Neuropsychologia 48 (2010) 1923–1929

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

Figurative language processing after traumatic brain injury in adults: A preliminary study

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ARTICLE INFO

Article history:
Received 16 April 2009
Received in revised form 5 March 2010
Accepted 9 March 2010
Available online 15 March 2010

Keywords:
Semantic
Memory
Control
Prefrontal cortex
Left inferior frontal gyrus
Abstraction
Traumatic brain injury
Metaphor
Figurative
Language
fMRI

ABSTRACT

Figurative speech (e.g., proverb, irony, metaphor, and idiom) has been reported to be particularly sensitive to measurement of abstract thinking in patients who suffer from impaired abstraction and language abilities. Metaphor processing was investigated with fMRI in adults with moderate to severe post-acute traumatic brain injury (TBI) and healthy age-matched controls using a valence-judgment task. We hypothesized that TBI patients would display decreased activation of the left inferior frontal gyrus (LIFG), which is considered central to semantic memory retrieval and abstract thought, in comparison with healthy controls. We also predicted that decreased activation in TBI individuals would correlate with their behavioral response times. A whole-brain analysis across the two participant groups revealed that patients did not strongly engage frontal and temporal regions related to semantic processing for novel metaphor comprehension, whereas control participants exhibited more intensive and concentrated activation within frontal and temporal areas. A region of interest (ROI) analysis verified that the LIFG was underactivated in TBI patients compared to controls across all conditions. TBI patients' impaired abstraction of novel stimuli may stem from reduced prefrontal control of semantic memory as well as disrupted interconnectivity of prefrontal cortex with other regions.

1. Introduction

Adults who have sustained traumatic brain injuries (TBI) may experience deficits in higher order cognitive abilities including language comprehension and inferencing. Prior research has proposed that the linguistic competence of TBI patients is affected by levels of cognitive functioning and that the impairment in understanding and use of figurative language is indicative of deficits in overall cognitive functions (Wigg, Alexander, & Secord, 1988). Impairment in figurative language comprehension has been considered to result from problems in conceptual integration and abstract thought (Groher, 1983; Hagen, 1984; Levin, Benton, & Grossman, 1982). Abstract thinking commonly refers to the representation and synthesis of stimuli to deal with abstract concepts. These prior studies used several types of figurative language (e.g., proverb, irony, metaphor, and idiom) to measure patients' ability to understand abstract thought. In this case abstract thought refers to the ability to detect that the literal interpretation of language is less appropriate than a symbolic interpretation which typically invokes similarities between prior situations and the current situation. Intact figurative language comprehension reflects the ability to detect a higher order meaning in language and judge this meaning to be more informative than a narrower literal interpretation. A typical example of a metaphor is "She is a peach". A person with intact abstract thought would be able to detect the similar "sweet" property of the fruit and an agreeable personality and infer that the referred female is a person with an agreeable quality in interpreting this sentence. Understanding pragmatic meanings as figurative language has been suggested to be a particularly sensitive measurement of abstract thinking in both children with language and learning disabilities (LLD) and patients with TBI (Blue, 1981; Donahue & Bryant, 1984; Elmore & Gorham, 1957; Wig & Semel, 1984; Winner & Gardner, 1977; Winner et al., 1980). Although there is a growing body of literature on linguistic deficits, including figurative language, found in populations who have suffered TBI, no previous studies have employed functional neuroimaging techniques in order to investigate the involvement of brain regions that subserve metaphor comprehension in TBI populations. Therefore, no research to date has examined the possible neural deficits associated with abstract thinking after TBI.

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doi:10.1016/j.neuropsychologia.2010.03.011

Two theories have been proposed to understand language and communication deficits after TBI. An early theory focused on whether observed language impairments were categorical deficits or the result of a global disorganization process. Support for a categorical linguistic deficit came initially from research that reported that language impairments following TBI resembled Wernicke's aphasia (Heilman, Safron, & Geschwind, 1971). An increasing amount of research emerged in support of the global disorganization theory in the 1980s. Several studies suggested that language after TBI was disrupted in qualitatively different ways from left hemisphere cerebral vascular accident aphasia (Hagen, 1984; Holland, 1982). Holland (1982) observed that TBI patients talk better than they communicate, which suggests that their problem lies in pragmatics rather than speech production. Hagen (1984) reported that TBI language impairments are often found in language organization rather than the linguistic dataset. Hagen also observed that abstract thought and conceptual integration were impaired after TBI and consequently affected language formulation. He concluded that the language disorganization results from the global breakdown of the ability to structure mental processes and to shift cognitive sets. This line of research influenced the direction of research, assessment, and rehabilitation of TBI patients. A common consensus formed suggesting that cognitive dysfunction affects patients' linguistic performance and cognitive function levels can be assessed by performance on measures of metalinguistic and metacognitive measures. Wiig, Alexander, and Secord (1988) used the Test of Language Competence (TLC) that they developed for assessing language and learning disabilities in adolescents to study TBI patients' impairments. A subtest of TLC specifically tests interpretation and matching metaphoric expressions, planning for and recreating speech acts and interpreting sentence ambiguities. Since then, studies have identified metaphoric comprehension as a special domain of impairment for TBI patients and as a particularly sensitive measurement of abstract thinking in patients (Towne & Entwisle, 1993; Wig & Semel, 1984).

The current research tests two hypotheses. First, metaphor processing is affected by deficits in abstract thought, which is part of the disorganization process. By abstract thought we refer to the executive control processes necessary to detect multiple possible semantic interpretations of a linguistic statement and the ability to override a literal meaning in favor of a broader symbolic meaning that typically conveys greater information about the subject of the statement. Our second hypothesis is that abnormal neural activation in TBI patients in response to metaphors, both at global and local regions, will be correlated with impairment in abstract thought. Investigation of differences in patterns of activation within TBI patients may help us to identify the neural contributions to the observed deficits in abstract thinking and also allow us to better understand the regional contributions to semantic memory control by areas typically involved in language processing. For instance, several neuroimaging studies have investigated the links between language comprehension and semantic memory leading to the proposal of specialized roles for the frontal and temporal cortices in these processes (Bedny, McGill, & Thompson-Schill, 2008; Thompson-Schill & Gabrieli, 1999). For language processing, semantic memory retrieval relies heavily upon the temporal cortices (Neary, Snowden, Northen, & Goulding, 1988), while the left inferior frontal gyrus (LIFG) is considered to be important in the selection of appropriate interpretations when contextual information is not sufficient (Badre & Wagner, 2007; Duncan & Owen, 2000; Fiez, Petersen, Cheney, & Raichle, 1992; Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997).

Several prior fMRI studies have reported increased activity in the LIFG (Mashal, Faust, Hendler, & Jung-Beeman, 2007; Stringaris, Medford, Giampetro, Brammer, & David, 2007) when subjects read novel metaphors (e.g., She is a strawberry) in contrast to literal sentences (e.g., She is a liar) or conventional metaphors (e.g., She is a peach). This suggests that additional semantic processing capacities are required in the novel metaphor comprehension relative to the comprehension of familiar expressions such as literal statements and conventional metaphors. Since inferring the meaning of metaphors is a sensitive measure of patients' abstract thinking (Wigg et al., 1988), activations in LIFG are likely to reflect the synthesis of abstract concepts in addition to selection of context-appropriate semantic representation.

The purpose of the present study is to identify brain regions involved in impaired abstraction abilities through investigation of neural activation during figurative language processing in TBI patients compared to healthy controls. We use a valence-judgment task similar to that used in several prior fMRI studies on comprehension of metaphors in healthy individuals (Mashal et al., 2007; Rapp, Leube, Erb, Grodd, & Kircher, 2004; Stringaris et al., 2007). Valence-judgment tasks require a determination of the positive or negative values of sentences. According to previous studies, the valence task is able to evoke active processing of metaphors in contrast to passive reading. Using a valence task, we predict that TBI individuals in the current study will show a behavioral deficit in abstract thinking revealed by differential performance in novel metaphor comprehension. In addition, we predict that TBI patients' difference in neural activity will be manifested in less intensive activations in multiple regions globally and specifically in the LIFG compared to healthy controls. We predicted less LIFG activation in patients due to their potentially disrupted connectivity of the prefrontal cortex (PFC) with other regions through white matter injuries. We will also investigate whether additional language regions such as areas within the temporal cortex display significant differences in activations using whole-brain analyses. If reductions in activation are observed in the PFC only, this would likely reflect a compromised executive control function as primarily responsible for language deficits. By contrast, reductions of activation in the temporal region, would suggest that language deficits may be more associated with the loss of semantic knowledge. If both PFC and temporal lobes reveal abnormal activation, it would suggest that patients suffer from a complex impairment of the semantic memory system that includes contributions from both semantic networks of the temporal lobes and frontally mediated executive function abilities such as selection, and retrieval of knowledge that underlie abstract thought.

2. Method

2.1. Participants

Twelve right handed TBI patients with age-matched thirteen healthy controls, all native English speakers, participated in the study. Mean age of patients was 30.9 (SD: 10.51, range: 21–49) years and mean age of healthy controls was 27.6 (SD: 7.05, range: 25–48). The patients were at least 2 years post-trauma and were not in intensive care. They were able to read and speak and received an average of 14 years of education (SD: 3.4, range: 12–18). The patients were assessed in terms of their levels of functioning in physical social and psychological domains using structured interviews of Glasgow Outcome Scale-Extended (GOS-E; Wilson, Pettigrew, & Teasdale, 1998) and Functional Status Examination (FSE, Dikmen, Machamer, Miller, Doctor, & Temkin, 2001). Both are measures designed to evaluate change in activities of everyday life as a function of an event or illness. The causes of injuries included car accidents, bicycle accidents, and being the victim of assault. Structural images (T1-weighted MRI, T2-weighted MRI, and Diffusion Tensor Imaging (DTI)) were acquired in this study. All patients sustained diffused axonal injuries marked by their DTI images showing shorter white matter fiber length, reduced fiber counts, reduced fiber density, as well as reduced functional anisotropy (FA), a measure of direction of water movement in white matter tracts, compared with healthy controls. The demographic details of the TBI patients are presented in Table 1. Typical Exclusion criteria for fMRI were applied. Subjects with past or present medical or psychiatric illness and impaired language skills were excluded. The study was approved by the internal review boards at the University of Texas Southwestern Medical Center and the University of Texas at Dallas. After a complete description of the study, subjects gave their informed consent.

Table 1
Patient demographics.

Patients	($n=12$) Mean
Age	30.9
Gender (% male)	75
Education (years)	14
Functionality	
FSE	26.08
GOS-E	5.67

Note: FSE: Functional Status Examination, GOS-E: Glasgow Outcome Scale-Extended.
The FSE measures outcome in 10 domains, including personal care, ambulation, work or school activities, and so on. Outcome for each category is rated along a four-point scale with lower scores associated with better outcome. A rating of "zero" signifies no change from pre-injury; and "three" means that the individual is completely dependent upon others or that the individual does not perform that activity at all. Ratings from each domain are summed to give an FSE total score of 0–30. The mean FSE of patients in the present study is 26.08. This suggests that patients depend on others to perform the activities in most domains. The GOS-E employs an eight-point ordinal scale with higher scores associated with better outcome. The mean GOS-E of patients enrolled in the study is 5.67, which suggests that they are moderately disabled on average.

2.2. Experimental stimuli

A set of 230 short English sentences were initially created *de novo* for the experiment. Sentence pairs differed only in the final one, two, or three words. Sentence pairs were created for three conditions: Literal sentences (LIT), conventional metaphors (CON), and novel metaphors (NOV). For example, the sentence for the LIT condition was, "She is a liar", for the CON condition, "She is a peach", and for the NOV condition, "She is a strawberry". We controlled all stimulus sentences to be simple statements of the form "X is a Y" in order to exclude possible confounding factors such as complex syntax processing.

Prior to the study, 22 healthy young subjects, who did not take part in the fMRI experiment, rated each sentence on a 7 point familiarity scale (1 completely unfamiliar; 7 very familiar), and a similar imageability scale (1 least imageable; 7 highly imageable) and judged if the sentences had valence values. Thirty sentences were discarded because they were regarded to be uninterpretable and without obvious valence values by at least 90% of the raters. From the remaining 200 sentences, 100 sentences were taken for an imageability experiment for use in a separate study (Yang, Edens, Simpson, & Krawczyk, 2009). From the pool of 100 sentences, 72 sentences (24 for each condition) were chosen as stimuli for the valence-judgment task for the current fMRI experiment. 63 sentences (21 for each condition) controlled for imageability were chosen for analysis. The numbers of positive- and negative-valenced sentences were approximately the same for all conditions. The number of highly imageable and non-imageable sentences was also equal across all conditions. All 63 stimuli analyzed in this experiment were rated as being greater than four in imageability (NOV mean = 5.35, SD = 0.27, CON mean = 5.38, SD = 0.20, LIT mean = 5.34, SD = 0.16). The mean imageability values of the three conditions were not significantly different from each other ($F(2,63) = 0.22$, $p > 0.05$). In terms of the estimated familiarity, LIT and CON were rated as the most familiar, whereas NOV was rated the least familiar (NOV mean = 3.2, SD = 1.99, CON mean = 5.83, SD = 1.75, LIT mean = 5.55, SD = 1.71). NOV was significantly less familiar than CON ($F(1,42) = 21.669$, $p < 0.001$) and than LIT ($F(1,42) = 17.648$, $p < 0.001$). The cutoff point for novelty was 3.5 on the familiarity scale. All stimuli were matched for tense, number of words, word frequency of the last 3 words and positive connotation.

2.3. Task and procedure

Subjects were given instructions and practice trials on the two tasks prior to performing the fMRI task. During the valence task, subjects were asked to read each presented sentence silently and decide as fast and as accurately as possible whether this item had a positive meaning or negative meaning, indicating their decision by pressing one of three buttons. Subjects were advised to try their best to make sense of novel sentences and assign values to them even though these sentences might seem unusual to them. Complete Sentences were visually presented via a mirror mounted above the head coil within the scanner. We used a block design. Each sentence was presented on one line in silver-white letters against a black background. The task was presented in 6 blocks with each block containing 12 stimuli of one condition (LIT, CON or NOV). Sentences were presented for a fixed duration of 6 s. The number of positive-valenced and negative-valenced sentences was balanced in all conditions. Each condition had an equal number of high- and low-imageability sentences. Intervals between stimuli were jittered between 4 and 8 s around an average inter-stimulus interval of 6 s to increase trial variance and avoid concealment of signal information due to overlap of the hemodynamic response. During the inter-stimulus intervals, a fixation cross was displayed on the screen. Subjects' responses and RTs were recorded with Eprime software (www.pstnet.com/e-prime/).

2.4. Analysis of behavioral data

Behavioral data collected during scans were averaged across each condition. Results across the three conditions were compared using ANOVA. We also compared each condition across the patient and control groups in order to investigate the performance differences in the two participant groups.

2.5. Image acquisition

Imaging was performed on a 3-T Scanner (Philips MR systems Achieva Release 2.5.3.0). Functional images were acquired with an echo-planar image sequence sensitive to BOLD-contrast (TE 30 ms, TR 2 s, α flip angle 70°). The volume covered the whole brain with a 64×64 matrix and 36 transverse slices (4 mm thickness with a 0 mm inter-slice gap); (voxel size 3.44 mm × 3.44 mm × 4 mm). Two runs consisting of 160 volumes were acquired during the experiment. Structural images of individual subjects were acquired and serve as template images onto which the functional data were mapped. The structural scans include a T1-weighted Spin Echo image sequence with 36 transverse slices and a Magnetization Prepared Rapid Access Gradient Echo image sequence with 160 sagittal slices.

2.6. Imaging data analysis

Data analysis was performed with SPM 5 (www.fil.ion.ucl.ac.uk/spm/). The functional images of each subject were corrected for motion and realigned in the first stage of data analysis. T1 anatomical images were co-registered to the mean of the functional scans and normalized to the SPM T1 template in the MNI space. The same transformation was applied to normalize the functional data. Finally, the functional images were smoothed. Model time courses were calculated by defining stimulus onset asynchrony from the protocol using a function convolved with the canonical SPM hemodynamic response function (HRF) to specify the design matrix. Condition and subject effects were estimated according to the general linear model at each voxel. Significant signal changes for each subject and condition were assessed using *t*-statistics uncorrected ($p = 0.001$). A group map for the patients was generated based on the results of the 12 subjects and a group map for the 13 healthy controls was also generated. In order to avoid a possible imageability confound, we analyzed only 63 stimuli (21 for each condition) that have similar imageability ratings.

2.7. Region of interest analysis

A functional region of interest (fROI) in the left inferior frontal gyrus was drawn for each individual subject. We first located the Talaraich coordinates representing the peak voxel activation (based on each subject's local maxima) of the activated voxel cluster in the LIFG. We created a mask using the coordinates as the center of a 5 mm sphere. The ROI we chose within the LIFG consisted of the pars triangularis portion and this portion was consistently the location of the local maxima across all subjects. We extracted the β values (regression co-efficient values) for each condition. This procedure was repeated for each subject. We compared the mean ROI β value of the TBI patients with that of the healthy controls.

Table 2
ANOVA of reaction time and percent accuracy for all conditions between TBI and control groups.

	Control		TBI		$F(1, 23)$	p
	Mean	SD	Mean	SD		
Reaction time (RT)						
RT literal	1867.8	396.6	2509.1	649.3	9.046	0.006*
RT conventional	2059.9	372.4	2565.4	527.5	7.762	0.011*
RT novel	2414.5	465.5	2957.4	554.5	7.071	0.014*
Percent accurate (AC)						
AC literal	89.8	6.9	82.1	7.4	7.250	0.013*
AC conventional	85.9	5.9	87.5	7.4	0.360	0.554
AC novel	80.8	7.4	67.9	13.0	9.492	0.005*

TBI patients responded significantly slower than healthy controls for all three conditions. The controls' percent accuracy of LIT and NOV conditions were significantly higher than the TBI patients. However, the percent accuracy for CON condition showed no significant difference between the two groups.
** Significance at $p < 0.001$.
* Significance at $p < 0.05$.

3. Results

3.1. Performance of metaphor comprehension

Table 2 presents mean reaction time (RT) and accuracy (AC) of the healthy and TBI groups for all conditions when they were in the scanner. TBI patients responded significantly slower than healthy controls for LIT ($F(1, 23) = 9.05$, $p = 0.006$), CON ($F(1,23) = 7.76$, $p = 0.011$) and NOV conditions ($F(1.23) = 7.07$, $p = 0.014$). The controls' percent accuracy of LIT ($F(1,23) = 7.25$, $p = 0.013$) and NOV conditions ($F(1,23) = 9.49$, $p = 0.005$) were significantly better than the TBI patients. However, the percent accuracy for CON condition ($F(1,23) = 0.36$, $p = 0.554$) showed no significant difference between the two groups.

With regard to the within-group comparison in the TBI group, RTs for LIT and CON conditions ($F(1,22) = 0.054$, $p = 0.818$) showed

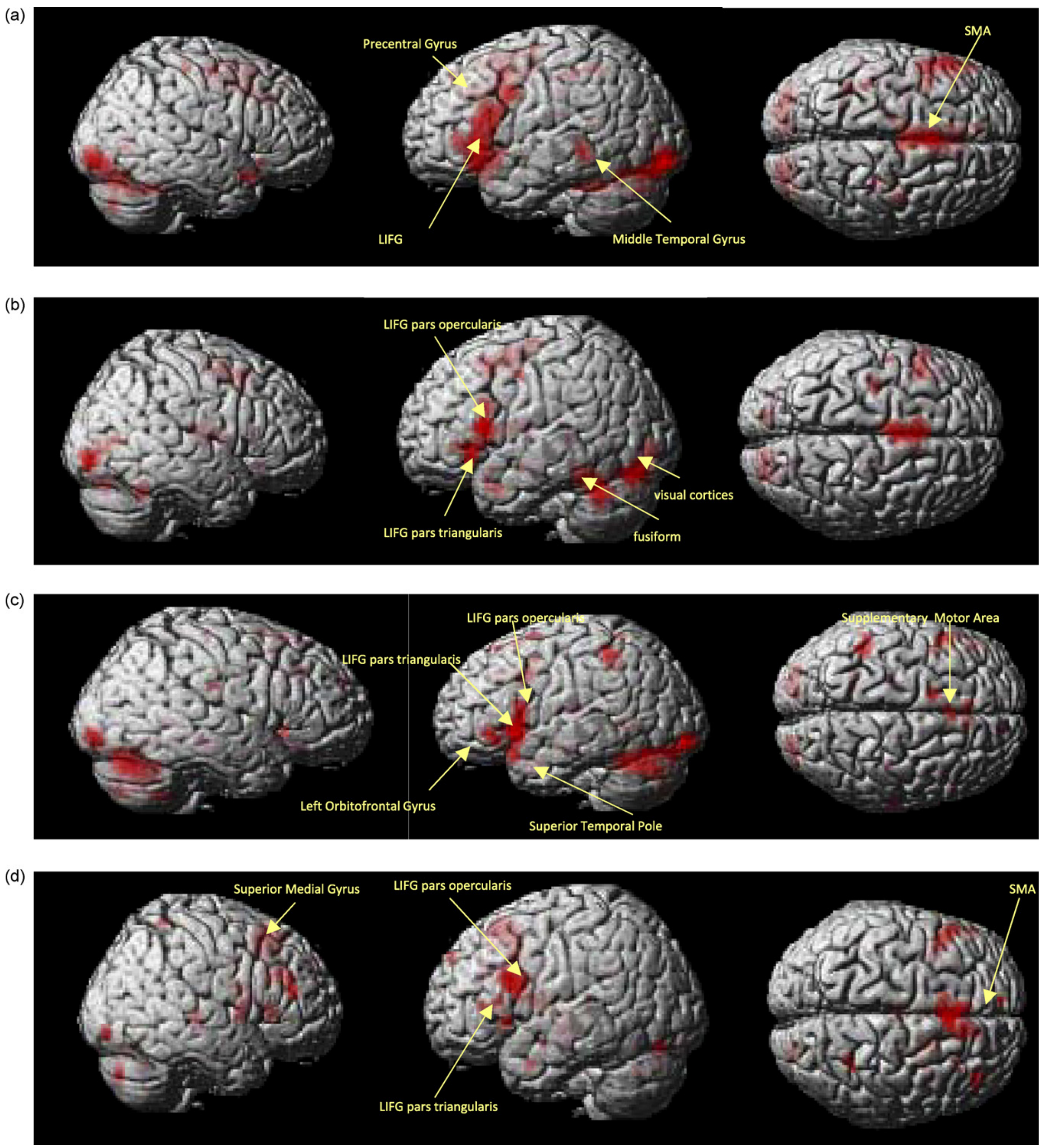

Fig. 1. Activations for metaphors. Compared to the TBI group, the control group demonstrated significantly more activation in 7 clusters, including triangularis and opercularis of LIFG, precentral gyrus, supplementary motor area (SMA), superior temporal pole and left posterior middle temporal gyri (cf. (a)). The TBI group revealed distributed and relatively weak activations in the triangularis and opercularis of LIFG and inferior temporal gyrus in addition to visual cortex (cf. (b)). For conventional metaphors, patients exhibit bilateral involvement and employ more motor regions and frontal subregions whereas control subjects used left-lateralized traditional language regions in the temporal and frontal lobes.

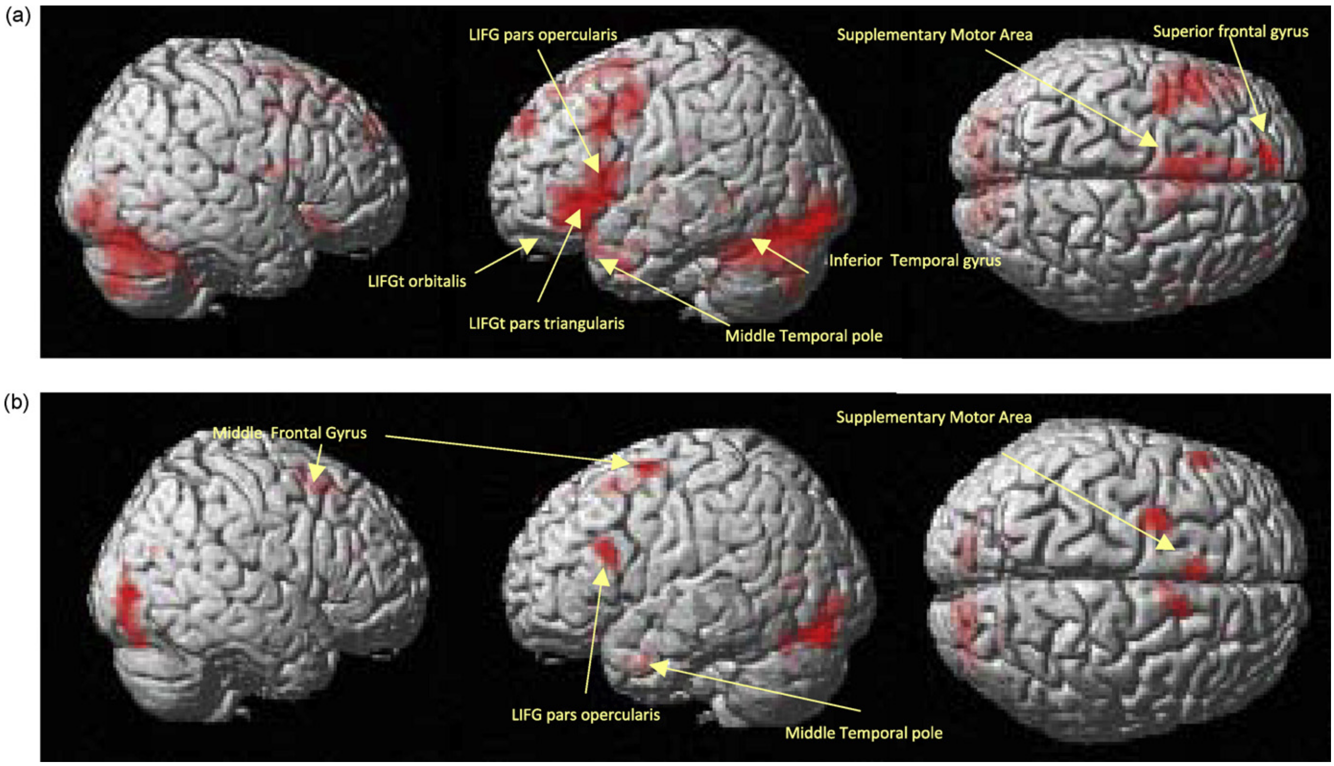

Fig. 2. Activations for literal sentences. Compared to the TBI group, the control group displayed extensive activations in the frontal lobe, including triangularis, orbitalis and opercularis of LIFG, superior and middle frontal gyri, as well as temporal regions such as the middle temporal pole and the inferior temporal gyrus (cf. (a)). The TBI group showed significant activation in the superior frontal gyrus and opercularis of LIFG (cf. (b)).

no significant difference. Comparisons of RTs for NOV and LIT conditions ($F(1,22) = 3.308$, $p = 0.083$) and RTs for CON and NOV conditions ($F(1,22) = 3.148$, $p = 0.09$) did not reach significance, either. RTs for LIT and CON conditions within the control group did not show significant difference ($F(1,24) = 1.621$, $p = 0.215$). However, comparisons of RTs for the LIT and NOV conditions ($F(1,24) = 10.389$, $p = 0.004$) and the RTs for the LIT and CON conditions ($F(1,24) = 4.600$, $p = 0.042$) showed significance.

3.2. Whole-brain analysis

Group maps for both subject groups were generated at a threshold of 10 contiguous active voxels using an FDR correction ($p = 0.05$). Details of activated clusters are presented in Appendix B.

3.3. Novel metaphors

The NOV condition showed more activations than the CON condition in both subject groups. The TBI group revealed distributed and relatively weak activations in the triangularis and opercularis of LIFG and inferior temporal gyrus in addition to visual cortex, thalamus and fusiform (cf. Fig. 1b). Compared to the TBI group, the control group demonstrated significantly more activation in 7 clusters, including triangularis and opercularis of LIFG, precentral gyrus, supplementary motor area (SMA), superior temporal pole and left posterior middle temporal gyrus (cf. Fig. 1a). This result indicates that LIFG was most sensitive to novel metaphors across two subject groups.

3.4. Conventional metaphors

TBI activations were bilateral and distributed in frontal and temporal subregions. Six active clusters were observed in the TBI group, including the triangularis and opercularis portions of LIFG, bilateral superior medial gyri, SMA and right hippocampus (cf. Fig. 1d). In contrast, the control group displayed more concentrated activation within the pars opercularis and triangularis of LIFG, left orbitofrontal gyrus, parahippocampal gyrus, superior temporal pole, the left inferior temporal gyrus and the inferior parietal lobule (cf. Fig. 1c). The different activation patterns across the two subject groups suggested that the TBI patients engaged more motor regions and frontal subregions in addition to LIFG to process conventional metaphors, whereas control subjects relied upon left-lateralized traditional language regions in the temporal and frontal lobes to comprehend conventional metaphors.

3.5. Literal sentences

The TBI group showed significant activation in the middle frontal gyrus and pars triangularis of LIFG (cf. Fig. 2b). Compared to the TBI group, the control group displayed increased activation in the triangularis and opercularis of LIFG and the middle temporal pole (cf. Fig. 2a). The control group showed greater activation in the frontal gyri for the LIT condition compared to the CON condition. This indicates that literal sentences may be more difficult to process than conventional metaphors for controls in terms of judgment. However, TBI patients engaged more cognitive resources in the motor regions in order to comprehend conventionalized figurative language in comparison to literal sentences. For TBI patients, conventional metaphor is a special category that requires greater processing in motor regions, which can be a sign of compensatory processing.

3.6. Functional ROI analysis

The LIFG ROI for the healthy controls was generally more active than for the TBI group across all conditions. However, specific comparisons of each condition showed that the differences

Table 3
ANOVA of fROI values for all conditions between TBI and control groups.

ROI values for condition	Control		TBI		$F(1,23)$	p
	Mean	SD	Mean	SD		
LIFG literal	1.509	0.818	0.773	0.724	5.636	0.026*
LIFG conventional	1.0	0.716	0.670	0.530	1.691	0.206
LIFG novel	2.580	1.580	1.080	0.422	10.118	0.004*

The LIFG ROI for the healthy controls was more active than for the TBI group across all conditions. The LIFG ROI was significantly more active in healthy controls than in the TBI group for LIT and NOV conditions but not for the CON.

* Significance at $p < 0.05$.

between TBI patients and controls were only significant for the LIT ($F(1,23) = 5.64$, $p = 0.026$) and NOV ($F(1,23) = 10.12$, $p = 0.004$) conditions, but not for the CON condition ($F(1, 23) = 1.69$, $p = 0.206$). The comparison of each condition across two groups is presented in Table 3.

4. Discussion

Overall, the TBI group displayed less intensive activation for all conditions in comparison with the control group. The ROI analysis also showed that LIFG was less intensively involved in TBI patients than healthy controls. The whole-brain pattern and the ROI results will be explained in the following subsections.

4.1. Global disorganization and metaphor comprehension

As mentioned in Section 1, the global disorganization theory hypothesized that language and communication deficits in TBI patients, like other cognitive deficits, are part of a global disorganization process, as communication disorders often co-occur with problems in conceptual integration and abstract thought (Groher, 1983; Hagen, 1984; Levin, Benton, & Grossman, 1982). The present study supports the global disorganization proposal that impaired metaphoric comprehension in TBI arises from deficits in abstract thought, which is the ability to structure and synthesize abstract concepts. We had hypothesized that TBI patients would show reductions in activation of the LIFG, which is an important center for semantic memory control and abstract thought, in comparison with healthy controls. In addition, we hypothesized that global disorganization would be reflected in patients' less intensive activations throughout the brain in comparison with healthy controls. The results presented here support our prediction that TBI patients display abnormal patterns of fMRI activation both at the whole-brain level and in specific ROIs. Specifically, we observed different degrees of LIFG involvement and activation of language and non-language regions between healthy controls and TBI patients, which will be elaborated in the following sections.

4.2. Group difference in activation

Patients exhibited a globally lower activation pattern in comparison to controls in all conditions. This is consistent with our hypothesis that disorganized cognitive processes following TBI are reflected in less intensive activation in multiple regions. In novel metaphor comprehension, the activated regions for our control group were similar to prior results reported in a majority of fMRI studies on metaphors (Giora, 1997; Giora et al., 2000, 2003; Giora, 2007; Mashal et al., 2007, 2009; Pobric, Mashal, Faust, & Lavidor, 2008; Rapp et al., 2004; Stringaris et al., 2006; Yang et al., 2009). These regions included triangularis and opercularis of LIFG, precentral gyrus, supplementary motor area (SMA), superior temporal pole and left middle temporal gyrus. However, TBI patients showed less intensive activation in the pars opercularis and triangularis of LIFG and middle and inferior temporal gyri compared with controls. This finding suggests that TBI patients did not intensively engage PFC and temporal regions for semantic control to comprehend novel metaphors as healthy controls. The reduced involvement in semantic control and retrieval may be interpreted to be a result of global disorganization.

While the controls' were more left-lateralized, the TBI group activations for the CON condition were bilateral. This difference suggests that healthy controls involved the cognitive control region (LIFG), language regions (temporal gyri), and motor regions (SMA and precentral) for inference of novel abstract expressions, but that TBI patients only activated this inference circuit for familiar figurative language. The right hemispheric involvement may indicate compensatory effortful processing in the TBI group. It may be that the patients were not capable of performing abstract thought of novel stimuli as actively as healthy subjects due to disrupted interconnectivity of prefrontal cortex (PFC) with other regions relevant to novel metaphor processing. This interpretation is consistent with the position proposed by Newsome et al. (2008) suggesting that TBI compromises frontally mediated working memory abilities and a deficit in allocating additional neural resources to cope with increases in memory load. Since the present metaphoric stimuli were matched on imageability with other conditions, it is likely that TBI patients showed more extensive activation for conventional metaphors because these trenched expressions usually have clear valence values that were easier to judge. TBI patients may be more likely to engage both hemispheres in familiar metaphors than the novel metaphors and literal sentences.

Notably, SMA has been found to be activated for all conditions with higher intensity in metaphoric conditions. In an fMRI metaphor study, Yang et al. (2009) noted that the SMA was recruited when the processing load of the target condition was increased compared with conditions with less cognitive load regardless of task types. Using a valence task, they reported that the NOV condition evoked more activations than the LIT and the CON conditions. In an imageability task, the LIT conditions activated more intensive activations than the NOV and CON conditions and LIT was processed significantly slower than both metaphoric conditions. This suggests that SMA is sensitive to processing load in linguistic judgments. In addition, the motor regions including precentral gyrus and SMA have been suggested to be parts of a common semantic network (Chee et al., 1999) as well as a general linguistic network that also includes phonological function (Binder, Desai, Graves, & Conant, 2009; De Carli et al., 2007; Paulesu, Frith, & Frackowiak, 1993). Therefore, the SMA involvement observed in the current research may also indicate communication of subregions within the semantic network that consists both speech and motor regions.

4.3. LIFG and abstract thought

The ROI analysis indicated that healthy subjects significantly activated a greater extent of cortex within LIFG for novel metaphor comprehension than TBI patients ($p < 0.05$), though both groups display increased activations in this region. This finding is consistent with pervious studies on healthy adults suggesting a specific role of LIFG for semantic judgment (Costafreda, Fu, Lee, Brammer, & David, 2003; McDermott, Petersen, Watson, & Ojemann, 2003). The increased demand from LIFG in novel metaphors may reflect a search for relevant semantic information, supporting the hypothesis that LIFG mediates selection of semantic information when contextual information was insufficient (Badre & Wagner, 2007; Duncan & Owen, 2000; Fiez et al., 1992; Thompson-Schill et al., 1997). Alternatively, this may be attributable to increased demand for semantic control as proposed by Wagner, Pare-Blagoev, Clark, and Poldrack (2001). Either hypothesis can explain increased activation in response to increased demand in abstract thought for both subject groups. Patients' relatively minimal increase in ROI activation across three conditions in contrast to healthy participants may be taken to reflect their failure in active retrieval and selection of semantic knowledge or inability to execute semantic control when they process novel abstract thought.

4.4. Summary

In a metaphor valence task, healthy individuals demonstrated significant activation in language regions in the PFC and temporal lobes, as well as motor regions in processing novel metaphors. TBI patients activated distributed subregions of LIFG and temporal gyri in comprehension of the same novel stimuli. Overall, TBI patients' activations across all conditions displayed a less intensive and more distributed pattern than healthy controls. This suggests that abnormality or disorganization may occur at a global level consistent with diffuse axonal injuries present in the TBI group. The LIFG ROI analysis indicated that patients did not employ this region as robustly during abstract thought compared to healthy participants. TBI patients' impaired abstraction of novel stimuli appears to be related to compromised semantic memory control in the frontal lobes as well as disrupted interconnectivity of the PFC with other regions. Future neuroimaging research may manipulate other language-memory paradigms to investigate TBI patients' semantic memory system in relation to other types of memory networks. This could provide greater insight into the impact of TBI on memory as well as affected interconnectivity of neural circuits for language processing.

This study provides evidence that may support of global cognitive disorganization process after TBI and demonstrated differences in neural involvement in cognitive control between patients and controls. One potential caveat to this interpretation is that TBI injuries are often variable in terms of both cortical and white matter damage. Specifically, there are still many unknown factors regarding how and to what extent TBI result in loss of neurons, axonal damage, and disruption in integrity of white matter tracts and how this affects cerebral blood flow. The consequences of structural damage and altered blood flow on brain functioning and cognitive processing may impact the fMRI BOLD signals in unknown ways. The continued use of other imaging modalities that provide volumetric grey matter measures and white matter integrity measures should be used in concurrently with fMRI on larger samples in order to provide more information about the nature of deficits and uncover correlations of structural and functional deficits.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.neuropsychologia.2010.03.011.

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