; it may also have an inhibitory effect on the process of idea generation. In this report, we aim at examining the possible inhibiting role of the evaluation network through its underlying neural network.

Hitherto, neuroimaging and lesion studies have linked creativity to multiple neural regions, including anterior prefrontal regions, fronto-temporal regions, medial frontal regions and the posterior cingulate (Carlsson et al., 2000; Howard-Jones et al., 2005; Jung et al., 2010), particularly on the right hemisphere (Mihov et al., 2010). Interestingly, findings from neurological studies demonstrate that certain brain diseases especially those accompanied by left

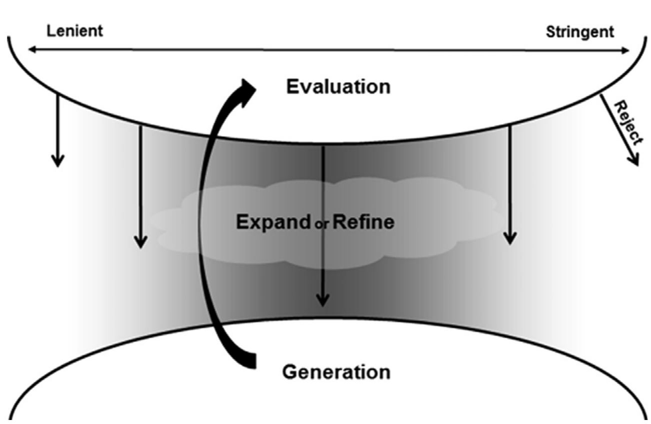

Fig. 1. Dual-model of creativity.

lateralized damage (Miller et al., 2000) may induce the emergence of artistic creativity. Several studies have found that patients with frontotemporal dementia involving predominantly left frontal or temporal degeneration characterized by semantic dementia (Miller et al., 1996) or progressive aphasia (Seeley et al., 2008) develop de novo artistic abilities. Seeley et al. (2008), for example, presented a case of gains in artistic creativity following degeneration of left inferior frontal-insular, temporal and striatal regions. Furthermore, Shamay-Tsoory et al. (2011) presented evidence that lesions in left parietal areas and left inferior frontal gyrus (IFG) are associated with elevated levels of creative fluency and originality as measured by DT tasks (although Abraham et al. (2012) reported that patients with parietal–temporal lesions were comparable to controls on the originality factor of the a divergent thinking task). These studies imply that degeneration of left temporoparietal and inferior frontal regions may be associated with increased creativity. This effect of increased function following brain disease has been previously referred to as paradoxical functional facilitation (Kapur, 1996). Thus, the reported increase in creativity following brain damage can be seen as a release from inhibition by the damaged areas, leading to intensified activity in other brain regions. Moreover, based upon the twofold model of creativity, according to which creativity involves the generation and the evaluation of ideas, the left frontal and temporoparietal regions may contribute to creativity by mediating the evaluation process of creative thinking through a selection effect on the final output. The studies reviewed above may consequently provide preliminary evidence regarding the existence of an evaluative neural system operating alongside the generation system in the creative process and can provide indications regarding the brain areas that might be part of it, i.e. left temporoparietal and frontal regions. Greater activations in these areas during the creative process would indicate greater involvement of the evaluation process and a more stringent evaluative process. Indeed, in a recent examination of the twofold model, Ellamil et al. (2012) found that while evaluative processing during creative thinking was linked with activation in the executive network and in a frontoparietal system, the generation process was related to medial temporal lobe activations (Ellamil et al., 2012). Thus, when areas in the evaluation network are damaged, executive cognitive control on the generation network may be released, which may result in increased creativity. It is important to mention here that while several models of creativity have focused on cognitive control and inhibition other models have highlighted the tradeoff between regions involved in rule-based processing (prefrontal cortex) and posterior regions involved in object processing (Chrysikou et al., 2013; Thompson-Schill et al., 2009). It has been hypothesized that generating ideas in a creative divergent thinking task requires distancing from top-down knowledge based thought (cognitive control mechanism), and focusing on bottom-up data-driven thought (Chrysikou et al., 2013). This view has been supported by studies showing hypofrontal neural activation during jazz improvisation (Limb and Braun, 2008) and studies involving observations of increased availability of bottom-up information coupled with suboptimal prefrontal functioning seen in individuals with autism, some of which become musical, mathematical, or artistic savants (Snyder, 2009). In view of the dual model of creativity, involving a cyclic motion between generation and evaluation processes, we propose that these findings can be interpreted as a shifting between the evaluation (which can represent one aspect of the cognitive top-down control mechanism) and generation, in a way that the evaluation process utilizes a more top-down knowledge based approach, while the generation process utilizes a more data driven bottom-up approach. More specifically, the evaluation process represents only one aspect of top-down cognitive control mechanisms. Based on the neuropsychological and neuroimaging findings, it was hypothesized that the evaluation network involves several regions within the left

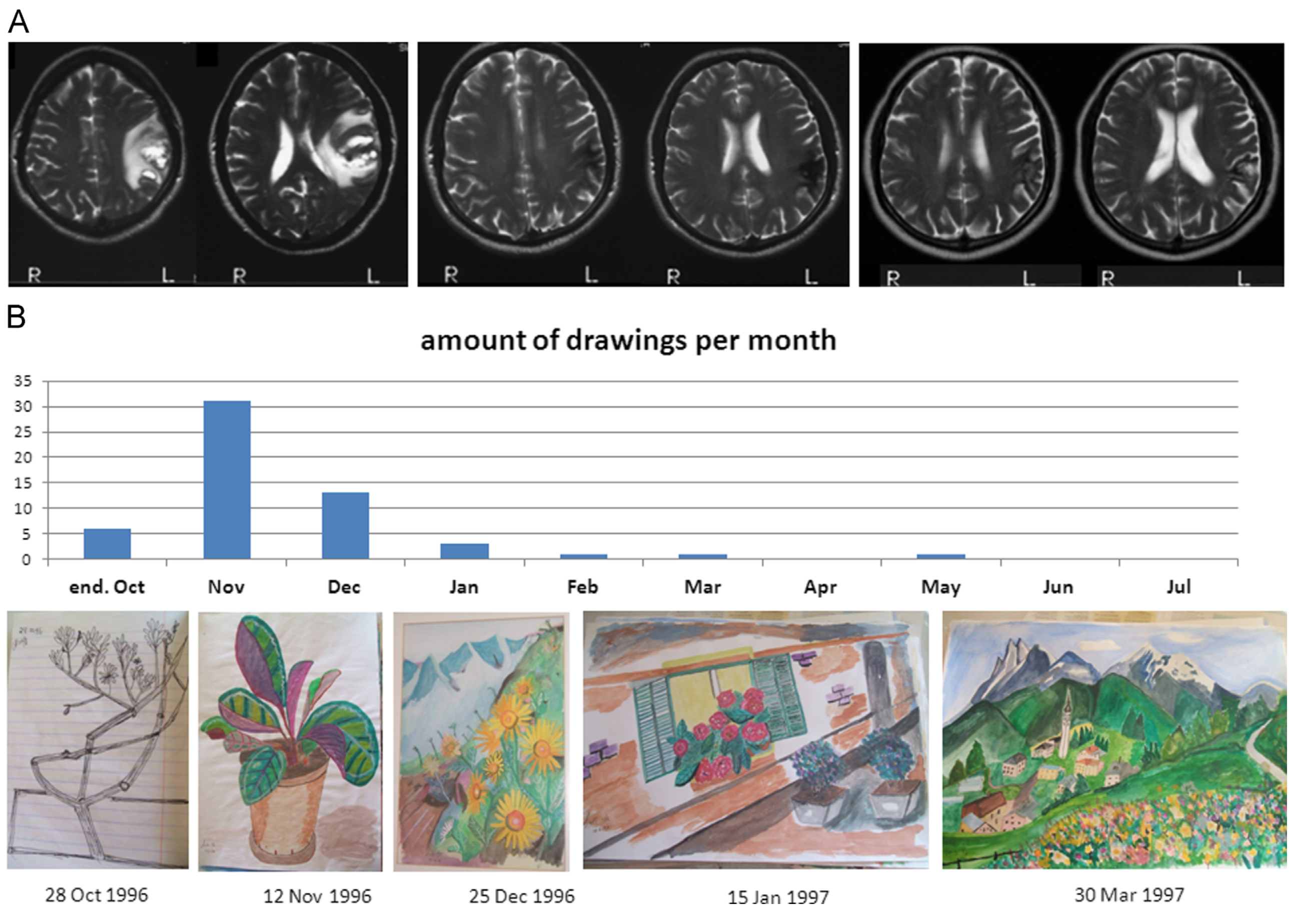

Fig. 2. Patient EP—MRI scans and art production. (A) MRI scans of EP (from left to right) at 1. The time of the initial hematoma; 2. 3 months later; 3. 10 years later .(B) On the top are amount of drawings per month produced by EP beginning 1 month after his stoke . On the bottom are example of drawings he produced during this period. Note that the drawings evolved from two-dimensional pencil drawings to complex colorful scenes.

hemisphere including the IFG and the temporoparietal region and that activations in these regions influence the degree of stringent evaluation.

Accordingly, here we report two studies, a clinical case study and an fMRI study, that provide multi-method converging evidence that left temporoparietal regions may be important to various types of creativity (artistic, DT) through their involvement in the process of evaluation and inhibition of creativity. In line with recent studies indicating that damage to frontotemporal and parietal regions in the left hemisphere may have a prolonged effect on increased creativity (Miller et al., 1996; Seeley et al., 2008; Shamay-Tsoory et al., 2011), in Study 1 we report on an individual with extensive left temporoparietal hemorrhage, who had no previous experience as an artist and developed remarkable transient gains in artistic creativity that diminished as the hemorrhage receded (Fig. 2). Study 2 describes a functional magnetic resonance imaging (fMRI) study conducted among healthy participants as they performed a creativity (DT) evaluation task. The goal of the neuroimaging study was to further examine the neural underpinning of the evaluation network and specify the inhibiting role of the components of this network. The hypothesis was that the left temporoparietal regions would be activated during the evaluation of creativity and that lower activation in this creativity evaluation network would be associated with greater creativity. Particularly, we were interested in examining the activation patterns during evaluation of creativity in a region of interest corresponding to the region damaged in the case study reported in Study 1. It was reasoned that if the region damaged in the case reported in Study 1 resulted in increased creativity due to a decrease in the evaluation of creativity network, then we would expect to see a negative correlation between creativity and activity in this region among healthy participants.

2. Study 1

2.1. Materials and methods

2.1.1. Participants

EP (aged 46 at initial hematoma, male) and a sample of seven age-matched healthy controls (mean age=42.85, SD=8.51, 1 female) participated in this study. All participants were right-handed and had normal or corrected-to-normal vision. EP suffered a stroke in 1997 that left him with a left temporoparietal hematoma involving the left supra-marginal gyrus and temporal lobe (see Fig. 2A).

2.1.2. Neuropsychological evaluation

EP was evaluated three times following the stroke. The first neuropsychological (NP) evaluation was carried out 6 months after his stroke, and the second was carried out 3 years later. The third evaluation was carried out 13 years later and involved an interview in order to assess the artistic urges and overall progress. The first and second NP evaluation included the Wisconsin Card Sorting Test (WCST, administration and scoring based on (Heaton et al.,1993), the Verbal Fluency test (category [animals, fruit and vegetables] and letter fluency) and the Trail Making test (parts A and B). Table 1 summarizes the results of the neuropsychological evaluations.

2.2. Results

2.2.1. Case study

Patient EP, a 46-year-old professional accountant with no previous experience as an artist, presented with motor dysphasia,

Table 1
Case report neuropsychological test scores. EP's test scores for the two neuropsychological (NP) evaluations and a group of 7 aged matched healthy controls (WCST – Wisconsin Card Sorting Task). The first NP evaluation was carried out 6 months following the stroke. EP's evaluation was repeated 3 years later. "Single-Bayes" one-tailed probability p values are presented for the comparison between EP's scores in 1997 and 2000 compared to the control group.

	Mar-1997	Jun-2000	Controls (mean ± SD)	Single-Bayes p	
	EP	EP		1997	2000
Age (years)	46	49	42.5 ± 9.2	0.37	0.27
Education (years)	15		14.1 ± 3.1	0.40	0.40
Trail Making test Part A (s)	25	26	40.3 ± 7.8	0.06	0.07
Trail Making test Part B (s)	44	46	86 ± 24.8	0.08	0.09
Phonetic fluency	12	13	10.8 ± 4.6	0.40	0.33
Semantic fluency	26	28	19 ± 3	**0.03**	**0.01**
WCST—categories	6	8	9.1 ± 1.1	**0.02**	0.19
WCST—perseverative errors	6	13	10.1 ± 3.1	0.13	0.20
WCST—errors	8	24	19.6 ± 5.5	**0.05**	0.24

speech impairments, heaviness, and numbness in his face and right arm. He was diagnosed with a left temporoparietal hematoma involving the left supra-marginal gyrus and temporal lobe (Fig. 2A). Repeat MRI 3 months later revealed a residual hypointense area consistent with absorption of the hematoma. According to the hospitalization log, at the time of hospitalization EP had language difficulties which manifested as difficulties in communicating speech and partial comprehension. A few days after the acute event, EP reported experiencing strong desires to draw, something he had never experienced before. He began to draw in notebooks at the hospital and continued to paint several paintings a day at home. His artwork evolved from two-dimensional line drawings into complex color paintings, which in his own words represented "the development of a talent that wasn't there before." The patient described being "preoccupied with pencil sketching and pastel paintings and feeling as if I was suddenly able to see visual objects in a different perspective and wanting to paint them." Although he had never formally learned how to paint, he felt he had independently developed new skills for painting pictures of objects and scenes (Fig. 2B). Remarkably, in the course of the following 8 months, as his language abilities gradually returned and the hemorrhage receded, EP's urges to draw diminished to the point that he felt he was no longer able to draw. He was evaluated three times following the hemorrhage. Each evaluation revealed that his language, memory and spatial abilities had improved and that his verbal fluency was normal (Table 1). The first neuropsychological evaluation was carried out 6 months after the stroke, when EP began experiencing diminished drawing ability and after he had undergone a rehabilitation program with a speech therapist. He noted that at the time of the initial hospitalization he had blurred speech and felt that he could not find the correct words and would find himself saying a different word then indented, though his comprehension was intact. He also noted that "despite recurring attempts to paint, I have felt a striking reduction in my ability to paint since my language abilities have improved." At that time his speech was fluent with occasional word searching difficulties, and his comprehension and fluency were intact. He was in a good mood and had no complaints of depression or anxiety. During the second evaluation 3 years later, EP reported that he was no longer producing art and felt that drawing no longer came naturally to him, a repeat MRI taken approximately 10 years after the initial hematoma in 2007 revealed that the hematoma had receded (Fig. 2A). This has not changed to this day.

We used the Single-Bayes procedure (Crawford and Garthwaite, 2007) to conduct statistical analysis on EP's NP scores compared to those of a healthy age-matched control group. The Single-Bayes procedure utilizes Bayesian Monte Carlo methods and provides a point estimate of the abnormality of the case's score (with 95% credible interval). Differences between EP and the control group were considered significant in cases where the one-tailed probability was equal to or below.05. As can be seen in Table 1, only for the first NP examination was significant differences present for semantic fluency for both NP evaluations ($p < 0.05$), WCST categories ($p < 0.05$) and WCST errors ($p < 0.05$). On the Trail Making test, EP's results were marginally higher (faster responses) than those of the healthy controls, though this difference did not reach significance.

In Study 1 presented above, we presented an individual with no previous experience in art who developed remarkable transient gains in artistic creativity following extensive left temporoparietal hemorrhage. According to our hypothesis, these gains are due to a decrease in activation of the evaluation process which resulted in a release from inhibition of generation processes. In order to test this, an fMRI study (Study 2) was conducted among healthy individuals. The goal of the neuroimaging study was to examine the neural network associated with the evaluation process and to specify the inhibiting role of the networks' components. More specifically, we were interested in examining how activations during evaluating creativity in the ROI damaged in the case reported above are related to creative production.

3. Study 2

3.1. Materials and methods

An fMRI experiment was conducted to examine the hypothesis that a left lateralized network including frontal and temporoparietal regions modulates creativity through involvement in the evaluation phase of creativity. The study was conducted among healthy participants who performed a creativity evaluation task while being scanned. The evaluation task was part of a larger study designed to investigate the underlying neural networks associated with creative thinking. In addition to the evaluation task participants completed a creative generation task as well as a lingual task switching task. All tasks were run as separate runs with the same order which was generation task first, anatomical scan, evaluation task and lastly the lingual task switching. Items in the generation task were the same as the evaluation task. In addition, participants' creativity levels were assessed prior to scanning using measures of DT. Although DT is not synonymous with creativity, DT tests provide structured and objective measurements of creativity (Jung et al., 2009; Sternberg and Lubart, 1999). The creativity evaluation task was based on answers provided to the Alternate Uses task (AUT) (Guilford et al., 1978), and involves evaluating the originality of ideas generated by other individuals (Fig. 3). The AUT is a DT task that measures aspects of creativity related to the ability to respond with multiple solutions to a given problem (Dietrich and Kanso, 2010).

3.1.1. Participants

Thirty-seven healthy right-handed volunteers (mean age 25.9, SD=2.7, 17 female) participated in the study and underwent brain fMRI. Two participants were excluded due to excessive movement, one left the study voluntarily and four were excluded due to technical problems. All participants had normal or corrected-to-normal vision, all provided their written informed consent and all were paid for their participation. The consent and protocol were approved by the Helsinki Committee of the Rambam Medical Center in Haifa, Israel.

3.1.2. Assessment of creativity

Prior to scanning, participants were shown the circles subset of the Torrance Test for Creative Thinking (Torrance, 1974) (TTCT) and asked to draw as many different meaningful objects as possible. Scoring was based on the TTCT scoring system and guidelines, and included scores for fluency (total number of items produced) and originality (total originality score based on Torrance, 1974). A 1 min phonetic fluency task was used as a control task for general fluency. Participants were given 1 min to write as many words as possible that begin with a given letter. Three letters were used and an average score was calculated representing an average phonetic fluency measure.

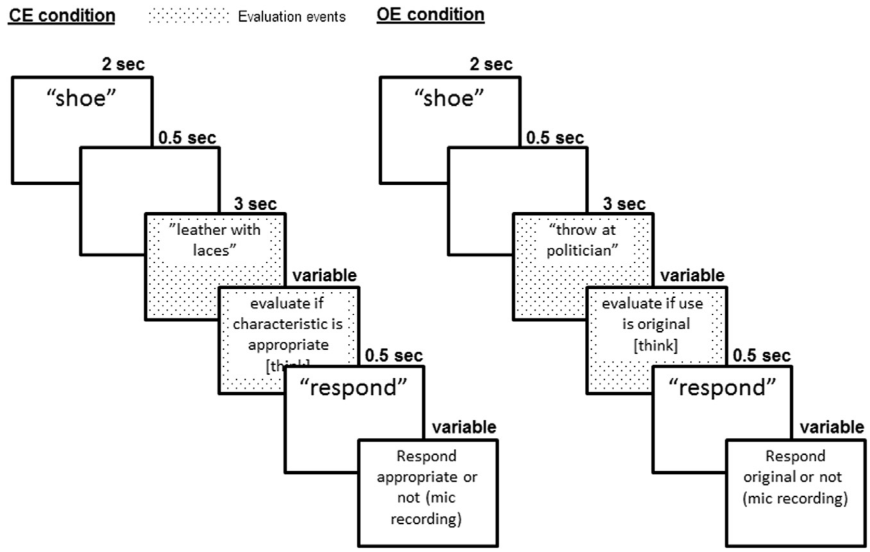

Fig. 3. fMRI task procedure: Participants were presented with an everyday object (2 s) followed by a possible use for this object (3 s) and were then requested to evaluate whether or not they thought this use was original, to press a key once their evaluation was completed, and to state their response aloud ("original"/"not original"). The control condition followed the same procedure except for the instructions, which were to evaluate whether or not the characteristics of the object represented the object.

3.1.3. Procedures

For the purpose of assessing the neural network thought to mediate the evaluation phase of creativity, all participants were scanned while completing a creativity evaluation task involving originality evaluation (OE) and a control condition involving characteristic evaluation (CE). The evaluation task was based on the original AUT (Guilford et al., 1978)

As detailed in Fig. 3, in the OE condition, participants were requested to evaluate whether or not they thought a stated use of an object was original or not. In the CE condition they were asked to evaluate whether the stated characteristic of the object represented the object. CE was chosen as a control condition because it is thought to involve evaluation of the concrete physical characteristics of an object rather than of creative ideas.

Pretest: Objects and their possible uses were selected from a pretest involving healthy volunteers ($N=100$, age 18–40). Participants were given a list of five objects randomly selected from a list of 10 objects, with each object's everyday use provided in parentheses next to the object. They were then asked to list as many additional uses as possible for each object and to focus on uses other than the normal everyday use. For each object, a list was compiled consisting of all possible uses provided across participants. According to the scoring guidelines (Torrance, 1974), an originality score was assigned to each possible use according to the percentage of participants that provided that answer (a score of 2 was assigned if fewer than 2% of subjects gave the answer, a score of 1 if 2–5% gave the answer, and a score of 0 if more than 5% gave the answer). After this pretest, 12 possible uses with high originality scores (answers with a score of 2 indicating that percentage of participants who gave this use was less than 2%) and 12 possible uses with low originality scores (answers with a score of 0 indicating that percentage of participants who gave this use was more than 5%) were selected.

3.1.4. fMRI procedure

In the OE condition, the participants were presented with an everyday object (2 s), followed by a possible use for this object (3 s). Participants were requested to evaluate whether or not they thought this use was original, to press a key once they were sure of their evaluation and to respond by stating their response aloud ("original"/ "not original"). Responses were recorded via an fMRI-compatible optical microphone (FORMRI-II www.optoacoustics.com). The CE control condition followed the same procedure except for the instructions, which were to evaluate whether or not the characteristics of the object represented the object (see Fig. 3). The instructions either for the CE or the OE conditions were given before the start of each block. Examples of objects and their uses are car tire: use as swing (not original); drinking glass: use to draw a circle (not original); pencil: use as screwdriver (original); cardboard box: use for a puppet show (original).

The experimental run consisted of 48 trials (24 trials per condition CE/OE). In order to avoid problems with task switching, the run was divided into 4 blocks; each block consisted of 12 trials of one condition (either CE or OE) and was separated from the preceding block by an instruction slide indicating to the participant if the following block is OE or CE. The order of the blocks was randomized and items and their uses or characteristics appeared only once. Average time per trial and standard deviation was 8.9 ± 1.9 s for the OE condition and 8.3 ± 1.9 s for the CE condition. Average run time was 11.3 ± 1.5 min. Reaction times were calculated starting from the time of presentation of the possible use, and ending at the first button press indicating that an answer was chosen (the variable time).

3.1.5. Image acquisition

Participants were scanned using a 3T GE scanner at the Rambam Medical Center in Haifa, Israel. Functional magnetic resonance imaging (fMRI) was carried out with a gradient echo-planar imaging (EPI) sequence of functional T2*-weighted images (TR/TE/flip angle: 2000/30/60; FOV: 217 mm; matrix size: 64×64) divided into 40 axial slices (thickness: 3.4 mm; gap: 0 mm) covering the whole cerebrum. Anatomical 3D sequence spoiled gradient (SPGR) echo sequences were obtained at high-resolution 1-mm slice thickness (matrix: 256×256; TR/TE: 8/3.1 ms).

3.1.6. fMRI data analysis

Data were processed using Brain Voyager QX software (Brain Innovation, Maastricht, The Netherlands). To allow for T2* equilibration effects, the first two images of each functional scan were rejected. Imaging pre-processing of functional scans consisted of head movement assessment (with rejection of participants whose head movements were greater than 1.5 mm); slice scan time correction (using sinc interpolation); spatial smoothing (FWHM: 4 mm); and voxel-wise linear detrending and high-pass filtering of frequencies (above three cycles per time course). For each participant, structural and functional data were transformed to standard Talairach space (Talairach and Tournoux, 1988). The blood oxygen level-dependent response across the scanning run was modeled per participant using a general linear model in which all stimuli conditions were positive predictors (evaluation events ranging from the beginning of presentation of a possible uses/characteristic to the first button press indicating an answer has been chosen, providing answer, hearing). A random effect of general linear model was used for the group analysis.

3.1.7. Contrast analysis and region-of-interest (ROI) analysis

In order to model activation during evaluation of originality, times of evaluation ranging from the beginning of presentation of a possible uses/characteristic to the first button press indicating an answer has been chosen were used for contrast analysis (evaluation events; see Fig. 3). The following contrasts were analyzed: OE vs. CE, OE vs. baseline and CE vs. baseline. For OE vs. CE contrast, a threshold of $p<0.001$ single voxel threshold combined with Brainvoyager's cluster level statistical threshold estimator. This allows to estimate a corrected cluster-level confidence for the entire volume (at $\alpha=0.05$, 1000 iterations) (Forman et al., 1995; Goebel et al., 2006). The method uses a nonparametric Monte Carlo simulation that calculates the likelihood of obtaining a cluster of randomly generated voxels across the entire volume at the given individual voxel probability threshold. After 1000 iterations the minimum cluster size with a cluster-level false-positive rate of 5% or less was used to threshold the statistical maps. The cluster threshold was estimated at a minimum cluster size of 275 anatomical voxels (mm^3) for the group comparison. For OE vs. baseline and CE vs. baseline, a threshold of $p(\text{bonf})<0.05$ was used (Bonferroni corrected for multiple comparisons as implemented in BrainVoyager which is equivalent to $p<0.000001$ uncorrected).

To examine brain–behavior correlations, mean beta values were extracted from the ROI's identified in the OE > CE contrast. For each ROI, the mean beta value was extracted for each condition (OE and CE) and evaluated for correlation with behavioral measures (DT fluency, DT originality and phonetic fluency). In addition,

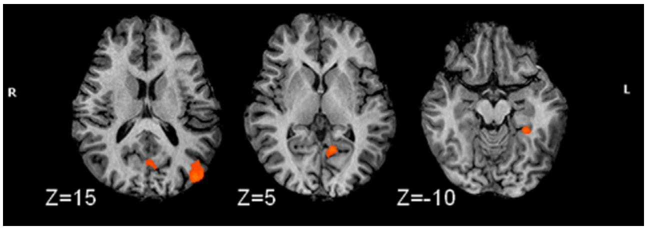

Fig. 4. fMRI contrast results: Evaluation of originality relative to the control condition of characteristic evaluation; activated areas are in the left parahippocampal gyrus (BA 36), the left lingual gyrs and the posterior cingulate (BA 18/30) and the left occipital–temporal area (BA 19/39) $p<0.001$, single voxel threshold combined with Brainvoyager's cluster level statistical threshold estimator (see Table 5 for complete results).

in order to test for valid correlations between originality evaluation and behavioral measures, we only looked for correlations within "masked" brain regions that were more active in evaluating originality vs. evaluating characteristics. Within this mask, we performed random effects analysis of covariance between brain response to evaluation of originality and DT fluency, DT originality and phonetic fluency across the entire sample as well as the behavioral measures of the task performed in the fMRI (reaction times and percent of stringent evaluation; see Section 3.1.9).

3.1.8. ROI analysis based on case report in Study 1

The ROI was selected based on the regions damaged by EP's initial hematoma as reported here and seen on an MRI scan performed at the time of the stroke (see Fig. 4A). The specific areas damaged were identified by superimposing individual scans on a healthy brain template using Brain Voyager software (Maastricht, the Netherlands). The lesion was drawn by the first author and was verified by J.A.P., an expert neurologist with experience in neuroimaging. The outline of the lesion was transposed manually onto slices of the normal brain, taking into consideration the relation between the lesion and anatomical landmarks (Fellows and Farah, 2007) and resulted in a lesion size of 32,556 voxels which encompasses the left IFG, left supra-marginal gyrus and temporal lobe. The mean beta value was extracted for each condition (OE and CE) and evaluated for correlation with behavioral measures.

3.1.9. fMRI behavioral analysis

Behavioral results obtained from button presses and from the microphone recordings when participants were in the magnet were analyzed offline. Of the 30 final participants whose data were used for the fMRI imaging analysis, button presses were recorded but the verbal responses of six subjects were not recorded due to technical difficulties with the recording. Therefore, for the behavioral responses we report on 24 subjects. Reaction times and percent of stringent as well as lenient evaluation were calculated for each participant and each condition. Stringent evaluations were considered those where a "not original" response was given to an original use as assessed in the pretest, whereas lenient evaluations were considered those where a "yes original" response was given to a non original use as assessed in the pretest. The number of stringent and lenient responses was counted and a percentage score was calculated resulting in a score of stringent evaluation and a score of lenient evaluation (the lower the score, the more stringent/lenient the evaluation). A repeated measure ANOVA with two within-subjects variables [condition (originality/characteristic) × type of evaluation (stringent/lenient)] was calculated separately for reaction times and for percentages of stringent/lenient evaluation.

3.2. Results

3.2.1. Behavioral results

For reaction times, a repeated measures ANOVA revealed a significant main effect for condition $F(1,23)=13.73$, $p<0.001$, indicating that evaluation of originality took longer (mean=3.22 s, SE=0.19) than evaluation of characteristics (mean=2.88 s, SE=0.15) (Table 2). There was no significant effect for type of evaluation (stringent/lenient).

For percentages of stringent/lenient evaluation, a repeated-measures ANOVA revealed a significant main effect for condition $F(1,23)=62.28$, $p<0.001$ and for evaluation (stringent/lenient) $F(1,23)=36.97$, $p<0.001$ but they are qualified by a significant interaction between type of evaluation (stringent/lenient) and condition $F(1,23)=41.05$ $p<0.001$. Following the significant interaction effect, paired *t*-tests were conducted in each condition separately between evaluation types. This analysis revealed significant differences between types of evaluation for the originality condition ($t=6.63$ $p<0.001$) but not for the characteristic condition ($t=0.62$ $p=0.53$), indicating that participants tented to be more lenient than stringent in their originality evaluations (Table 2). There is a risk that performing a generation task with the same items before performing the evaluation task could potentially influence these results; however, unpublished findings from our lab replicate these findings in a group of participants performing the evaluation task without previously performing a generation task with the same objects. Thus it is unlikely that the generation task influenced these results.

Table 2
Behavioral data from fMRI study. Reactions times (in sec) and percentages of stringent/lenient evaluation percentage of the evaluation task. Lower scores in the type of evaluation percentage indicate more stringent or lenient evaluation.

Condition	Answer	Reaction time		Percentages of stringent/lenient evaluation	
		Mean	Std. error	Mean	Std. error
Originality	Lenient	3.133	0.195	52.775	4.957
	Stringent	3.325	0.203	92.706	1.687
Characteristic	Lenient	2.891	0.191	92.358	1.58
	Stringent	2.887	0.124	93.748	1.826

Table 3
Activation peaks during evaluation of originality vs. baseline. Brain regions showing a significant BOLD response for evaluation of originality [$p(\text{bonf})<0.05$] with Bonferroni corrections for multiple comparisons. Brodmann areas (BA) of peak voxel activations are presented as well as *T* values and cluster sizes.

Region	BA	Voxel of peak activation (*x*,*y*,*z*)	*T*	Cluster size
Right superior temporal gyrus	41	50 −23 3	12.50	12,468
Right insula	13	44 −5 3	7.77	408
Right insula	47	32 16 −3	8.55	1293
Right thalamus		11 −23 3	7.62	707
Cerebellum		−4 −53 −33	7.68	3114
Left thalamus		−16 −20 6	10.14	1649
Medial frontal gyrus	24/6	−7 −5 45	11.86	8242
Left inferior frontal gyrus	44/45	−49 7 21	12.05	47,029
Left fusiform gyrus	37	−46 −50 −15	7.48	673

3.2.2. Imaging results

Originality evaluations were associated with stronger activations (relative to baseline) in a set of regions with large clusters in the right superior temporal gyrus (peak activation $x=50$ $y=-23$ $z=3$) and the left inferior frontal gyrus (peak activation $x=-49$ $y=7$ $z=21$). Additional areas of activation were found in the right insula (peak activation $x=44$ $y=-5$ $z=3$), cerebellum (peak activation $x=-4$ $y=-53$ $z=-33$), right and left thalamus, left cingulate gyrus (peak activation $x=-7$ $y=-5$ $z=45$) and left fusiform gyrus (peak activation $x=-46$ $y=-50$ $z=-15$). See Table 3 for complete results. The control condition of characteristics evaluation was associated (relative to baseline) with large clusters of activations in the right precentral gyrus (peak activation $x=47$ $y=-11$ $z=33$), the left inferior frontal gyrus and the left precentral gyrus (peak activation $x=-55$ $y=-17$ $z=36$). Additional areas of activation were observed in the right insula (anterior peak activation $x=38$ $y=13$ $z=-3$ and posterior peak activation $x=29$ $y=-26$ $z=15$), medial frontal gyrus (peak activation $x=-4$ $y=-5$ $z=51$), cerebellum (peak activation $x=-1$ $y=-53$ $z=-30$), left thalamus and left putamen (peak activation $x=-22$ $y=-5$ $z=3$) (see Table 4).

The contrast of the originality evaluations and the characteristics evaluations (OE > CE) revealed left hemispheric activations, including the left parahippocampal gyrus (peak activation $x=-28$

Table 4
Activation peaks during evaluation of characteristics vs. baseline. Brain regions showing a significant BOLD response for (p(bonf) < 0.05) with Bonferroni corrections for multiple comparisons. Brodmann areas (BA) of peak voxel activations are presented as well as T values and cluster sizes.

Region	BA	Voxel of peak activation (x,y,z)	T	Cluster size
Right precentral gyrus	6	47 −11 33	11.27	19,765
Right insula (anterior)	13	38 13 −3	7.96	419
Right insula (posterior)	13	29 −26 15	8.20	324
Medial frontal gyrus	6	−4 −5 51	11.64	7109
Cerebellum		−1 −53 −30	7.73	1075
Left thalamus		−16 −23 3	7.91	853
Left putamen		−22 −5 3	7.13	458
Left inferior frontal gyrus/left precentral gyrus	44/45/43/4	−55 −17 36	13.87	49,230

Table 5
Activation peaks during evaluation of originality vs. evaluation of characteristics. Brain regions showing a significant BOLD response for evaluation of originality vs. evaluation of characteristics at $p < 0.001$ single voxel threshold combined with Brainvoyager's cluster level statistical threshold estimator. Brodmann areas (BA) of peak voxel activations are presented as well as T values and cluster sizes.

Region	BA	Voxel of peak activation (x,y,z)	T	Cluster size
Left lingual gyrus, left posterior cingulate	18/30	−10 −56 6	5.16	953
Left parahippocampal gyrus	36	−28 −38 −9	4.85	409
Left occipital–temporal area	19/39	−43 −77 15	5.11	2089

Table 6
Correlation analysis. Correlations between the three behavioral measures and beta weights during evaluation of originality.

Brain areas	With DT fluency	With DT originality	With phonetic fluency
Left lingual gyrus, left posterior cingulate	**$r = -0.44$** **$p = 0.01$**	$r = -0.36$ $p = 0.05$	$r = -0.01$ $p = 0.96$
Left parahippocampal gyrus	$r = -0.28$ $p = 0.13$	$r = -0.12$ $p = 0.51$	$r = 0.14$ $p = 0.45$
Left occipital–temporal area	**$r = -0.41$** **$p = 0.026$**	$r = 0.16$ $p = 0.39$	$r = 0.29$ $p = 0.11$
EP ROI	**$r = -0.46$** **$p = 0.01$**	$r = -0.10$ $p = 0.58$	$r = 0.05$ $p = 0.77$

$y = -38$ $z = -9$), the left posterior cingulate and lingual gyrus (peak activation $x = -10$ $y = -56$ $z = 6$) and the left occipital–temporal area (peak activation $x = -43$ $y = -77$ $z = 15$) (Fig. 4; see Table 5 for the complete results). The reverse contrast (CE > OE) did not yield any clusters of activations under the significance threshold used.

3.2.3. ROI correlation analysis

Correlation analyses were used to further investigate the relationship between individual brain activations during evaluation and DT. Correlations were run between activation during evaluation of originality in the ROI's found to be significantly activated during originality evaluation (based on OE > CE contrast, Table 5) and three behavioral measures: divergent thinking fluency (mean = 14.60 SD = 6.80), divergent thinking originality (mean = 33.80 SD = 15.50) and phonetic fluency (mean = 14.28 SD = 3.05). As shown in Table 6, significant correlations were found between DT fluency and activations during originality evaluation for two ROIs: the left occipital–temporal area (BA 19/39 $r = -0.40$, $p = 0.026$) and the lingual gyrus and posterior cingulate (BA 18/30 $r = -0.44$, $p = 0.016$). These findings indicate that lower activity in these ROIs during evaluation of originality predicted higher fluency on the DT task. No significant correlations were found for DT originality or for phonetic fluency. Additionally, no significant correlations were found between any of the three behavioral measures and activations in the ROIs during the control condition of characteristic evaluation.

In addition, within the regions more responsive to originality evaluation than characteristic evaluation we found that evaluation of originality correlated with DT fluency in the left Middle Temporal Gyrus ($r = -0.44$, $p < 0.05$). There were no significant correlations with DT originality or with phonetic fluency. There were also no significant correlations with reaction times, or with percent of stringent evaluation, as measured from the fMRI task.

3.2.4. ROI analysis based on the case report

Based on the case of EP, we predicted that diminished activity in the left temporoparietal region during creativity evaluation would be associated with higher creativity. In order to test this, we traced a region of interest (ROI) according to the regions damaged in patient EP's initial hematoma (see Section 3.1 for details). The case report based ROI was positioned more anterior than the ROI which resulted from the contrast analysis of the fMRI task. Despite this, some areas overlapped between the basic contrasts of the fMRI analysis of OE vs. baseline and CE vs. baseline, including the left IFG area as well as left insula.

We examined the relationship between individual DT abilities measured outside the scanner (separate measurements for fluency and originality) and activity in this ROI during evaluation of originality. This analysis revealed a significant negative correlation for DT fluency scores ($r = -0.45$, $p = 0.01$; Fig. 5C), demonstrating that lower activations in this ROI predicted higher creativity. Interestingly, we did not find a significant correlation between individual DT fluency scores and activation under the control condition of characteristic evaluation ($r = -0.27$, $p = 0.14$), indicating that the correlation found was specific to the evaluation of creativity and not applicable to evaluation in general. In addition, we did not find significant correlations between DT originality scores and activity during evaluation of originality ($r = -0.10$ $p = 0.58$) or between DT originality scores and the control condition of characteristic evaluation ($r = -0.02$ $p = 0.91$).

4. Discussion

We report on two studies aimed at examining the evaluation of creativity phase in the creative process. Although previous studies report emergent artistic creativity following degenerative brain damage (Miller et al., 2000; Miller and Hou, 2004; Seeley et al., 2008), to the best of our knowledge, the case of EP is the first involving transient emergent artistic creativity in the sense that not only did his creative abilities emerge de novo due to the injury, but they also disappeared as the damage receded.

It is important to note that there have been several accounts of visual artists with brain damage who continue to produce art and even show improvement despite the damage and independently of its laterality or localization (Bogousslavsky, 2005; Zaidel, 2010).

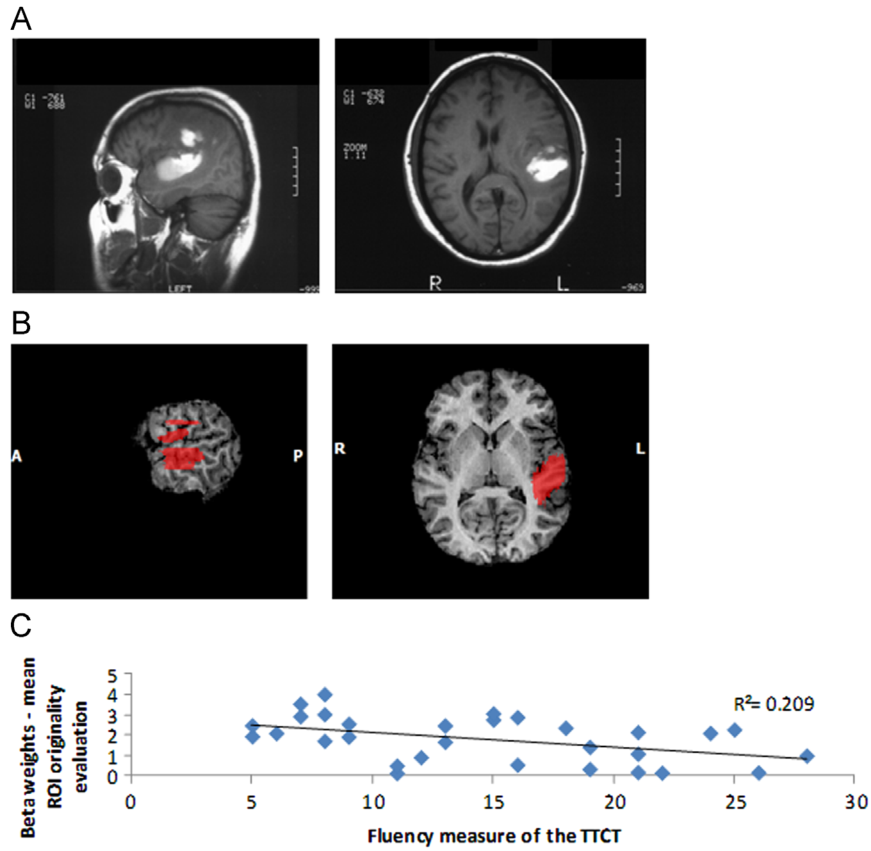

Fig. 5. ROI analysis: (A) MRI scans of EP at the time of the initial hematoma. (B) Images of the ROI selected, as described in Section 3.1. The ROI was traced according to EP's initial damage.(C) Beta weights in ROI for evaluation of originality correlate with divergent thinking fluency ($R^2=0.209$).

The increase in creative artistic productivity following brain disease among naïve artists could be explained by the concept of “paradoxical functional facilitation” (Kapur, 1996). Kapur (1996) proposed that “paradoxical functional facilitation” may account for behavioral facilitation following brain damage. This explanation follows the rule of “release of inhibition,” according to which the damaged region releases its impact on other regions, thereby augmenting certain behaviors. An example of this can be seen in savant autistic individuals, where atypical hemispheric imbalance associated with a right-hemispheric bias and a left hemisphere dysfunction can lead to improved drawing ability specifically related to low level information (Snyder, 2009). Thus, EP's transient increase in artistic is probably a direct result of the recovery of function. Another point to be considered is the idea that other regions of the brain, remote from the lesion, might be affected. This effect is a result of deafferentation (or diaschisis) and implies that following the acute, localized lesion of the central nervous system, there are immediate depressions of neuronal synaptic functions in other areas of the central nervous system remote from the lesion (Meyer et al., 1993). Therefore, the transient changes in EP's behavior may be related to the localized lesion but also to intra and inter-hemispheric activity related to deafferentation.

As can be seen in Fig. 2 depicting the amount of drawings produced by EP, the amount of drawings was largest during the month following the stroke and decreased over the subsequent months. There are some accounts of emergent creativity experienced as an urge to create, which has been previously described as compulsive (Miller and Hou, 2004), obsessive (Lythgoe et al., 2005), impulsive (Finkelstein et al., 1991) and irrepressible (Thomas-Anterion et al., 2010). In line with this, it has been recently suggested that this compulsion to create art is an integral part of the neurological phenomena and can be seen as a compulsive behavior (Schott, 2012). Creative compulsive behavior can be seen in many diseases and neurological disorders, ranging from Parkinson's disease (Kulisevsky et al., 2009) to subarachnoid hemorrhage (Lythgoe et al., 2005) and brain lesions affecting both hemispheres (Finger et al., 2013; Miller et al., 2000). Liu et al. (2009) indicated that compulsive behaviors are often seen in dementia patients which in the case of artistic creativity may lead the patients to obsessively practice art and even perfect their artistic techniques (Miller et al., 2000). In line with these accounts, it is possible that the improvement in artistic creativity observed in the case of EP (see Fig. 2) is related to the obsessive urge to practice art that EP experienced following the stroke. Although it may be argued that the increase in artistic creativity often reported in neurologic population is related to the amount of leisure time during recovery, numerous studies suggest that cases of de novo artistic creativity are specific to lesions involving the left hemisphere (Miller and Hou, 2004; Miller et al., 1996; Seeley et al., 2008). This may indicate that indeed regions in the left hemisphere are part of a network that mediates creativity. Close examination of EPs neuropsychological evaluation scores revealed that EP exhibited higher semantic fluency and lower executive control compared to a group of age-matched healthy controls. After EP was released home and before the first neuropsychological evaluation, 3 months later, EP participated in a rehabilitation program that included speech therapy. Thus, one possibility is that the high scores in the verbal fluency task reflect the progress in his rehabilitation. On the other hand, given the relationship between verbal fluency and creative fluency, it is possible that these scores may also reflect the increase in his creative fluency. Therefore, higher semantic fluency during the first examination when EP's artistic urges were strong may coincide with his apparent increased drawing fluency, in the sense that both are increased measures of fluency and production. It should be noted that EP's semantic fluency was still high 3 years later, when his artistic urges had already diminished. If in fact EP's artistic urges were only a consequence of increased general fluency, we would expect that since this fluency persisted, EP would continue experiencing the urge to create and would continue to produce art at the level demonstrated before. Yet, during the second neuropsychological evaluation, when EPs semantic fluency was still high, he did not produce art, nor did he show signs of any desire to do so. This reinforces the idea that EP's initial damage had an added impact on his artistic creative urges and was not merely an expression of high fluency. In addition to the high semantic fluency, EP exhibited good set shifting abilities as measured by the Trail Making A and B tasks; however he also showed lower scores on the WCST categories. A low score in the number of categories coupled with the lower errors and higher score on the Trail Making task may imply that EP did not have problems with task switching at the time, but may have had difficulties with conceptualizing abstract categories which could indicate a problem in abstract reasoning (Grant and Berg, 1993).

The neuroimaging study was designed to further specify the inhibiting role of the different components of the evaluation of creativity network. In line with the case of EP, the neuroimaging findings indicate that evaluation in general activates a diverse network, including areas in the left frontal and precentral gyri (including the left IFG), the right insula area and the right precentral area. Indeed, the left IFG has been previously suggested as a possible source of inhibitory control (Huang et al., 2013; Swick et al., 2008). Since the left IFG as well as other areas such as the left insula was found to be activated in both types of evaluations, it can be reasoned that these regions mediate a general process of evaluation. These findings are in line with recent reports of left IFG involvement in the processing of conceptual expansion taken to signify the controlled retrieval and selection of semantic knowledge (Abraham, Pieritz, et al., 2012; Kröger et al., 2012; Rutter et al., 2012).

While the left IFG may be generally responsible for evaluation, evaluation of originality was associated with activations in the left occipital–temporal area, the left posterior cingulate and lingual area and the parahippocampal gyrus. Jung et al. (2010) found that cortical thickness in the left lingual gyrus (BA 18) was negatively correlated with divergent thinking. These findings are also in line with our brain–behavior correlation results showing reduced activity and enhanced DT fluency, as discussed below. Parahippocampal and medial temporal areas have been shown to be involved in the processing of novel compared to familiar stimuli (Stern et al., 1996), of exposure to original compared to common ideas (Fink et al., 2012) and of verbal associative novelty (Hunkin et al., 2002). In the context of the current study, it is possible that evaluating the originality of ideas (some ideas are perhaps more novel than others) requires initial processing of these ideas on the dimension of novelty, thus recruiting the parahippocampal area. The left occipital–temporal area has been previously found to be involved in creativity through divergent thinking and problem-solving (Aziz-Zadeh et al., 2013; Fink et al., 2009), brainstorming (Shah et al., 2013) and story generation (Bechtereva et al., 2004), and is thought to be related to flexibility and imagination (Shah et al., 2013). In line with these findings, Kowatari et al. (2009) found that activations in parietal cortices (overlapping with our left temporal and occipital ROI) during the creation of new designs were negatively correlated with the originality of the designs as well as with productivity among a group of design novices. Thus, the activations reported here in left occipital–temporal areas during evaluation of originality may point to the involvement of the evaluative process (according to the twofold model) in the production tasks used in these studies. This may indicate that during tasks requiring DT, both the generation process and the evaluation process are required to produce successful results.

Previous studies have used a similar method of judging novelty and appropriateness of ideas to study creativity through the process termed conceptual expansion (Abraham, Pieritz, et al., 2012; Kröger et al., 2012; Rutter et al., 2012). The authors report activation in the IFG, temporal pole and frontopolar cortex during conceptual expansion (Kröger et al., 2012; Rutter et al., 2012). It is possible that the frontal activations reported in these studies are related to the contrasts used, which involved more semantic retrieval processes that have been shown to involve the left IFG (Whitney et al., 2011). Furthermore, specific contrasts revealing processing of novelty resulted in increased activation in left supramarginal gyrus (Kröger et al., 2012) which is in accordance with the areas reported in the current study. Moreover there have been several reports of left inferior parietal brain activation in association with creative thought (Benedek et al., 2014a,b).

The brain and behavior analysis showed that activations in the left temporal and parietal regions during the evaluation of creativity were negatively correlated with individual DT fluency scores but not with phonetic fluency. Furthermore, the brain and behavior correlation analysis did not reveal any significant correlation with the control condition of characteristic evaluation, indicating that the relationship between DT and left temporal and parietal activations was selective to evaluation of creativity condition. These findings suggest that activation in these areas during the evaluative process is not merely due to evaluation processes but rather is discriminative with respect to creative evaluations and creative processes. This idea is strengthened by the significant negative correlation between the contrasted beta values and DT fluency in the left Middle Temporal Gyrus, and is in line with the notion that the evaluation-of-originality network may act to inhibit creativity by influencing the surge of ideas specific to DT. It was hypothesized that activations in the left temporoparietal region, which could indicate a more stringent evaluation process, would predict lower creativity. Indeed we found that activations in the left occipital–temporal area (and the lingual gyrus) and posterior cingulate were negatively correlated with creativity. The correlation found in the left occipital–temporal area is in accordance with our hypothesis of a left temporoparietal network, while the left posterior cingulate was not predicted. In line with these findings, Ellamil et al. (2012) found activations in posterior cingulate together with other areas (such as temporoparietal jusnction) which are part of the default network during a task of evaluation of ideas. The authors interpreted these findings as demonstrating integration of information from associative cortices and as representing relevant information generated internally (Buckner et al., 2008; Ellamil et al., 2012). It is possible that the posterior cingulate integrates the activity of the evaluation network and therefore high activity in this region may inhibit creative generation by imposing strict constraints on integration of information and thus restraining free flow of new associations. In keeping with this, although not initially hypothesized here as part of the evaluation network, the negative correlation finding suggests that not only is the posterior cingulate part of the neural network underlying the evaluation process, but that greater activation during evaluation in this areas, interpreted as more stringent integration processes, can lead to lower creative generation. Within the dual process model of creativity (Fig. 1), it is reasoned that the evaluation process can move on a continuum between stringent evaluation and lenient evaluation. The evaluation process can be detrimental to creative production if it is too stringent or erroneous, such that, reducing the effect of the evaluation process may lead to more creative ideas. In this study we explored the activation patterns of the evaluation of originality network, and found that its activity was negatively correlated with DT fluency but not DT originality, which can imply that reduced evaluation of originality results in higher fluency but not originality. In addition, it may imply that originality and fluency are mediated by two distinct neural networks, and that inhibition and evaluation of ideas may occur on both of these levels. It should be acknowledged that these brain–behavior correlations are based on activations in response to an evaluation of creativity task based on the AUT, while behavioral creativity was assessed before scanning using a task from the figural subset of the TTCT which is a non-verbal task. Future studies may use a non-verbal task as the basis for the evaluation of creativity measurement to further test these results, and refine the role of the evaluation network in both originality and fluency.

It is important to note that the area specific to evaluation of originality revealed by the contrast analysis was more posterior than the area damaged in the case of EP. Despite this, areas activated for both the evaluation of originality and the evaluation of characteristics did overlap with areas damaged in the case of EP (left IFG area as well as left insula). Additionally, the correlation analysis indicated that these temporoparietal activations during the evaluation of originality (but not of characteristics) were negatively correlated with DT fluency. Furthermore, the ROI based on the areas damaged in the case of EP was rather extended, and therefore can influence the specificity of the areas correlated with behavior. Despite this, a negative correlation was found specifically between activations in this ROI during evaluation of creativity and DT fluency. Although the large ROI does not allow us to speculate as to more specific areas within this ROI, the results of the correlation analysis coupled with the more specific ROIs generated from the fMRI contrasts point to the direction of a negative association between an evaluation of creativity network and DT fluency. This suggests that evaluation of creativity can be inversely related to creative fluency, and thus, that it has an inhibitory effect on the creative process (see Fig. 1).

Based on the clinical case report and the follow-up neuroimaging study, we focus on an explanatory model of creativity centered upon the key role of the evaluation process in filtering and inhibiting creativity. It is possible that while a network of regions within the right hemisphere is responsible for the generation of ideas (Mihov et al., 2010), a left temporoparietal network is responsible for evaluating and filtering ideas. In the case of EP, as long as this left temporoparietal network remained damaged, a strong surge of creativity emerged. As these areas recuperated, however, the art produced by EP diminished to nothing. As noted above, Ellamil et al. (2012) suggested that creative evaluation may be supported by activations in a network of areas that have been previously linked to cognitive control. Furthermore, a recent fMRI study proposed that successful creative thinking during generation of creative uses for everyday objects may benefit from reduced cognitive control (Chrysikou and Thompson-Schill, 2011). In the context of the model proposed here, it can be speculated that less cognitive control during the evaluation of creativity may lead to increased creative productivity. Nonetheless, there have been several reports of a positive relationship between cognitive control and creativity (Benedek et al., 2012; Zabelina and Robinson, 2010). Benedek et al. (2012) for instance reported that cognitive control as measured by cognitive inhibition and assessed by means of the random motor generation task was positively correlated with ideational fluency. Research investigating the association between functional or dysfunctional impulsivity and creativity shows that mild impulsivity or lower inhibition is related to higher creativity. However, severe impulsivity, or excessively low inhibition, is related to low creativity (Colzato et al., 2010; Mayseless et al., 2013). Furthermore, in a recent study Benedek et al. (2014b) reported that creativity of ideas was linearly related to brain activation in the left IFG, an area associated with executive control. These findings may point to a positive association between executive control mechanisms and creativity; thus more executive control can lead to more creative ideas. Collectively, these reports point to a complex relationship between cognitive control and creativity and suggest that further research is needed to clarify the relationship between cognitive control and creativity.

As previously stated, several models have addressed the issue of a tradeoff between different neural networks in the creative process. These tradeoffs include a shifting between symbolic (linguistic) and perceptual regions or between top-down (cognitive control) and bottom up (perceptual) networks (Chrysikou et al., 2013; Ellamil et al., 2012; Snyder, 2009). In the context of the dual model of creativity, where evaluation of creativity can have a facilitating effect or an inhibitory effect on generation of ideas, it might be reasoned that this evaluative process represents one aspect of the cognitive control mechanism. Furthermore, the linguistic or symbolic regions may be part of the evaluation network, insomuch that when these areas are damaged or impaired, a shift is made to the more posterior perceptual regions, thus allowing for less cognitive control on the process.

One limitation of the current design is the use of trials with different durations. Thus, it is possible that the difference in reaction times between the fMRI conditions can lead to possible confounding activations in the contrast analysis. To ensure that the findings reported here are not related to different durations of the trials we re-analyzed a sub group of participants whose reaction times did not differ between the two conditions, and replicated our findings in this sub group. We found that regions which showed increased activations in the contrast OE > CE (including left posterior cingulate and left occipital–temporal areas) did not change. Notwithstanding, future studies might use a design in which trials are not contingent on reaction times in order to avoid this problem. Although the statistical power used in the current study is relatively conservative, another potential limitation is the borderline trial count (24 trails for each condition) in the fMRI study, which can influence the spatial extent of activation and the statistical power due to noise within the time series (Desmond and Glover, 2002; Huettel and McCarthy, 2001). Finally, given that many cases of de novo artistic creativity have been associated with the deterioration of language abilities, it can be speculated that language abilities may be inversely related to creativity. This may indicate that language may play a crucial role in mediating creativity. If this is the case, higher creativity should be observed in individuals with language impairments. Indeed, Chakravarty (2009) observed that artistic abilities are more prevalent among individuals with developmental dyslexia, and suggested that development delay in the left hemisphere helps “disinhibit” the right hemisphere and “releases” this talent. In line with this supposition, it has been reported that individuals with dyslexia may possess visual–spatial strengths and higher creativity (Everatt et al., 1999; Wolff and Lundberg, 2002). Yet these results are sparse and require further research.

In conclusion, our findings suggest that individual differences reflected in creativity may be related to a differentially activated network of evaluation that imposes a stricter process of evaluation on creative output and hence inhibits creative production. The current study proposes several interesting directions for future studies. The first is that DT fluency and DT originality, though generally correlated (Hocevar, 1979; Silvia et al., 2008), may be mediated by two different neural systems and may be influenced by different patterns of activations. Furthermore, dividing the creative process into an evaluative process and a generative process may contribute to explaining some of the conflicting reports in the neuroscientific literature examining creativity. In this context, the present fMRI study did not test the difference between evaluating highly original ideas and evaluating low original ideas. In order to do so, the stimuli used need to be better differentiated by choosing stimuli that are highly original (scored by infrequency score or a subjective measure) and stimuli that are very low in originality (Silvia et al., 2008). In addition, future work should use non-verbal and more artistic stimuli in the fMRI evaluation task, in order to examine the generalizability of the evaluation of the creativity network. Finally, the proposed study examines "small c" creativity, the type of creativity humans display in their daily functioning, but this model may generalize to "Big C" creativity—the extreme forms of originality and breakthroughs that lead to changes in society.

Author contributions

N.M. designed and performed the experiments, analyzed the data and wrote the paper; J.A.P. conducted the neuropsychological assessment on the patient, helped draw the lesion and helped write the paper; S.G.S.T. designed the experiments and wrote the paper.

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