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Creative cognition and the brain: Dissociations between frontal, parietal–temporal and basal ganglia groups

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ABSTRACT

The objective of the study was to investigate creativity in relation to brain function by assessing creative thinking in various neurological populations. Several measures were employed to assess different facets of creative thinking in clinical groups with frontal lobe, basal ganglia or parietal–temporal lesions relative to matched healthy control participants. The frontal group was subdivided into frontolateral, frontopolar and frontal-extensive groups. Hierarchical regression analyses were employed to assess the significance levels associated with the effects after accounting for IQ differences between the groups. Findings were only considered noteworthy if they at least suggested the presence of a strong trend and were accompanied by medium to large effect sizes. The parietal–temporal and frontolateral groups revealed poorer overall performance with the former demonstrating problems with fluency related measures, whereas the latter were also less proficient at producing original responses. In contrast, the basal ganglia and frontopolar groups demonstrated superior performance in the ability to overcome the constraints imposed by salient semantic distractors when generating creative responses. In summary, the dissociations in the findings reveal the selective involvement of different brain regions in diverse aspects of creativity. Lesion location posed selective limitations on the ability to generate original responses in different contexts, but not on the ability to generate relevant responses, which was compromised in most patient groups. The noteworthy findings from this exploratory study of enhanced performance in specific aspects of creative cognition following brain damage are discussed with reference to the generic idea that superior creative ability can result from altered brain function.

1. Introduction

How human beings in comparison to other animal species have evolved the singularly astonishing capacity that is the ability to think creatively in such a wide realm of contexts from everyday problem solving to spectacular accomplishments in the arts is still a matter of much mystery. It is little wonder that there has been a veritable burst of brain-related

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investigations on creative thinking in the past decade that have been carried out with a view to rectify this situation. These investigations have taken the form of neuroimaging and electrophysiological investigations (for a review, see Dietrich and Kanso, 2010) alongside neuropsychological studies on neurological (Reverberi et al., 2005; Shamay-Tsoory et al., 2011) and psychiatric populations (Abraham et al., 2007, 2006; Andreasen, 2008; Andreasen and Powers, 1975). Creativity is customarily defined as the ability to generate *original* (novel/unique) and *relevant* (fitting/appropriate) responses (Hennessey and Amabile, 2010; Runco, 2004), and a range of different tasks that have been developed to assess this complex ability.

The study of creativity and brain function has primarily focused on issues such as enhanced creative or artistic ability following or as a function of brain damage (Miller et al., 1996; Seeley et al., 2008), left versus right brain contributions to creativity (Bowden and Jung-Beeman, 2003a; Carlsson et al., 2000; Kounios et al., 2008; Seger et al., 2000; Shamay-Tsoory et al., 2011), and the brain basis of high or exceptional creativity in intact brains (Fink et al., 2009; Limb and Braun, 2008; Loui et al., 2011). Bringing the insights of these studies together with that of individual findings associated with the structural and functional neuroimaging of creativity in healthy brains (Dietrich and Kanso, 2010) is a highly challenging endeavor. This is because such an undertaking requires making generalizations concerning the mechanisms underlying creative thinking while taking into account that there are several conceptualizations of what creativity entails ranging from emerging artistic proficiency to originality during problem solving. There is as yet no single theoretical framework that brings together the problem solving and proficiency aspects of creativity. So the question of how far one can generalize the findings found in one domain to the other is still unclear. The problem with making sense of the multitudinous findings associated with the different approaches to investigate creativity is compounded by the fact that a wide range of creativity tasks, that are difficult to compare with one another, have been employed in studies on creativity (Arden et al., 2010).

One means to deal with this issue is by assessing the creative ability of several clinical groups on standard creativity tests (e.g., Shamay-Tsoory et al., 2011), or by having a clinical and control group carry out a variety of creative cognition tasks that tap different mental operations involved in creative thinking (Abraham et al., 2007), or by employing a combination of multiple clinical groups and multiple creativity measures (Abraham et al., 2006). Such approaches would allow us to understand the specificity of creativity-based differences in relation to brain function. Shamay-Tsoory et al. (2011), for instance, compared four patient groups with selective lesions of the medial prefrontal cortex, inferior frontal cortex, medial and inferior frontal cortices, or posterior parietal–temporal cortex on two standard tests of creative thinking—the Alternate Uses task and the Torrance Test of Creative Thinking. The presence of medial prefrontal lesions was associated with poorer performance on the originality component of both creativity measures whereas the groups with selective inferior frontal lesions and parietal–temporal lesions performed comparably to the healthy control group. These results speak for the selective role of medial prefrontal regions in comparison to the inferior frontal or parietal–temporal regions in the originality component of creative thinking.

Other investigations have focused on assessing one or more clinical groups on several creative cognition measures that assess different facets of creative thinking (Abraham and Windmann, 2007). The objective behind such investigations is to move beyond making generalizations about creative function (or dysfunction) in relation to select populations by uncovering the selectivity of the associated information processing biases. For instance, in their study on adolescents with attention-deficit hyperactivity disorder (ADHD), a clinical group known to be associated with insufficiencies of the frontostriatal system (Bradshaw and Sheppard, 2000; Cherkasova and Hechtman, 2009; Dickstein et al., 2006), Abraham et al. (2006) found that while the ADHD group performed comparably to the healthy controls on some aspects of creative cognition (such as conceptual expansion), they demonstrated poorer performance on other aspects of creative cognition (such as originality in creative imagery), and superior performance on still other aspects of creative cognition (such as the ability to overcome the constraining influence of examples).

Had the performance of the ADHD group only been assessed on a single creativity measure, one would have obtained a very limited understanding about the specificities underlying their performance, which may have even led to erroneous conclusions (e.g., generally lower creative ability in ADHD based on their poor performance on the creative imagery task). Including a wide range of tasks that tap different operations associated with creativity enables one to make more specific claims about which aspects of creativity are affected in a particular group, whether these can be related to the cognitive insufficiencies associated with the group, and if this can be done in a predictable fashion. This approach allows us to take significant steps forward in understanding the complex cognitive mechanisms that underlie creativity.

Such an undertaking was conducted in a study of patients with chronic schizophrenia, another clinical population known to be associated with impairments of the frontostriatal system in the brain (Eisenberg and Berman, 2010; Robbins, 1990; Simpson et al., 2010), relative to a healthy control group (Abraham et al., 2007) where participants carried out a range of creative and executive cognition tasks. This was part of a larger effort to explore factors that contribute to the purported link between cognitive disinhibition or insufficiencies at the level of executive function and elevated creative ability (Martindale, 1999; Reverberi et al., 2005). The analyses revealed that while the schizophrenics performed poorly on most of the creative and executive function tasks compared to the controls, their performance on the creative measures were only partly modulated by their performance on the executive function measures. After differentiating the tasks in terms of the extent to which they tapped the two defining properties of creativity (Boden, 2004; Hennessey and Amabile, 2010; Runco, 2004)—originality (unusualness) and relevance (appropriateness)—it appeared that the degree of executive functioning fully or partially modulated performance on creativity tasks that included a strong relevance component but that the degree of executive functioning had no significant influence on tasks that primarily included a strong originality component. So although poor executive function modulated poor performance on relevance-dominant creativity tasks, it did not significantly impact performance on originality-dominant creativity tasks.

These investigations of creative performance in selected psychiatric groups provided indirect evidence for the influence of specific parts of the brain in creative thinking. While severe executive impairments as seen in schizophrenia were associated with overall poor creative performance, assessing patients with ADHD, a disorder customarily associated with milder and more specific executive insufficiencies such as poor inhibitory control, revealed a more complex picture depending on the demands of the creative task in question. As executive functions are known to be predominantly orchestrated by frontostriatal systems in the brain (Brocki et al., 2008), we endeavored to investigate the contributions of this system in creative cognition by assessing patients with frontal lobe lesions (FL) and patients with basal ganglia (BG) lesions in the current study.

Further comparisons were also made within the FL group in that they were divided into three subgroups based on the location and extent of the frontal lesions (EXT—extensive frontal lesions, LAT—lateral lesions, POL—frontopolar and orbital lesions). This was to assess the impact of lesions in specific parts of the frontal lobe (FL-LAT, FL-POL) on differing aspects of creative cognition, and whether these were differentiable from the performance profile of those with more extensive and heterogeneous lesions of the frontal lobe (FL-EXT). Moreover, given that executive dysfunction only partially modulated creative performance, we also targeted other regions of the brain which might play a critical role in creative cognition. A candidate region was the parietal–temporal cortex given the significance of this region in semantic cognition, language processing and creative thinking (Bedny and Caramazza, 2011; Price, 2010; Shamay-Tsoory et al., 2011; Takeuchi et al., 2010a). Creative cognition was therefore also assessed in patients with parietal–temporal lesions (PTL).

This exploratory study was carried out with the objective of gaining a clearer understanding of how lesions in different parts of the brain (Fig. 1) influence general creative performance, as assessed by standard creativity tests such as the alternate uses task (Wallach and Kogan, 1965) and the remote associates test (RAT: Mednick, 1962), in addition to specific aspects of creative cognition such as conceptual expansion, originality and practicality in creative imagery, insight and non-insight incremental processes during problem solving, and overcoming the constraints of examples when engaging in creative thinking (Finke et al., 1996; Ward et al., 1995).

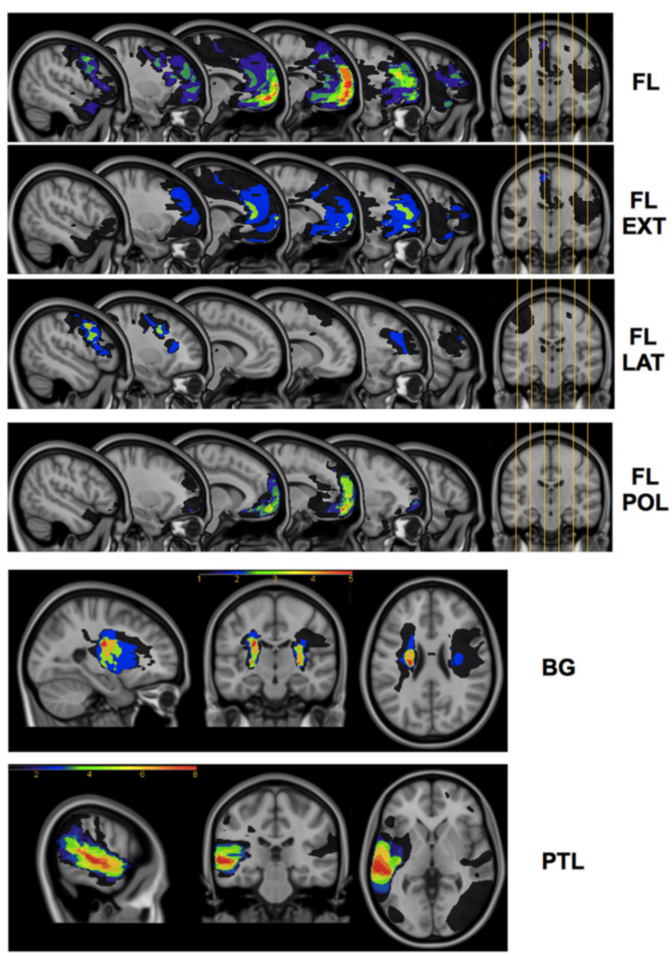

Fig. 1 – Lesions sites for the frontal lobe (FL), frontal-extensive (FL-EXT), frontal-lateral (FL-LAT), frontal-polar (FL-POL), basal ganglia (BG), and the parietal–temporal (PTL) groups. Extent of overlap (minimum: blue to maximum: red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Results

The descriptive data for all variables across all three patient groups (frontal lobe: FL, basal ganglia: BG, parietal–temporal: PTL) and their corresponding control groups (CT) are presented in Table 1 whereas that of the three FL-subgroups (FL-EXT, FL-LAT, FL-POL) and their corresponding control groups are presented in Table 2. Findings were only treated as consequential if they were accompanied by medium to high effect size AND were significant at the standard level ($p<0.05$) or suggested the presence of a meaningful trend ($p<0.1$).

Comparing the clinical and control groups on their levels of premorbid IQ revealed some significant findings such that the BG, FL, FL-EXT and FL-POL patient groups had significantly lower IQ scores than their respective control groups (all $p<0.05$). To rule out the possibility that the differing IQ-levels between the groups explained the differences between the groups on the creativity measures, hierarchical regression analyses were carried out for all comparisons between every clinical group and their respective control groups (for details, see Section 4.2). Extended results of the hierarchical regression analyses are presented in the supplementary material (Tables S2–S7) while a summary of the findings across all group comparisons is presented in Table 3. Graphical representations of the significant findings associated with the creativity measures are presented in Figs. 2–6, whereas the remaining findings are presented in Figs. S1–S3 (Supplementary material).

Table 1 – Descriptive data for the frontal (FL), basal ganglia (BG) and parietal–temporal (PTL) groups alongside their matched control groups (CT). Unless indicated otherwise, the values refer to means and standard deviation (in brackets). Abbreviations: AUT—alternate uses task, BG—basal ganglia lesion group, CT—control group, FL—frontal lobe lesion group, NART—national adult reading test, PS—problem solving, PTL—parietal–temporal lesion group, RAT—remote associates test.

	FL	FL-CT	BG	BG-CT	PTL	PTL-CT
Female:male (N)	9:20	9:20	4:12	4:12	1:10	1:10
Age	52.21 (9.74)	52.42 (10.16)	53.06 (10.51)	53.00 (10.58)	50.00 (12.86)	50.00 (14.05)
NART: IQ	97.59 (10.07)	106.78 (7.90)	97.75 (6.92)	107.06 (5.86)	101.93 (11.62)	107.10 (8.58)
AUT: originality	2.17 (0.44)	2.59 (0.29)	2.17 (0.43)	2.67 (0.35)	2.55 (0.32)	2.69 (0.18)
AUT: fluency	17.78 (7.84)	26.40 (6.58)	19.61 (6.54)	33.80 (15.14)	21.84 (7.18)	29.05 (7.52)
Conceptual expansion	1.78 (0.93)	2.03 (1.09)	1.06 (1.00)	1.38 (0.96)	1.45 (0.82)	1.73 (1.01)
Constraints of examples	1.29 (1.08)	1.37 (1.08)	1.23 (0.83)	1.81 (0.66)	2.20 (0.79)	1.50 (0.71)
Creative imagery: originality	2.35 (0.63)	2.63 (0.53)	2.63 (0.57)	3.03 (0.46)	3.01 (0.80)	3.14 (0.60)
Creative imagery: practicality	2.56 (0.65)	3.04 (0.38)	2.63 (0.45)	3.04 (0.39)	2.33 (0.54)	2.86 (0.23)
RAT: total score	15.90 (3.32)	16.79 (3.29)	14.25 (4.84)	17.06 (2.98)	14.09 (4.78)	17.64 (2.84)
RAT: non-standard score	2.82 (1.28)	2.31 (1.42)	2.25 (1.34)	2.44 (1.26)	2.18 (1.47)	2.73 (1.62)
Insight PS: candle task —solved (unsolved)	22 (7)	26 (3)	11 (5)	11 (5)	8 (3)	10 (1)
Incremental PS: Hanoi task—solved (unsolved)	17 (12)	21 (8)	8 (8)	11 (3)	5 (6)	8 (3)

Table 2 – Descriptive data for all three frontal subgroups alongside their matched control groups (CT). Unless indicated otherwise, the values refer to means and standard deviation (in brackets). Abbreviations: AUT—alternate uses task, CT—control group, FL—frontal lobe lesion group, EXT—extensive lesions, LAT—lateral lesions, NART—national adult reading test, POL—polar and/or orbital lesions, PS—problem solving, RAT—remote associates test.

	FL-EXT	FL-EXT-CT	FL-LAT	FL-LAT-CT	FL-POL	FL-POL-CT
Female:male (N)	3:6	3:6	4:5	4:5	2:9	2:9
Age	55.89 (10.30)	56.44 (10.54)	54.78 (7.43)	55.00 (7.57)	47.09 (9.46)	47.00 (10.09)
NART: IQ	99.50 (4.15)	107.47 (8.52)	99.40 (10.20)	105.50 (7.99)	95.72 (10.23)	107.27 (7.97)
AUT: originality	2.13 (0.38)	2.48 (0.34)	2.13 (0.52)	2.64 (0.26)	2.23 (0.45)	2.62 (0.28)
AUT: fluency	16.33 (3.98)	25.98 (5.46)	15.64 (3.59)	28.09 (8.27)	20.71 (11.55)	25.36 (6.22)
Conceptual expansion	2.00 (0.53)	2.11 (1.17)	1.75 (1.39)	2.22 (1.30)	1.64 (0.81)	1.82 (0.87)
Constraints of examples	1.25 (0.89)	1.00 (0.93)	1.38 (1.41)	0.88 (0.99)	1.25 (1.04)	2.00 (1.00)
Creative imagery: originality	2.22 (0.54)	2.53 (0.48)	2.14 (0.85)	2.60 (0.31)	2.62 (0.41)	2.75 (0.72)
Creative imagery: practicality	2.46 (0.61)	3.10 (0.41)	2.51 (0.82)	3.11 (0.31)	2.69 (0.58)	2.93 (0.41)
RAT: total score	16.89 (3.06)	16.11 (3.44)	14.78 (3.87)	16.78 (4.24)	16.00 (3.07)	17.36 (2.38)
RAT: non-standard score	2.67 (1.22)	2.33 (1.73)	3.00 (1.50)	2.44 (1.42)	2.80 (1.23)	2.18 (1.25)
Insight PS: candle task—solved (unsolved)	6 (3)	8 (1)	7 (2)	8 (1)	9 (2)	10 (1)
Incremental PS: Hanoi task—solved (unsolved)	6 (3)	7 (2)	6 (3)	6 (3)	5 (6)	8 (3)

2.1. Frontal lobe findings

The FL group demonstrated significantly poorer performances relative to their control group (FL-CT) on both the fluency ($p<0.001$) and originality ($p<0.001$) measures of the alternate uses task, as well as the practicality measure of the creative imagery task ($p=0.001$). They also showed a trend to provide an increased proportion of non-standard responses

Table 3 – Presented below is the summary of the findings across all groups and all tasks. The direction of the arrow shows the direction of the effect (downward: patient group exhibit poorer performance than their matched healthy control group, upward: patient group exhibit better performance than their matched healthy control group). The significance level is indicated by the number of arrows (3 arrows: $p<0.01$, 2 arrows: $p\leq0.05$, 1 arrow: $p\leq0.1$). Cohen's f^2 values indicate the effect size associated with each of the hierarchical multiple regression analyses that is attributable to the addition of Group variable to the Model. Effect sizes can be classified as small (0.02), medium (0.15), or large (0.35) in accordance with Cohen (1988). Abbreviations: AUT—alternate uses task, BG—basal ganglia, FL—frontal lobe, EXT—extensive lesions, LAT—lateral lesions, POL—polar and/or orbital lesions, PS—problem solving, PTL—parietal–temporal lesions, RAT—remote associates test.

	FL	FL-EXT	FL-LAT	FL-POL	BG	PTL
AUT: originality	↓↓↓ $f^2=0.22$		↓↓ $f^2=0.44$		↓ $f^2=0.14$	
AUT: fluency	↓↓↓ $f^2=0.25$	↓↓↓ $f^2=0.78$	↓↓↓ $f^2=1.01$			↓ $f^2=0.20$
Conceptual expansion						
Constraints of examples				↑ $f^2=0.18$	↑ $f^2=0.13$	↓↓ $f^2=0.25$
Creative imagery: originality			↓ $f^2=0.22$			
Creative imagery: practicality	↓↓↓ $f^2=0.22$	↓↓ $f^2=0.30$	↓↓ $f^2=0.33$		↓ $f^2=0.10$	↓↓ $f^2=0.37$
RAT: total score						↓ $f^2=0.15$
RAT: non-standard score	↑ $f^2=0.06$					
Insight PS: candle task						
Incremental PS: Hanoi task					↓↓ $f^2=0.16$	

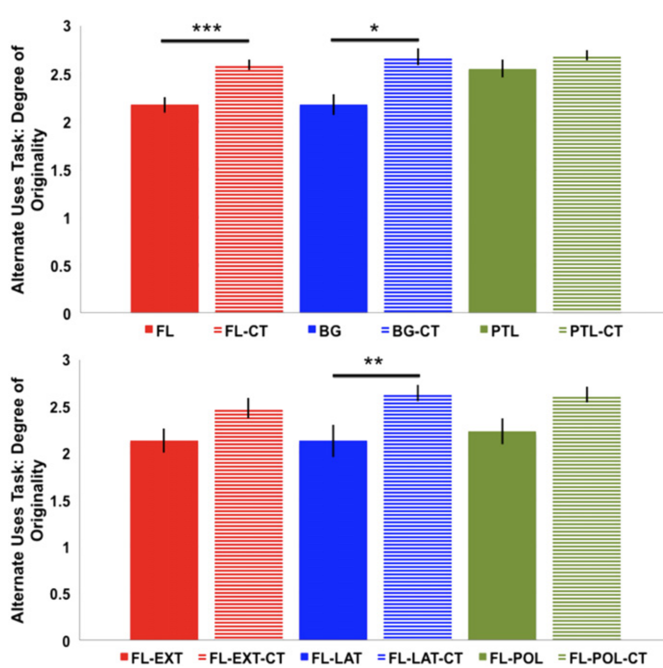

Fig. 2 – Degree of originality (mean and standard error) on the alternate uses task across all clinical and healthy control groups. The significance level is indicated by the number of asterisks (*: $p<0.01$, **: $p\leq0.05$, *: $p\leq0.1$). Significant results were also accompanied by medium to large effect sizes.**

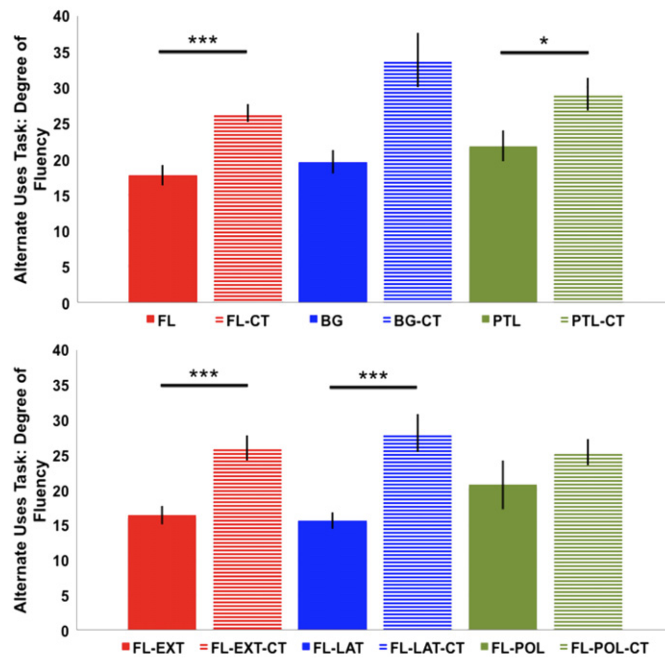

Fig. 3 – Degree of fluency (mean and standard error) on the alternate uses task across all clinical and healthy control groups. The significance level is indicated by the number of asterisks (*: $p<0.01$, **: $p\leq0.05$, *: $p\leq0.1$). Significant results were also accompanied by medium to large effect sizes.**

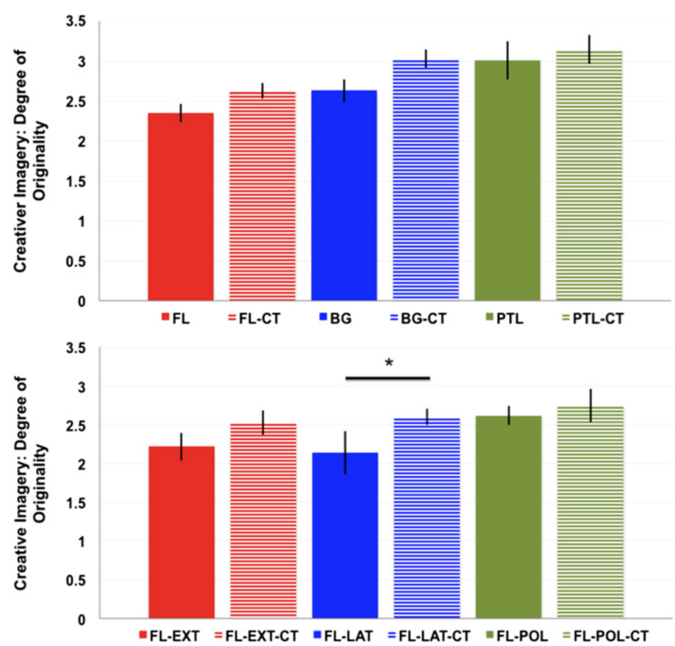

Fig. 4 – Degree of originality (mean and standard error) on the creative imagery task across all clinical and healthy control groups. The significance level is indicated by the number of asterisks (*: $p<0.01$, **: $p\leq0.05$, *: $p\leq0.1$). Significant results were also accompanied by medium to large effect sizes.**

on the RAT ($p=0.086$), but as this result was only accompanied by a small effect size, it will not be discussed further. The FL group showed comparable performance to their control group on the remaining creative cognition measures ($p>0.1$).

2.2. *Frontal lobe subgroup findings*

The frontal lobe subgroup analyses allowed us to determine to what extent findings associated with the FL group as a whole would be also associated with the respective

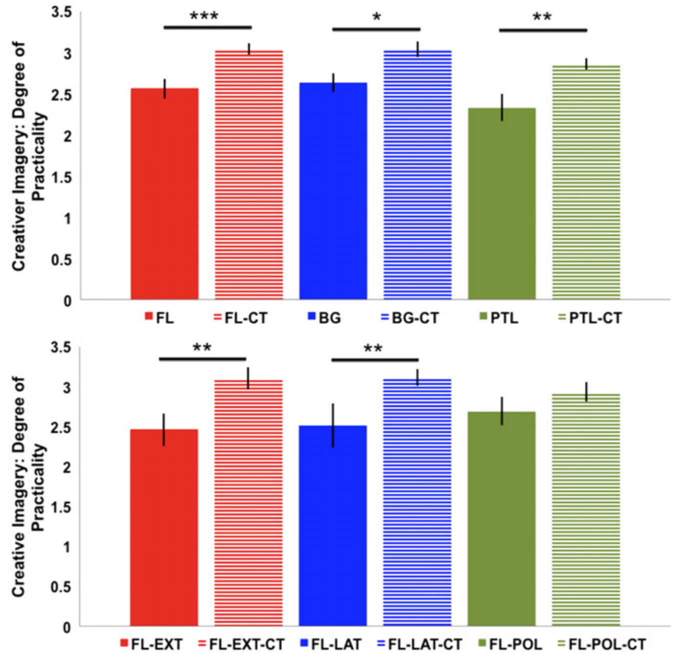

Fig. 5 – Degree of practicality (mean and standard error) on the creative imagery task across all clinical and healthy control groups. The significance level is indicated by the number of asterisks (*: $p<0.01$, **: $p\leq0.05$, *: $p\leq0.1$). Significant results were also accompanied by medium to large effect sizes.**

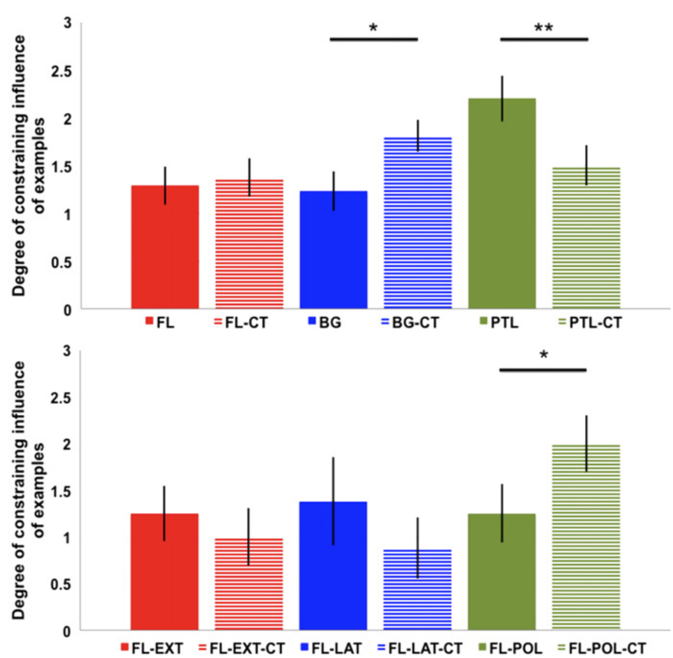

Fig. 6 – Degree of constraining influence of examples (mean and standard error) across all clinical and healthy control groups. Note that a higher score here indicates poorer performance. The significance level is indicated by the number of asterisks (*: $p<0.01$, **: $p\leq0.05$, *: $p\leq0.1$). Significant results were also accompanied by medium to large effect sizes.**

subgroups. The frontolateral group (FL-LAT) was found to most closely match the FL group in terms of the pattern of findings. Just as in the case of the FL-group, the FL-LAT group demonstrates significantly poorer performance relative to their control group (FL-LAT-CT) on both the fluency ($p=0.001$) and originality ($p=0.022$) measures of the alternate uses task, as well as the practicality measure of the creative imagery task ($p=0.042$). Moreover, the FL-LAT group also revealed poorer performance on the originality measure of the creative imagery task ($p=0.092$). The group with extensive lesions to the frontal lobe (FL-EXT), however, performed significantly worse than their control group (FL-EXT-CT) only on the fluency measure of the alternate uses task ($p=0.004$) and the practicality measure of the creative imagery task ($p=0.05$). The frontopolar group (FL-POL) was found to perform comparably to their healthy control group (FL-POL-CT) on all measures ($p>0.1$) except the constraints of examples task ($p=08$), where they demonstrated *better* performance than their control group.

2.3. *Basal ganglia findings*

Like the FL group, the BG group demonstrated poorer performances relative to their control group (BG-CT) on the originality measure of the alternate uses task ($p=0.057$) and the practicality measure of the creative imagery task ($p=0.1$). Unlike the other clinical groups, they additionally demonstrated poorer performance in incremental problem solving ($p=0.037$). While they performed comparably to their control group on all other creative cognition measures, the BG group demonstrated *better* performance than their control group on the constraints of examples task ($p=0.066$). This latter finding was similar to that of the FL-POL group.

2.4. *Parietal–temporal findings*

Like the FL group, the PTL group demonstrated poorer performances relative to their control group (PTL-CT) on the fluency measure of the alternate uses task ($p=0.065$) and the practicality measure of the creative imagery task ($p=0.015$). Unlike the FL group, they additionally demonstrated poorer performance on the constraints of examples task ($p=0.041$) and the RAT total score ($p=0.1$). The PTL group was not associated with better performance than their control group on any creative cognition measure.

3. Discussion

The objective of this exploratory study was to uncover how lesions in different parts of the brain influence specific aspects of creative cognition such as conceptual expansion, originality and practicality in creative imagery, insight and incremental analytical operations during problem solving, and overcoming the constraints of examples (Finke et al., 1996; Ward et al., 1995). Standard creativity tests such as the alternate uses task (originality and fluency measures) (Wallach and Kogan, 1965) and the remote associates test (RAT: Mednick, 1962) were also employed to assess how brain lesions impact originality and fluency in creativity under divergent or open-ended settings (where there are many potential solutions to a problem, such as in the alternate uses task) as well as convergent or non-open-ended settings (where there is only one correct solution to the problem, such as in the RAT).[1]

[1] The divergent-convergent dichotomy referred to in the current study is limited to the context of the number of solutions that are possible in a given experimental setting (divergent-unlimited versus convergent-single). Alternative conceptualizations have been used by other studies to assess the interaction between purportedly divergent and convergent thought processes during creative thinking (e.g., Jaarsveld et al., 2012).

The rationale behind using creative cognition tasks and standard creativity tests is that the focus in the former is on specific mental operations that contribute to generate a creative response whereas the latter focuses primarily on the final assessment of the degree of overall creativity associated with the generated responses or products. The advantage of employing creative cognition tasks is that they allow us to be more specific regarding which operations are affected in relation to a specific population. It is also easier to link the findings associated with the creative cognition tasks together with the literature on normative cognition and brain function. The advantage of using standard creativity tests over creative cognition tasks is that standard tests have been more widely employed in the past, and the findings associated with them are more accessible regarding the global picture associated with creativity. The use of measures from both approaches rendered possible the comprehensive examination of creative operations.

Patients with brain lesions in the frontal lobe, basal ganglia and the parietal–temporal lobe were investigated relative to healthy matched control groups on several creativity measures after taking into account potential differences in relation to IQ. These populations were selected in light of previous investigations that implicated the frontostriatal system in executive and creative cognition (FL, BG) (Abraham et al., 2007; Reverberi et al., 2005; Takeuchi et al., 2010b) as well as the frontal and parietal–temporal regions in creative and semantic cognition (FL, PTL) (Razumnikova, 2007; Schwartz et al., 2011). In addition, subgroups of the frontal lobe group were classified based on the lesion sites within the frontal lobe (EXT—frontal extensive, LAT—frontolateral, POL—frontopolar/orbital) to ascertain the extent to which patterns of findings associated with the frontal lobe group as a whole were generalizable to subgroups with more specific lesions of the frontal lobe. After providing an overview of the general findings, the results associated with the standard creativity tests will be described first followed by those of the creative cognition tasks.

3.1. *General findings across groups and tasks*

All patient groups were found to perform comparably to their respective control groups on the conceptual expansion and the insight problem solving measures. There were no tasks on which every one of the patient groups performed better than their respective control groups. Apart from the frontopolar group (FL-POL), all other patient groups (FL, BG, PTL, FL-LAT, FL-EXT) were similar in that they performed poorly on the practicality component of the creative imagery task by producing inventions that were less functional or relevant compared to their respective healthy control groups. The remaining experimental measures were associated with more selective responses, as detailed below. While all other patient groups were associated with poorer performance on one or more tasks compared to their control group, the frontopolar patients (FL-POL) did not perform significantly worse on any of the creative thinking measures relative to their control group.

3.2. *Alternate uses task: originality and fluency*

While the frontal patients demonstrated poorer performance than their respective controls on both the originality and the fluency measures of the alternate uses task, the parietal–temporal patients showed worse performance only on the fluency measure whereas the basal ganglia patients performed worse only on the originality measure. The former finding fits with literature from neuroimaging studies on verbal fluency where the key influence of frontal and parietal–temporal regions of the brain has been reported (Ostberg et al., 2007; Vitali et al., 2005). With regard to the latter finding, it is important to note that in the alternate uses task, uses are considered to be acceptable only if they are relevant or fitting in a context, so the relevance component of creativity is embedded within the originality measure of this task. The generation of original and fitting responses here requires searching beyond dominant semantic associations by selecting and evaluating novel options with the goal of finding new uses for a specific object. Brain regions involved in cognitive control and executive function, such as frontostriatal regions (Robbins, 2007), would be expected to effectively orchestrate such operations.

It is also noteworthy that among the frontal lobe subgroups, only the frontolateral patients exhibited poorer performance on both the originality and fluency measures of the alternate uses task. The frontal-extensive lesion group only displayed poorer performance on the fluency measure whereas the frontopolar patients showed no insufficiencies relative to their healthy control group. Lateral regions of the frontal lobe have been most strongly implicated in cognitive control (Badre, 2008) which could explain why the frontolateral group performed poorly on both alternate uses measures. The fact that neither extensive lesions of the frontal lobe nor frontopolar/frontoorbital lesions had a significant impact on the originality measure speaks for the selective involvement of specific regions of the frontal lobe in generating original (and fitting) responses as assessed by the alternate uses task.

3.3. *Remote associates task (RAT)*

Performance on the RAT was largely associated with non-significant findings. The only notable finding was that parietal–temporal patients relative to their controls performed poorly on the RAT by generating fewer responses that could be semantically associated with the presented word triads. This is in line with other findings that have indicated verbal and semantic fluency deficits to be commonly associated with this patient group (see above). As a caveat, we would like to point out that while the RAT is among the most widely used creativity tasks in the literature, it is critical to keep in mind that despite that superficial similarity, the German RAT is not comparable to the English RAT in terms of its conceptual foundations. These distinctions (detailed in Section 4), only became apparent during the course of the study. To our knowledge, this issue has never been discussed in the literature. Given that there are other language versions of the RAT in use (e.g., Chermahini and Hommel, 2010) and that it is unclear how comparable the parameters of such translated versions are to the original RAT, it is absolutely essential that such issues are explicitly addressed with future use of this task as they have implications for the interpretations and the accruing conceptual knowledge in relation to this task.

3.4. *Problem solving: insight and incremental*

All patient groups were found to perform in a comparable manner relative to their respective control groups on the insight problem solving task (Duncker Candle Task), which is a task that requires overcoming functional fixedness by engaging in a perspective shift for successful completion. Performance on the incremental problem solving task (Tower of Hanoi) was also largely associated with non-significant findings. Only the basal ganglia patients were found to be less successful than their control group in completing this task. The three-ring version of the Tower of Hanoi requires, as a first step, that the participant overcomes the prepotent or dominant response of moving the topmost ring to the nearest tower. Such an act requires optimal inhibitory control over one's reactions so as to successfully complete the task using the least possible moves. The fact that patients with lesions of the basal ganglia perform worse on this task fits well with the literature on inhibitory control operations, as they are considered a central function of the basal ganglia (e.g., Aron, 2007). Damage to this region is therefore likely to compromise such inhibitory control functions.

3.5. *Creative imagery: originality and practicality*

Barring the frontopolar patients, all other patient groups and subgroups performed significantly worse on the practicality component of the creative imagery task in that they produced inventions that were less functional or relevant compared to their respective healthy control groups. This pattern was, however, not associated with the originality component of the creative imagery task as only the frontolateral subgroup was found to generate significantly less original or unique responses relative to their controls. This finding on a nonverbal index of creativity parallels that of the verbal measure of the alternate uses task where the frontolateral group was also found to display poorer performance on the originality measure. In the context of the creative imagery task, it is important to note that the relevance or appropriateness component of creativity (practicality measure) is considered to be separable from the novelty or unusualness component of creativity (originality measure). The findings therefore indicate that while virtually all the patient groups performed worse than their controls in generating relevant or appropriate responses on this nonverbal creativity task, only the frontolateral group were worse at generating both original and relevant responses.

3.6. *Constraints of examples and conceptual expansion tasks*

All patient groups were found to perform comparably relative to their respective control groups on the conceptual expansion task. A highly interesting pattern of findings, however, was associated with performance on the constraints of examples task. While the parietal–temporal patients were exhibited significantly poorer performance on this task relative to their control group, the basal ganglia patients were found to perform *better* than their control group. In doing so, the basal ganglia patients showed that they were more capable of overcoming the constraints imposed by salient examples when creating something new compared to their matched healthy control participants, whereas the opposite was true of the parietal–temporal patients. So being provided with an active salient context imposed more constraints on the ability to think outside-the-box in the parietal–temporal group. The poor performance by the parietal–temporal patients may be explained by semantic perseverative responses that are associated with this clinical group especially in the presence of semantic distractions (Corbett et al., 2009, 2011). In fact, indirect support for these findings of the parietal–temporal group is provided by a recent structural neuroimaging study which reported that greater cortical thickness in the angular gyrus was associated with better performance across varied tests of creative thinking and achievement (Jung et al., 2010).

Lesions of the basal ganglia, in contrast, appear to confer selective advantages on the constraints of examples task. These results parallel those from a study on ADHD adolescents who also displayed superior performance on the constraints of examples task relative to healthy controls. The better performance on the part of the ADHD patients was attributed to the insufficiencies of the executive function and cognitive control operations that are subserved by the frontostriatal system. Lesions to basal ganglia regions, for instance, are associated with poor inhibitory control, marked inattention and increased distractibility (Aron et al., 2003; Fielding et al., 2006), all of which would be an advantage when performing the constraints of examples task. This is because good performance on this task requires inhibiting relevant and salient information that have been engineered such that a great deal of effort is required to see past that information and optimally complete the task. Being easily distractible enables one to more readily overcome the constraints posed by such salient information as one's attention is constantly being diverted from any particular focus. In fact, even among patients with chronic schizophrenia, a high degree of thought disorder symptoms, which are characterized by disorganization of semantic content of thought, has been associated with better performance on the constraints of examples task (Abraham et al., 2007).

Neither the frontal group nor its subgroups showed insufficiencies in performance on the constraints of examples task. The frontopolar group though, like the basal ganglia group, displayed superior performance on this task relative to their healthy control group. It is possible that damage to parts of the executive and cognitive control networks which are held to be subserved by frontostriatal networks confer selective advantages on this particular facet of creative cognition. Such a rationale would not fully explain why damage to other regions in the frontal lobe were not associated with this information processing advantage, but it may be the case that only certain levels of cognitive control would be expected to abet performance on such a task. The frontopolar regions are a special case in point as this anterior most region of the prefrontal cortex is hypothesized to exert the highest and most abstract levels of cognitive control within the hierachically organized frontal lobes (Badre, 2008; Badre and D'Esposito, 2007, 2009).

Further indirect support for brain regions such as the basal ganglia and frontopolar/orbital structures in creative cognition can be gleaned from a recent structural neuroimaging study (Jung et al., 2010), where indices of white matter integrity in subcortical structures, such as the anterior thalamic radiation, were found to be inversely related to creative performance. The projections of this region fall within the five functionally segregated fronto-striatal-thalamocortical circuits in the brain (Alexander et al., 1991), of which damage to the orbitofrontal circuit is associated with disinhibition (Cummings, 1993). This fits well with the fact that the constraints of examples task provides a unique context in which cognitive disinhibition would confer information processing advantages.

It must be noted though that the finding of better creative performance in the frontopolar group is partially contrary to other work on the neuropsychology of creativity which have shown that lesions to medial prefrontal cortex (which can include frontopolar regions) were associated with poor originality (Shamay-Tsoory et al., 2011). The differing pattern of results may be due to the fact that the lesion extents only partially overlap between the studies. Moreover, Shamay-Tsoory et al. (2011), employed standard creativity tests such as the alternate uses task where only overall creative ability is assessed. Detecting subtle positive biases in select aspects of creative cognition, such as the ability to overcome the constraints posed by salient information, requires the use of tasks that are tailored to assess more specific creative cognitive operations.

The current study is also not the only study to show superior performance on cognitive performance following lesions of the frontal lobe. Reverberi et al. (2005) reported that patients with lesions of the lateral frontal lobe (which can include frontopolar regions) were better able to engage in creative or insight problem solving, as assessed by the matchstick problem, but not incremental problem solving relative to healthy control participants.

3.7. *Integration of the findings*

The approach of the current study, that is investigating multiple neurological groups on tasks involving creative thinking, has rarely been adopted in the past (Reverberi et al., 2005; Shamay-Tsoory et al., 2011). Both the experimental designs and the pattern of reported findings of both studies differ in many ways from those of the present study. One study reported (Shamay-Tsoory et al., 2011), for instance, that the neurological groups with medial prefrontal lesions performed worse than a healthy control group on measures of originality and that there was a negative correlation between extent of lesions in the medial prefrontal cortex and degree of originality. The same pattern was not true of the clinical group with lateral inferior frontal lesions. In contrast, another study (Reverberi et al., 2005) reported that specific advantages in creative operations, such as insight problem solving, accompany lateral frontal lesions, but that no advantages or disadvantages are associated with medial frontal lesions. These results also fit with further findings where lateral lesions of the frontal lobe (but not medial lesions) were found to be accompanied by the production of fewer semantically related words in a verbal fluency task (Reverberi et al., 2006).

It is as yet unclear how to relate these fascinating findings to those of the current study on the different frontal subgroups as we found mostly performance deficits on different facets of creative thinking in the frontolateral group which was in stark contrast to the performance of the frontopolar group. In fact, the frontopolar group even displayed superior performance on one creative cognition measure. The performance of the frontal-extensive group was on average better than that of the frontolateral group but worse than that of the frontopolar group. The link between the extent and/or the specific location of frontal lobe damage and its impact on creative cognition is therefore as yet still unclear. It should be noted that the previously discussed studies (Reverberi et al., 2005; Shamay-Tsoory et al., 2011) differ in several ways from the present study, including the lack of comparability of the lesion sites, the differences in the experimental measures used in the studies, and the dissimilarity in the statistical analyses of the data. Such differences render it difficult to bring together the findings from all three studies in terms of underlying brain function. Further research is imperative in order to clarify the specific roles played by the frontal lobe in creative cognition. This would complement the burgeoning neuroimaging and electrophysiological work on creativity that have consistently implicated the importance of the frontal lobe in creative thinking (Dietrich and Kanso, 2010).

While neuroimaging studies have implicated a central role for several regions of the frontal lobe in creative thinking including frontolateral, frontopolar and frontoorbital regions (e.g., Abraham et al., 2012; Carlsson et al., 2000; Ellamil et al., 2011; Goel and Vartanian, 2005; Howard-Jones et al., 2005; Jung et al., 2010; Kröger et al., 2012; Rutter et al., 2012; Takeuchi et al., 2010a, 2010b), some have also pointed to the involvement of parietal–temporal regions in creative thinking (e.g., Chávez-Eakle et al., 2007; Ellamil et al., 2011; Jung et al., 2010; Takeuchi et al., 2010b). Just as in the current study, Shamay-Tsoory et al. (2011) also assessed creative function in patients with lesions of the parietal–temporal cortex. Although they reported a positive correlation between the extent of lesions in the parietal–temporal cortex and the degree of originality associated within that clinical group, they did not find any overall differences in the performances of the parietal–temporal lesion group compared to a healthy control group (for opposing findings, see Jung et al., 2010). Their findings are partly at odds with the results of the current study where the parietal–temporal group was found to show no advantages in any aspect of creative cognition but instead revealed either insufficiencies or comparable performance relative to a matched healthy control group on different facets of creative cognition. The poor performance associated with the parietal–temporal group was interpreted with reference to the insufficiencies of the semantic cognition system that are associated with this brain region.

While neocortical regions of the brain have long been the chief focus of creativity research, the same cannot be said about subcortical regions such as the basal ganglia. The current study is the first to investigate the impact of lesions of the basal ganglia on creative thinking. However, several behavioral and neuroimaging researchers of individual differences in creativity have highlighted the indirect link between creative thinking and cognitive functions that are central to the basal ganglia in the frontostriatal system, such as cognitive inhibition (Carson et al., 2003; Flaherty, 2005; Storm and Angello, 2010). Structural neuroimaging studies indicate, for instance, that higher levels of creative function are associated with greater gray and white matter volume in regions such as the basal ganglia (Takeuchi et al., 2010a, 2010b) (for opposing findings, see Jung et al., 2010), whereas the behavioral studies have shown that decreased cognitive inhibition is associated with greater levels of creative ability (Carson et al., 2003).

The idea that mild insufficiencies at the level of attentional and inhibitory control can confer advantages in the ability to think creatively is one of the classical hypotheses in the literature (Dykes and McGhie, 1976) that has been frequently extended as a rationale to explain the link between mental illness and creativity (Carson, 2011; Eysenck, 1995). The current finding that basal ganglia patients showed a selective positive information processing bias such that they were less constrained by salient examples when engaging in creative thinking relative to healthy controls constitutes indirect support of this idea. It is important to note though that this information processing advantage was very specific in that it was not associated with any other aspect of creative thinking that was investigated nor with creativity in general. In fact, there were other facets of creative cognition (e.g., originality on the alternate uses task) in which the basal ganglia patients showed poorer performance. The divergence in the findings (poorer versus better creative ability) that are either directly or indirectly associated with this structure in relation to creative thinking may be explained by the use of different creativity measures across investigations. The tasks after all differ in terms of the underlying cognitive operations that they assess. It is also important to note that these findings clearly indicate the necessity to assess creativity in terms of its underlying cognitive operations because, by not doing so, we stand to miss the larger picture regarding creativity in relation to brain function and dysfunction.

3.8. *Caveats and conclusions*

The impact of damage to different regions of the brain on creative thinking was investigated in the current study. To this end, patients with lesions in frontal, parietal–temporal and basal ganglia lesions were tested on various measures of creative cognition as well as standard tests of creative thinking. The overall pattern of findings argues strongly against the idea that generally poor performance in creative thinking can be expected across clinical groups as a whole. The only generalization that appears to be true of most of the patient groups is that damage to the brain has a negative effect on one's ability to generate responses that are considered to be fitting, relevant or appropriate in a given context. The same generalizations of the impact of brain damage, however, cannot be made in relation to the originality or uniqueness or novelty of the generated responses.

In fact, the dissociations between the performances of the clinical groups on multiple measures reveal both the specificity of the presence and extent of altered creative function across patient groups. All findings were explored in relation to the cognitive profile most widely associated with each of the patient groups. A larger sample size as well as more circumscribed and homogenous lesions within each clinical group would have rendered a more optimal experimental design possible and these, as such, are the chief limitations of the current study. In fact, the disadvantages that typify lesion studies also apply in the case of the current study, such as low spatial resolution and overgeneralizations in region classification. In addition, some relevant clinical information, such as handedness data, was lacking. On the other hand, the strengths of the study include that the statistical analyses involved the use of rigorous multiple regression procedures in order to determine the significance of the effects after taking IQ differences into account. Effect sizes were also estimated to ensure the validity of the findings.

The present study was exploratory and is the first of its kind in terms of the comprehensive manner in which creative cognition has been assessed from a neuropsychological perspective. As mentioned in Section 1, the focus of most neuropsychological and neuroimaging investigations of creativity is to explore the issue of hemispheric specialization in creative thinking. We applied a different approach in the current study in that we sought to understand the impact of differing types of brain damage on diverse creative operations. We believe that adopting such an approach is a crucial step forward if the overarching aim in the field is to uncover the neurocognitive mechanisms underlying creativity. The dissociations between the findings associated with the clinical groups point to the selective involvement of specific brain regions in diverse aspects of creative cognition. Each of the clinical groups demonstrated a distinctive pattern of poorer, unimpaired and/or better performance relative to healthy matched control participants. This indicates that it is necessary to consider creative thinking as a multi-componential, as opposed to a unitary, construct with reference to brain function.

Further research will be necessary to explore the ramifications of the many findings explored in the current study. One avenue to explore would be the degree to which performance on semantic and executive function variables predict performance on varied creativity measures in different clinical groups. Such endeavors would allow us, not only to get closer to understanding the neurocognitive basis of creativity, but also attain a more complete picture concerning the consequences of brain damage on higher-order cognitive functions.

4. Experimental procedure

4.1. *Participants*

Seventy four patients who were native German speakers were initially recruited for the study from the Neurological Day Clinic database of the University of Leipzig in Germany. Only participants who did not suffer from severe visual, language or motor deficits, as determined by standard neuropsychological screenings at the Day Clinic, were eligible for recruitment. All patients were examined neurologically by the clinic's chief neurologist prior to the study. Lesion sites were determined by (T1- and T2-weighted) anatomical MRI datasets from a 3.0 T system (Bruker 30/100 Medspec) and evaluated by the clinic's chief neurologist and an experienced neuroanatomist. Fig. 1 displays the lesion sites of all the clinical groups. Exclusion criteria included the presence of large lesions in brain regions beyond the areas of interest, use of medication as well as a history of developmental or psychiatric problems. Based on screening and imaging data from the examinations, suitable candidates were identified and contacted. The criterion for time point of testing was at least six months following trauma or surgery. Each participant was assessed individually in a single session. All subjects gave written informed consent and received 7 Euros per hour for participating in the experiment. The study protocols were ethically approved by the Max Planck Institute for Human Cognitive and Brain Sciences Review Board.

After controlling for premorbid IQ, which was assessed using the German version (Lehrl, 2005) of the National Adult Reading Test (NART: Nelson, 1982), the final neurological samples (inclusion in the sample only if NART $IQ>85$) included patients with lesions of the frontal lobe (FL: $n=29$; 9 female: 20 male; education level in years: $mean=11.50$, $SD=1.64$, time since lesion in years: $mean=5.38$, $SD=2.83$), the parietal–temporal lobe (PTL: $n=11$; 1 female: 10 male; education level: $mean=11.79$, $SD=1.85$, time since lesion in years: $mean=5.64$, $SD=2.16$), and the basal ganglia (BG: $n=16$; 4 female: 12 male; education level: $mean=11.71$, $SD=1.4$, time since lesion in years: $mean=8.0$, $SD=2.64$).

The patients were classified into groups (Damasio, 2001) according to site and extent of lesions. Details concerning each patient's lesion sites and etiology are presented in Table S1 (Supplementary material). The FL group was classified as such if the major lesion site was located anywhere in the frontal lobe. Patients were classified in the BG group if the major lesion site was located in the caudate nucleus, putamen, or globus pallidus. Lesions in the angular, supramarginal or posterior superior temporal gyri resulted in a PTL group classification.

The FL group was further divided into 3 subgroups depending on the location of their lesions. The FL-EXT group ($n=9$) had extensive lesions in several parts of the frontal lobe (lateral frontal, medial frontal, frontopolar, orbital regions), whereas the FL-LAT group ($n=9$) had lesions primarily in frontolateral regions (superior, middle and inferior frontal regions), and the FL-POL group ($n=11$) had lesions primarily in frontopolar and frontoorbital regions. There were no significant differences between the frontal subgroups in terms of the time since lesion.

Healthy control participants (CT) were selected to match each patient on the criteria of age (maximum difference of 2 years), gender (perfect match) and education level (perfect match). Statistical analyses revealed that age differences between each patient and control group (FL versus FL-CT, BG versus BG-CT, PTL versus PTL-CT) were non-significant (all $p>0.1$).

4.2. *Materials*

The experimental tasks used within the study were all paper-and-pencil tasks and included the conceptual expansion task, the creative imagery task, the constraints of examples task, the alternate uses task, and analytical problem solving tasks (insight and incremental) (for an overview, see Abraham and Windmann, 2007). In all applicable cases, scorers were blind to the hypotheses and the nature of the study.

4.2.1. *Alternate uses task*

In this task (adapted from Wallach and Kogan, 1965), participants are asked to generate as many uses as possible for five common objects: a newspaper, a shoe, a brick, a paperclip, and a knife. The subjects' responses are assessed on the basis of two dimensions—fluency, which is judged by the number of acceptable solutions generated for each object, and originality, which is assessed by the infrequency or unusualness of the generated uses within the sample (Abraham and Windmann, 2007). The fluency score reflects the average number of responses generated for the five objects and the originality score reflects the average proportion of unusual responses generated for the five objects.

4.2.2. *Remote associates test*

The German version of the Remote Associates Test (RAT) (Bolte et al., 2003) was employed where 23 unrelated word triads were presented to participants and their task involved determining which fourth word is associated with all three words in the triad. Although this issue has never been broached as such in the literature, we discovered rather critically that the German version of the RAT is not entirely comparable to either of the English versions. In the compound version of the English RAT (Bowden and Jung-Beeman, 2003b), the fourth word (e.g., stone) to be linked with the 3 words in the word-triad (age/mile/sand) forms a compound word or phrase with each of the words (stone age, milestone, sandstone), whereas in the original version of the English RAT (Mednick, 1962), the words could also be linked by synonymy and semantic association. In both English versions of the RAT though, there is *only* a single correct solution to each word-triad problem. In the German RAT, in contrast, the associative predominance of the fourth word with the three words in a problem triad is not very high and this often results in there being more than one possible solution to each problem. As no norm data was provided in the original study (Bolte et al., 2003)[2] which indicated under what criteria the single solution reported for each problem was deemed to be the best solution, we carried out a pilot-norm study (unpublished data) with 22 participants on the German RAT where they were instructed to think of as many solutions as they could for each problem triad. The proportion of participants who picked the predetermined correct solution (as specified by Bolte et al., 2003) for each problem triad was found to greatly vary from trial to trial (4–22). We therefore decided to accept any word as a correct solution if it was clearly semantically related to all the three words of each problem triad in the current study. The reported measures from the German RAT include the total score, which is the sum of correctly solved word triads, and the sum of non-standard responses, which is the sum of solutions that were different from standard responses (generated by less than 2 people in the pilot-norm study).

[2] There was no reply to an email inquiry regarding the same.

4.2.3. *Problem solving (insight and incremental)*

The classic Duncker Candle Task was employed as the insight analytical problem solving task whereas the Tower of Hanoi Task (3-rings version) was employed as the comparison incremental analytical problem solving task (Karimi et al., 2007; Weisberg, 1995). In the Duncker Candle Task, participants are instructed to think of a solution that allows one to fix a candle to the wall using only the materials provided (candles, matchbox, nail tacks). For the Tower of Hanoi task, participants are instructed to find the fastest way to move the rings from the first tower to the third tower with as few moves (solution: 7 moves) as possible and keeping certain rules in mind. Each of the problems was scored as 1 or 0 depending on whether it was successfully solved or not.

4.2.4. *Creative imagery task*

In this task (adapted from Finke, 1990), participants are required to assemble an object that falls into a predetermined category using three figures from an array of 15 simple three-dimensional figures. Except for altering the form of the figures, the participants were allowed to vary the figures provided to them in any way with regard to size, orientation, position, texture, and so on. There were a total of five trials in which the subjects were presented with the same combination of figures and categories across trials (furniture: sphere/hook/tube, tools or utensils: cone/flat square/wheels, toys or games: cylinder/bracket/handle, weapons: half-sphere/rectangular block/ring, transportation: cube/wire/cross). Using a 5-point scale, the invented objects were rated by two trained raters along two dimensions: originality (how unusual or unique the invention is) and practicality (how functional or usable the invention is). The inter-rater correlations (Pearson's correlation coefficient) were highly significant for both the originality ($r=0.49$, $p<0.001$), and practicality ($r=0.41$, $p<0.001$) scales. The average of the ratings was taken as the scores for the inventions. Each participant therefore obtained an average score of originality and practicality from the five inventions they generated across trials.

4.2.5. *Conceptual expansion task*

In this task (adapted from Ward, 1994), participants are required to imagine and draw animals that lived on another planet that is very different from Earth. Each drawing was subsequently coded in accordance with the procedures described by Ward (1994) and Abraham and Windmann (2007) with the help of two independent scorers who had to note the presence or absence of the following features: bilateral symmetry of form, appendages (legs, arms, wings, tail), sense organs (eyes, mouth, nose, ears), atypical appendages, and atypical sense organs. A coding was deemed valid when both scorers were in agreement. In the occasional situation when both of the scorers were not in agreement (less than 1% of all observations), a third scorer was consulted and the majority result accepted. The coded data yielded five elements of conceptual expansion, namely (i) bilateral asymmetry, (ii) lack of appendages, (iii) lack of sense organs, (iv) unusual appendages, and (v) unusual sense organs. The presence of an element gave rise to a score of 1 or 0. In the case of elements (ii) and (iii), only a complete absence of all customary appendages and sense organs would be scored as lack of appendages or a lack of sense organs. The total expansion score for a drawing thus ranged from 0 to 5. The higher the score, the greater the degree of creative conceptual expansion.

4.2.6. Constraints of examples task

In this task (adapted from Smith et al., 1993), subjects are asked to imagine that they are employed by a toy company that is looking for new ideas for toys. The task was to imagine and draw this new toy. Duplication of toys that currently exist or previously existed was not allowed. Prior to the drawing of the toys, the subject is exposed to exemplars of three examples of toys that have three fundamental elements in common: the presence of a ball, the presence of high physical activity, and the presence of electronics. The subjects' drawings are thus assessed on the extent to which they include these three fundamental features of the examples. Two independent scorers noted whether the subjects' drawings contained any of these three elements. There was complete agreement between both scorers on all counts. The total score on this task ranged from 0 (none of the three common elements of the toy examples were present in the subject's drawing) to 3 (all three elements of the toy examples were present). The greater the constraining effect of the examples, the greater the degree of similarity of the toy generated by the subject to that of the previously presented toy examples. A higher score therefore reflects a poorer ability in overcoming the constraining influence of examples.

4.3. Statistical analyses of data

To rule out the possibility that the differing IQ-levels between the groups explained the differences between the groups on the creativity measures, hierarchical regression analyses were carried out for all comparisons between every clinical group and their respective control groups. In this procedure, a first regression analysis (Model 1) is carried out in which one creative cognition variable (e.g., Alternate Uses: Originality) is entered as the dependent variable and the IQ score is entered as the independent variable. A second regression analysis is then computed (Model 2) with the same dependent variable, with the experimental group (e.g., BG versus BG-CT) added as an independent variable alongside the IQ score. The difference in the R-square values between these two equations is then computed. If the difference is found to be significant, the result signifies that group status significantly explains individual differences in creative cognition even after variations in IQ are taken into consideration. Findings were only treated as consequential if they were accompanied by medium to high effect size AND were significant at the standard level ($p<0.05$) or suggested the presence of a meaningful trend ($p<0.1$). Effect sizes (Cohen's f^2 for multiple regression) are customarily classified as small (0.02), medium (0.15), or large (0.35) (Cohen, 1988).

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.brainres.2012.09.007.

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