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When "Crack walnuts" lies in different brain regions: Evidence from a voxel-based lesion-symptom mapping study

FABRIZIO PIRAS,[1,2] AND PAOLA MARANGOLO[3]
[1]Laboratorio di Neuroimmagini, Fondazione IRCCS Santa Lucia, Rome, Italy
[2]Center for Research in Language, University of California, San Diego, California
[3]Dipartimento di Neuroscienze, Facoltà di Medicina, Università Politecnica delle Marche, Ancona, Italy

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Abstract

Theories of lexical processing differ as to how multimorphemic words, such as compounds, are mentally processed. The most recent findings seem to support the *dual route hypothesis,* which assumes that complex words can be stored and retrieved either whole or by decomposition into their constituents. Despite great efforts to investigate the cognitive mechanisms involved in processing complex words, very little is known about how compounds are represented in the brain. The present study was designed to address this issue in a group of 20 left-hemispheric stroke patients who were submitted to four picture-naming tasks involving nouns, verbs, noun-noun (NN) and verb-noun (VN) compounds. To determine the brain lesions implicated in these tasks, we analyzed patients' performances together with their lesions using Voxel-based Lesion Symptom Mapping (VLSM). Results showed that while NN involved the same temporal areas as nouns, VN (although they belong to the noun category) involved different fronto-temporal regions. This latter finding is discussed within the view that distinct mechanisms process the different constituents of complex words. (*JINS*, 2010, *16*, 433–442.)

Key words: Compound words, Grammatical categories, Naming, VLSM, Lexicon, Aphasia

INTRODUCTION

Compounding is a productive process that allows speakers of most languages to create complex words by combining two or more simple lexical units. Compound words can be semantically transparent, when the meaning of the word can be easily inferred from the meaning of its constituents (e.g., *bedroom*), or semantically opaque, when no semantic relationship can be found between the whole word and its single elements (e.g., *eggplant*).

Since the 1980s, the main issue has concerned how multimorphemic words, such as compounds, are mentally represented. Two opposing theories have been proposed. *Full-listing* theories suppose that morphologically complex words are stored and retrieved as whole words, just like morphologically simple words (see, e.g., Butterworth, 1983). However, this hypothesis does not consider the principle of cognitive economy, which claims that the more productive a word formation process (such as in the agglutinated languages like Turkish), the more likely it will generate a potentially infinite number of complex words.

Conversely, *full-parsing* theories (e.g., Taft & Forster, 1975) argue that complex words are processed through the full decomposition of their single constituents. Based on this explanation, however, it is impossible to understand how semantically opaque compounds (such as the Italian word *corrimano* -handrail- lit. run-hand) are processed.

More recently, an alternative hypothesis, the so-called *dual route model*, was proposed. This model can be considered a sort of compromise between the *full-listing* and *full-parsing* accounts. Dual route theories assume that complex words can be stored and retrieved whole, through a single-lemma-single-morpheme structure, or by decomposition into their constituents and processed through a single-lemma-multiple-morpheme route. The former would apply to very frequent and/or opaque compounds (i.e., *hotdog* or *passport*) and the latter to less frequent and/or transparent compounds (i.e., *blackboard* or *sunshine*) (Levelt, Roelofs, & Meyer, 1999). Evidence for decomposition comes from psycholinguistic studies in healthy subjects and from reports

Correspondence and reprint requests to: Prof. Paola Marangolo, Dipartimento di Neuroscienze, Facoltà di Medicina, Università Politecnica delle Marche, Ancona, Italia. E-mail: p.marangolo@univpm.it

of patients with language deficits. Several studies using priming techniques in healthy subjects have showed that the recognition of compounds is facilitated if it is preceded by presentation of either the first or the second element, thus demonstrating the parallel activation of both constituents (Jarema, Busson, Nikolova, Tsapkini, & Libben, 1999; Libben, Gibson, Yoon, & Sandra, 2003).

Further evidence in favor of the decompositional hypothesis comes from studies investigating the processing of compounds in aphasic patients. In a group study, Hittmair-Delazer Andree, Semenza, DeBleser, and Benke (1994) found that when patients performed a compound naming task they preferentially produced semantic paraphasias that closely resembled the decomposed structure of the stimuli. Errors consisted of existing and nonexisting compounds whose single constituents had a close semantic relationship with the targets. Semenza, Luzzatti, and Carabelli (1997) found that Broca's agrammatic aphasics, unlike Wernicke's patients, tended to omit the verb component in verb-noun (VN) compounds even though in Italian they belong grammatically to the noun category. Moreover, this pattern was not due to a positional effect (such as impaired access to the first component) because in noun-noun (NN) compounds errors were equally distributed on the first and the second constituent. Similarly, Mondini, Luzzatti, Zonca, Pistarini, and Semenza (2004) confirmed that patients with disproportionate verb naming deficits were also more impaired on VN compounds than NN compounds. As patients with Broca's aphasia generally omit more verbs than nouns when processing simple words, the authors concluded that the omission of the verb component in VN compounds should be attributed to their decomposition into separate noun and verb forms.

More recently, Nasti and Marangolo (Nasti & Marangolo, 2005) described a patient who frequently omitted either the first or the second element in a compound word reading task and less frequently in naming and writing to dictation tasks. Moreover, as in previous studies the patient's errors always respected the decomposed structure of the stimuli. Furthermore, coherently with his residual agrammatism he showed a deficit in retrieval of the verb component in VN compounds.

In a sample of Italian agrammatic patients, Mondini, Luzzatti, Saletta, Allamano, & Semenza (2005) explored the processing of prepositional compounds (e.g., *mulino a vento* - windmill) and found that in naming, omission was the most frequent type of error; in repetition, reading, writing, and completion tasks errors were mostly substitutions of the target preposition. This trend was observed even with fully lexicalized compound forms, namely, those forms in which the linking preposition is syntactically and semantically opaque.

Taken together these results seem to be consistent with a dual-route interpretation of lexical access, which hypothesizes decomposition even in the case of opaque compounds (Badecker, 2001; Mondini et al., 2005). In fact, analysis revealed that the errors were almost always substitutions or omissions of one component only. Moreover, Italian aphasic patients with a verb-relative-to-noun deficit systematically drop the verb component in VN compounds [i.e., aspirapolvere (vacuum cleaner)]. This finding has been considered the strongest evidence of decomposition.

Despite great efforts to investigate the cognitive mechanisms involved in processing complex words, we still know little about the neural correlates of compound processing. The only report in the literature is a recent study by El Yagoubi and colleagues (El Yagoubi, Chiarelli, Mondini, Perrone, Danieli, & Semenza, 2008) in which NN compound processing was investigated by means of an event-related potential (ERP) technique. Normal Italian-speaking subjects were asked to perform a lexical decision task in which items were composed of noun-noun compounds [e.g., *capobanda* (band leader)], noncompounds with an embedded word [e.g., *coccodrillo* (crocodile), where *cocco* means "coconut"] and nonwords generated either by reversing the positions of the two constituents of the compound [e.g., for *capobanda* (leader) the corresponding nonword was *bandacapo*] or by reversing the positions of the word embedded in the noncompounds (e.g., for *coccodrillo* the nonword was *drillococco*).

Two main results were found. The first was a larger N400 lexicality effect for noncompound than for compound words. The authors argued that this effect was likely due to the presence of nonwords created by inverting the component word. Because the nonwords were derived from compound words that contained two real words, participants may have accessed the meaning of the two constituents by means of a decomposition process. Second, results showed a more negative peak in the left anterior negativity component (LAN, which is thought to be related to morphosyntactic processing) for compounds than for noncompounds, which was attributed to the formation of morphosyntactic constituents. Taken together these results are compatible with data from behavioral studies suggesting a decomposed representation of compound constituents.

Although these data provide remarkable insights into the temporal dynamics of compound words processing, they are less informative at the level of spatial localization.

The goal of the present study was to explore the brain areas involved in compound word processing. Previous behavioral findings in normal subjects (e.g., Jarema et al., 1999; Libben et al., 2003) as well as in aphasic patients (e.g., Hittmair-Delazer et al., 1994; Mondini et al., 2004; Nasti & Marangolo, 2005; Semenza et al., 1997) seem to suggest that the single elements of compound words are processed separately. Nevertheless, it is still unclear whether or not this hypothetical cognitive independence indicates the existence of distinct neural mechanisms devoted to processing the different constituents of compounds.

Currently, there is substantial evidence that the brain systems required for retrieving verbs and nouns are at least partially segregated. Indeed, some studies have suggested that areas lying outside the frontal regions (i.e., temporo-parietal cortices, Aggujaro, Crepaldi, Pistarini, Taricco, & Luzzatti, 2006; Luzzatti, Aggujaro, & Crepaldi, 2006; Piras

& Marangolo, 2007) might be responsible for processing verbs. Other studies have found that the frontal areas play a key role in processing verbs (Daniele, Giusstolisi, Silveri, Colosimo, & Gainotti, 1994; Shapiro, Moo, & Caramazza, 2006; Tranel, Martin, Damasio, Grabowski, & Hichwa, 2005). It has also been suggested that the inferior frontal gyrus (due to its location near the motor areas) supports the production of action names for which the availability of motor features is important (Parsons et al., 1995). With regard to noun processing, as nouns usually refer to concrete entities (i.e., objects, tools, animals) that involve the processing of perceptual features, previous lesion studies have frequently reported activation of the temporal lobe (Daniele et al., 1994; Luzzatti et al., 2006; Tranel et al., 2005).

The rationale behind our investigation was that if compounds are processed through a whole word representation both NN and VN, as nominal compounds (they all belong to the grammatical category of nouns), should recruit similar cerebral regions.

On the contrary, if the two elements of the compound are processed by separate brain regions involvement of different damaged areas might be found only in the case of VN compounds.

The present work was aimed at addressing this issue in a group of 20 patients with left brain damage using a recently devised lesion-behavior methodology, VLSM (Bates et al., 2003). VLSM uses fully continuous information both at the behavioral (no arbitrary cutoffs are stipulated) and the neuroanatomical level (all patients are included regardless of lesion location). Statistical analyses on the relationship between tissue damage and observed behavior are carried out on a voxel-by-voxel basis, as in functional imaging, and the results are plotted as color maps depicting the degree of behavioral involvement of each voxel. Here, VLSM was used to identify lesions associated with naming difficulties in four classes of stimuli: simple nouns, simple verbs, noun-noun compounds (NN), and verb-noun (VN) compounds.

MATERIALS AND METHODS

Subjects

Twenty participants (13 males, 7 females) who had suffered a single left hemisphere cerebrovascular accident (CVA) were included in the study. Subjects were recruited and tested at the Center for Neuropsychological Diagnosis and Rehabilitation of the Fondazione I.R.C.C.S. Santa Lucia in Rome, Italy. Inclusion criteria were native Italian language proficiency, premorbid right-handedness, a single left CVA at least 6 months before the investigation, suitability for MRI scanning and no previous neurological, psychiatric, or substance abuse history. Mean age of the patients was 62 years (*SD* 11), mean time poststroke was 13 months (*SD* 9) and mean education level was 12 years (*SD* 3) (see Table 1). The data analyzed in the current study were collected in accordance with the Declaration of Helsinki and the Institutional Review Board of the Fondazione Santa Lucia. Before participation, all patients signed informed consent forms.

Table 1. Clinical and sociodemographic data of the aphasic group

Participant	Sex	Age	Education	Etiology	Months post-onset	Type of aphasia	Severity
1	m	54	17	L I CVA	31	Broca	Mild
2	m	73	12	L H CVA	9	Rmd	Minimal
3	f	70	12	L I CVA	11	Broca	Mild
4	m	54	13	L H CVA	23	Conduction	Moderate
5	m	38	18	L H CVA	8	Conduction	Moderate
6	m	60	8	L I CVA	43	Conduction	Moderate
7	m	72	13	L I CVA	11	Rmd	Minimal
8	m	78	13	L I CVA	9	Anomic	Moderate
9	f	68	8	L I CVA	12	Anomic	Mild
10	m	72	12	L H CVA	7	Trans Mot	Mild
11	m	66	13	L I CVA	17	Broca	Mild
12	m	54	13	L I CVA	10	Broca	Minimal
13	f	64	7	L I CVA	10	Rmd	Minimal
14	f	66	8	L I CVA	10	Trans mot	Moderate
15	m	58	12	L H CVA	8	Rmd	Minimal
16	f	39	13	L I CVA	8	Anomic	Mild
17	m	52	11	L I CVA	9	Conduction	Mild
18	m	77	8	L H CVA	12	Anomic	Mild
19	f	68	8	L I CVA	6	Anomic	Mild
20	f	70	13	L H CVA	9	Anomic	Moderate

Note. LHCVA = left hemorrhagic cerebrovascular accident; LICVA = left ischemic cerebrovascular accident; Trans mot = transcortical motor; Rmd = residual minimal disorders.

Clinical Assessment of Aphasia

Aphasic disorders were assessed using the Italian version of the Western Aphasia Battery, which includes different subtests for the different language modalities, that is, naming, repetition, reading, and writing. The aim of the battery is to classify the patient in one of the major syndromes according to the standard aphasia taxonomy (Broca's, Wernicke's, Transcortical, Conduction, and Anomic aphasia) on the basis of his/her score on each language task (Kertesz, 1982). The aphasic symptoms shown by each participant varied from severe to residual minimal disorders. Thus, they covered a wide range of linguistic impairments (see Table 1). None of the patients had articulatory difficulties that could have confounded the error analysis of the picture-naming task.

Experimental Stimuli and Tasks

To investigate compound-word-naming performance, a total of 90 stimuli that could be depicted were divided into (i) 30 simple nouns; (ii) 30 simple verbs; (iii) 12 NN compounds (e.g., *mappamondo* -globe-); and (iv) 15 VN compounds (e.g., *apribottiglie* -bottle opener) (Appendix). Stimuli frequencies were obtained from the CoLFIS web source (Laudanna, Thornton, Brown, Burani, & Marconi, 1995; http://www.istc.cnr.it/material/database/colfis/), which is based on a large corpus of 3,798,275 lexical units gathered from Italian newspapers, magazines and books. Stimuli were matched across categories for frequency [means and standard deviations in parentheses for simple nouns: 9 (9); simple verbs: 8.7 (10); NN compounds: 6.3 (8.2); VN compounds: 8.6 (12.6)] and length [simple nouns: 8.2 (1.5); simple verbs: 8.7 (1.2); NN compounds: 8.8 (1); VN compounds: 9 (1.3)]. Ten age-and educational level matched normal controls were asked to rate the imageability of each noun, verb, NN and VN compound on a 7-point scale (1 = low imageability; 7 = high imageability). Statistical tests revealed no significant difference among the four groups of stimuli, which were all judged as highly imageable. The pictures were randomly presented to each patient in three separate sessions. Subjects were asked to name each picture without a time limit.

MRI Acquisition

Images were acquired using a 1.5 Tesla (T) Siemens Vision Magnetom MR system (Siemens Medical Systems, Erlangen, Germany).

To obtain a precise brain definition and to distinguish between the gliotic and necrotic parts of the vascular lesions and healthy tissue, four different anatomical sequences were acquired: (1) a T-2 weighted turbo spin echo image [repetition time (TR) = 3800 ms; echo time (TE) = 90 ms; field of view (FoV) = 173 × 230]; (2) a proton density image (TR = 3800 ms; TE = 20 ms; FoV = 173 × 230); (3) a fluid attenuated inversion recovery image (TR = 9999 ms; TE = 105 ms; FoV = 188 × 250); (4) a dedicated high-resolution (1 × 1 × 1 mm) T1-weighted image of the whole brain, using a 3-D Magnetization Prepared Rapid Gradient Echo (MPRAGE) sequence (TR = 11.4 ms; TE = 4.4 ms; flip angle = 10°, 256 × 256 matrix, 1 × 1 mm in-plane resolution, 220 contiguous 1-mm coronal slices).

Lesion Analysis and VLSM

Lesions were drawn manually slice-by-slice on the digital MPRAGE images using free MRIcro software (Rorden & Brett, 2000) and were saved as Regions of Interest (ROIs). During this process, the other clinical images acquired were visually co-inspected to obtain a detailed lesion image, which was corroborated by two clinical neuroradiologists who were blind to the aims of the study and the patients' behavior. The gliotic tissue was considered as part of the lesion.

Normalization of each patient's MRI to a common spatial framework was performed using SPM99 software (Wellcome Department of Cognitive Neurology, London, UK), implemented in MATLAB (The MathWorks Inc., Natick, MA, USA), through an automatic nonlinear stereotaxic normalization procedure (Friston, Ashburner, Poline, Frith, Heather, & Frackowiak, 1995). Estimation of the normalization parameters was restricted to healthy tissue (Brett, Leff, Rorden, & Ashburner, 2001). Distorted lateral ventricles were excluded from the computation.

Each patient's lesion image was entered in the VLSM analysis together with four behavioural scores: (i) number of correct responses in the noun-naming task; (ii) number of correct responses in the verb-naming task; (iii) number of correct responses in the NN-naming task; and (iv) number of correct responses in the VV-naming task. The VLSM method is as follows: at each voxel, patients are divided into two groups according to whether or not the voxel is lesioned. These groups are then compared (e.g., with a *t* test) and the resultant *t* values are overlaid on the single-subject MNI brain as color maps showing the degree of behavioural involvement of each voxel in the single tasks. The VLSM algorithms programmed in MATLAB (The Mathworks, Natick, MA) are available online at http://crl.ucsd.edu/vlsm. In the present study, a customized version of VLSM was used. Therefore, we were also able to submit lesion images to an automated anatomical labeling procedure based on macroscopic anatomical parcellation of the MNI single-subject brain (Tzourio-Mazoyer et al., 2002), which includes all main gyri of the cerebral cortex. Thus, for each patient we were able to compute the total volume of the lesion and the percentage of each damaged brain region.

Statistically, multiple comparisons were controlled by performing a correction so that the false discovery rate (FDR) was set at $p = .05$. Time postonset and lesion volume were used as covariates to ensure that these factors would not affect our results. Moreover, to maintain a reasonable level of statistical power, statistical analyses were restricted to those voxels where at least 5 patients were lesioned. Finally, to highlight differences and commonalities across tasks, the single *t*-maps were compared by conjunction and correlation analyses. For conjunction analyses, VLSM computes a map showing the minimum value of two images for each voxel. For correlation analyses, VLSM calculates the similarity between two maps by computing a correlation between the *t* values and generating a map on which each voxel is colored according to the *t* difference between the two maps.

RESULTS

Behavioral Results

Percentages of correct responses in the four tasks are reported in Table 2. To assess differences among tasks, a repeated measures analysis of variance (ANOVA) with type of stimulus (i.e., noun, verb, NN, and VN compound) as within-subjects variable was computed. It revealed no significant differences in the percentage of correct responses ($F(3,57) = .025$) among noun (mean = 64%; *SD* = 24.7), verb (mean = 63.2%; *SD* = 28.3), NN (mean = 62.1%; *SD* = 22.5), and VN (mean = 59.3%; *SD* = 25.8) picture naming. Pearson correlation tests were computed (i.e., noun-verb; noun-NN compound; noun-VN compound; verb-VN compound; verb-NN compound; VN compound-NN compound). Results showed a highly significant correlation only for the verb-VN compound ($r = 0.84$; $p < .001$) and the noun-NN compound ($r = 0.86$; $p < .001$).

As in previous studies (Nasti & Marangolo, 2005), errors were classified for noun and verb naming as: omissions (no response), semantic paraphasias [*elefante* (elephant) → *rinoceronte* (rhino)] and phonological paraphasias [*poliziotto* (policeman) → *piziotto*].

Table 2. Percentages of correct responses in the four naming tasks

Subject	Simple nouns	Simple verbs	NN compounds	VN compounds
1	100	47	83	53
2	100	93	100	87
3	93	67	83	67
4	47	53	42	40
5	33	87	25	80
6	47	83	50	80
7	97	97	100	93
8	17	10	17	13
9	63	40	50	47
10	60	33	67	33
11	77	20	58	13
12	80	37	67	47
13	73	80	67	67
14	57	47	58	33
15	97	93	92	80
16	40	73	50	73
17	57	83	58	67
18	37	97	75	100
19	57	93	42	80
20	47	30	58	33

For the compound-naming task, they were categorized as: omissions (no response); omission of the first component [e.g., *apribottiglie* (bottle opener) lit. open bottles →…*bottiglie* (…bottles)]; omission of the second component [e.g., *apribottiglie* → *apri*… (open…)]; compound paraphasias in which word substitutions could affect either the first [e.g., *apribottiglie* (corkscrew) → *portabottiglie* [bottle holder], lit. carry bottles`) or the second element of the compound (e.g., *mappamondo* [globe], lit. map world → *mappaterra* [map earth]; phonological paraphasias in which phonological errors could be either in the first (e.g., *apribottiglie* → *acribottiglie*) or the second element of the compound (e.g., *apribottiglie* → *apribottoglie*); decomposition [when the compound was broken up into its constituents, such as in *asciugamani* (towel), lit. dry hands → *asciugare le mani* (to dry the hands)]. Results are summarized in Table 3.

First, we were interested in assessing differences between the percentage of *whole word* (i.e., no responses) and *decompositional* errors (i.e., 1st component omission, 2nd component omission, 1st component substitution, 2nd component substitution, 1st or 2nd component phonological errors, compound decomposition) in NN- and VN-compound-naming tasks. To this aim, we computed a 2 × 2 repeated measures ANOVA with type of compound (i.e., NN and VN) and type of error (i.e., whole word *vs*. decompositional) as the within-subjects variables. Results revealed a significant effect only for type of error ($F(1,19) = 122{,}11$; $p < .0001$), which indicated that patients made significantly more decompositional errors ($p < .0001$; *post hoc* Scheffè analysis).

To determine whether a positional effect of the *decompositional* errors influenced NN and VN naming, a second 2 × 2 repeated measures ANOVA was computed with type of compound (i.e., NN and VN) and error position (i.e., 1st and 2nd position) as the within-subjects variables. Results showed no significant effects. Furthermore, no statistical differences emerged when we investigated whether the different aphasia categories affected processing of the first or second component of the compounds.

Voxel-Based Lesion-Symptom Mapping Results

We used VLSM to identify brain regions associated with performance on the four naming tasks. To this aim, we computed single *t*-maps for each word category (i.e., noun, verb, NN, and VN compounds) (see Figure 1).

Noun naming was primarily affected by lesions located in the temporal areas. Specifically, the highest *t* values (see Table 4) were found in the inferior, middle and superior temporal areas (BAs 20, 21, 22, 38, and 48). Similarly, lesions involving the temporal areas significantly affected the NN-compound-naming task (BAs 21, 22, and 38). On the contrary, verb naming recruited regions located in the inferior frontal areas (pars orbitalis, triangularis, and opercularis, BAs 44, 45, and 47). Of interest, VN-compound naming was also associated with infero-frontal regions (BAs 44, 45, and 47) (see Table 4).

Table 3. Number, percentage, and type of errors in compound naming tasks

Type of errors		Noun-noun		Verb-noun	
		n	%	*n*	%
	No responses	20	22	25	20,5
Omissions	1st component omissions	22	24,1	23	18,9
	2nd component omissions	20	22	20	16,4
Compound paraphasias	1st component word substitutions	9	10	17	12,3
	2nd component word substitutions	9	9,9	14	13,1
Phonological errors	1st component substitutions	0	0	0	0,6
	2nd component substitutions	1	1,1	1	0,2
	Decomposition	10	10,9	22	18,0
	Total	91 (38%)		122 (41%)	

To further highlight commonalities across tasks, VLSM conjunction maps were computed for N and NN compounds and for V and VN compounds which confirmed the previous results (Bates et al., 2003) (see Figure 2).

Therefore, its seems likely that while, as expected, NN compounds were processed by the same anatomical regions as simple nouns, VN compounds, although they belong to the noun category, recruited only those frontal regions recruited by simple verbs.

Because, as previously reported, frontally damaged patients sometimes make errors that systematically affect the first component in the VN-naming task, we asked ourselves whether the above result could have been partly due to the impact of inferior frontal lesions on VN-compound naming. We also wished to determine whether there was a correlation between the extent of damage in frontal areas and the type of decomposition errors found for VN compounds.

To this aim, we computed a VLSM map for the VN-compound task. The former included the proportion of the patient's lesion that affected the inferior frontal areas as covariate. Results revealed that even though frontal regions were still significantly affected, other regions, specifically

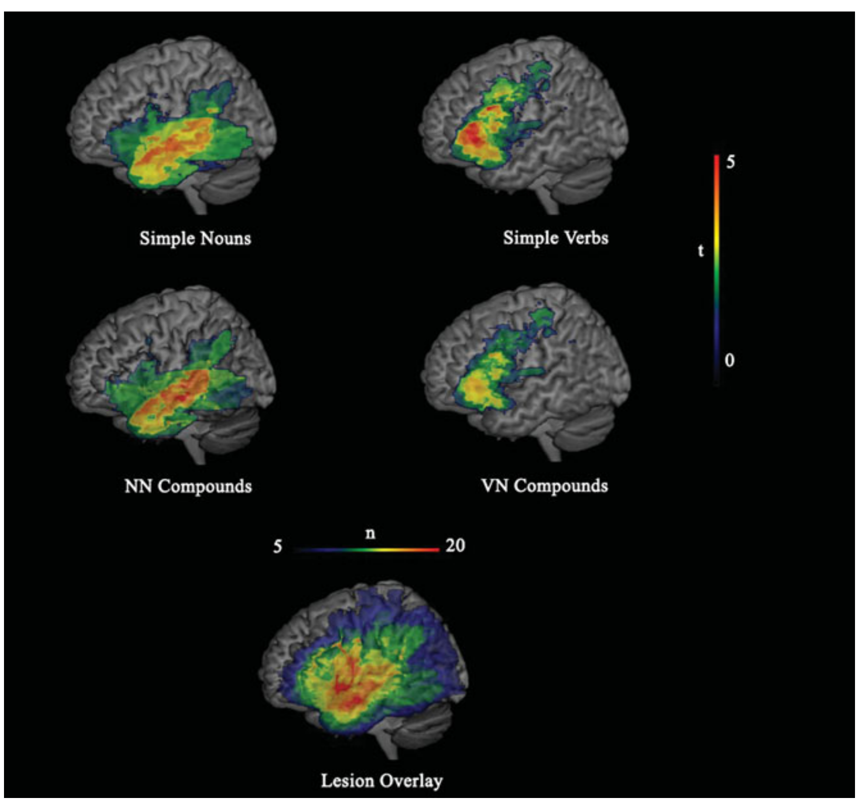

Fig. 1. First two rows: Lateral volume rendering of VLSM maps computed for the four naming tasks: simple nouns, simple verbs, noun-noun (NN) compounds, and verb-noun (VN) compounds. High *t* scores (yellow-to-red) indicate that lesions in the corresponding voxels affected behavior significantly. Low *t* scores (blue) indicate left hemispheric regions whose lesions had relatively little impact on behavior. All voxels above $t = 2.97$ were significant at $p = .05$ (FDR correction). Last Row: Overlay of patients' lesions. Maximum overlap is highlighted in red.

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Table 4. Highest *t* values for VLSM maps in the four naming tasks

t value	X,Y, Z	Region	BA
NOUN			
3.74	−46, 1, −30	Inferior temporal	20
3.79	−48, 20, −22	Superior temporal pole	38
4.67	−55, 2, −17	Middle temporal	21
4.21	−59, −5, 4	Superior temporal	48
4.29	−63, −23, 14	Superior temporal	22
VERB			
3.66	−31, 24, −18	Inferior frontal (orbitalis)	47
4.51	−33, 30, 0	Inferior frontal (triangularis)	47
4.11	−51, 37, 5	Inferior frontal (triangularis)	45
3.91	−55, 16, 14	Inferior frontal (opercularis)	44
NN COMPOUND			
4.11	−48, 20, −20	Superior temporal pole	38
3.93	−53, −14, −10	Middle temporal	22
4.11	−63, −32, 2	Middle temporal	21
VN COMPOUND			
3.39	−31, 25, −18	Inferior frontal (orbitalis)	47
3.57	−39, 40, 0	Inferior frontal (triangularis)	47
3.92	−51, 36, 4	Inferior frontal (triangularis)	45
3.37	−53, 16, 14	Inferior frontal (opercularis)	44

Note. Approximate MNI coordinates, region labeling and Brodmann's areas are given. NN Compound = Noun-noun compound : VN Compound = Verb-noun compound.

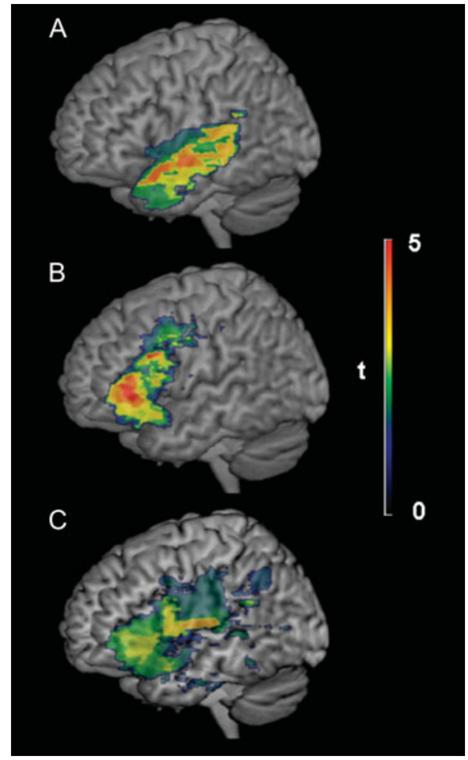

Fig. 2. Lateral volume rendering of VLSM conjunction maps computed for simple nouns and noun-noun (NN) compounds (A) and for simple verbs and verb-noun (VN) compounds (B). Yellow-to-red colors indicate left hemispheric regions where the maximum overlap between tasks was found. In C, VLSM map for VN including percentage of patient's lesion affecting the inferior frontal areas as covariate.

the superior temporal areas, were also involved (see Figure 2). Moreover, two separate correlation analyses between the percentage of lesioned frontal areas and i) the number of first component errors and ii) the number of second component errors revealed a highly significant correlation only for the first component errors (r = .89; $p < .001$) (see Figure 3).

DISCUSSION

The present study was aimed at investigating the brain areas involved in processing compound words. Previous behavioural and neuroimaging studies in normal subjects (e.g., El Yagoubi et al., 2008; Jarema et al., 1999; Libben et al., 2003) and in aphasic patients (e.g., Hittmair-Delazer et al., 1994; Koester, Gunter, & Wagner, 2007; Mondini et al., 2004; Nasti & Marangolo, 2005; Semenza et al., 1997) seem to suggest that complex words undergo a decompositional process. In the present study, we analyzed the MRI data of 20 subjects with left brain damage together with their performances on two single-word (nouns and verbs) and two compound-word (NN and VN) naming tasks using VLSM analysis (Bates et al., 2003). With this approach, we were able to explore the brain areas that had the greatest effect on the four tasks using fully continuous behavioral and lesion information. Stimuli consisted of simple nouns, simple verbs, noun-noun (NN), and verb-noun (VN) nominal compounds. We reasoned that if compounds are processed through a whole-word representation, both NN and VN compounds, which are grammatically like nouns, should be represented in the same anatomical regions. Conversely, if decomposition of its constituent morphemes occurs, we should find different areas involved in processing the different constituents of VN.

Two main results are worth considering. First, N and NN compounds primarily recruited temporal areas. Several previous lesion studies have demonstrated that the processing of simple nouns affects different regions mainly located in the temporal areas (e.g., Daniele et al., 1994; Piras & Marangolo, 2007; Tranel et al., 2005). Nouns usually refer to concrete entities (i.e., objects, tools, animals) intrinsically denoted by a rich set of perceptual attributes. Therefore, it is likely that the temporal lobe will be implicated when the processing of a stimulus requires detailed analysis of its perceptual features. In line with these results, it was predictable that the areas involved in NN-compound naming would be the same as those recruited for simple nouns because they both belong to the same grammatical category and therefore would involve the temporal regions. Nevertheless, although the qualitative analysis of errors suggests the presence of a decompositional effect in NN processing and a strong correlation between nouns and NN, because both elements of the compound are nouns, these results do not allow us to make any prediction about the type of process that takes place at the neural level.

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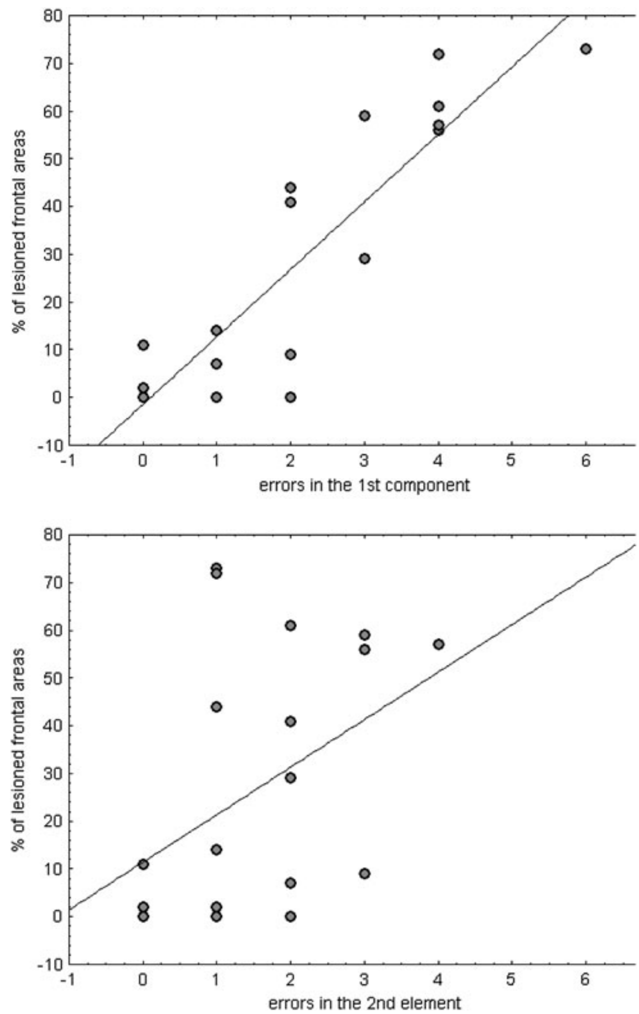

Fig. 3. Scatterplots showing the impact of a lesion in the left inferior frontal areas (*y* axis) in modulating the number of errors affecting the first (*x* axis on the top) or the second (*x* axis on the bottom) component of verb-noun (VN) compounds. Regression lines are reported in black.

This observation brings us to our second result. It was predictable that verbs would be subserved by the frontal regions. Indeed, various studies have suggested that the link between the prefrontal cortex and verbs might be partly due to the activation of action representation (Cappa & Perani, 2002). The intriguing result of this study is the strong similarity that emerged in the first analysis between the areas involved in V and VN naming, suggesting greater involvement of the same frontal regions. This result is hard to reconcile with the whole-word-representation account. In fact, it indicates that in VN naming there was a bias in favor of the verb component, suggesting morphological decomposable processing. This finding appears to contrast with the qualitative analysis of errors, which shows that overall the patients had an equal distribution of errors for both elements of the VN compound. However, differences between subjects in processing the first and/or the second constituents of the VN compound could have been responsible for the observed results (Nasti & Marangolo, 2005; Semenza et al., 1997). In other words, it is reasonable to assume that patients with anterior lesions will have greater difficulty in processing the verb component than those with different lesions, and this might have led to greater involvement of the frontal regions. This hypothesis was confirmed when patients' percentage of lesion in the inferior frontal region was treated as covariate. Although the inferior frontal region was still involved, significant foci of interest were found in the superior temporal region. According to the morphological decomposition view, the two constituents of the VN compound were processed separately in different fronto-temporal regions.

Moreover, in line with previous behavioral reports on aphasic patients, there was a high correlation between the number of verb component errors and the percentage of lesioned frontal area. As stated in the introduction, frontal aphasics frequently drop the verb component in VN compounds; similarly, our anterior patients made more errors on the verb component in the VN-compound-naming task (Mondini et al., 2004; Nasti & Marangolo, 2005; Semenza et al., 1997).

In conclusion, taken together our data seem to support a decomposable representation of compound constituents at the neural level. Although no other studies thus far have directly investigated the neural correlates of compound processing, we believe that our data complement the existing neuropsychological literature by suggesting that the already reported morphological decomposition between the two compound constituents is supported by distinct cortical networks.

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APPENDIX

List of the experimental stimuli used (for noun-noun and verb-noun compounds, the literal translation is in parentheses).

NOUN	NOUN-NOUN		VERB	VERB-NOUN	
Mattarello Rolling pin	Aliscafo	Hydroplane (Wings-Hull)	Spremere Squeeze	Aspirapolvere	Vacuum Cleaner (Inhale-Dust)
Serratura Lock	Mappamondo	Globe (Map-World)	Tosare Shear	Segnalibro	Bookmark (Mark-Book)
Sassofono Saxophone	Pescespada	Swordfish (Fish-Sword)	Strappare Tear	Asciugamani	Towel (Dry-Hands)
Passeggino Baby buggy	Telecomando	Remote control (TV-Command)	Sbadigliare Yawn	Portafoglio	Wallet (Carry- sheet)
Frigorifero Fridge	Filobus	Trolley bus (Wire-Bus)	Innaffiare Water	Portacenere	Ashtray (Carry- Ash)
Infermiera Nurse	Motosega	Chainsaw (Motor- Saw)	Dipingere Paint	Passaporto	Passport (Pass-Port)
Racchetta (Racket)	Videogioco	Videogame (Video-Game)	Accarezzare Caress	Schiaccianoci	Nutcracker (Squash-Nuts)
Rinoceronte Rhino	Marciapiede	Sidewalk (March-Foot)	Disegnare Draw	Scolapasta	Colander (Drain-Pasta)
Forchetta Fork	Minigonna	Miniskirt (Mini-Skirt)	Truccarsi Make up	Paracadute	Parachute (Parry-Drop)
Interruttore Switch	Pescecane	Shark (Fish-Dog)	Fischiare Whistle	Apribottiglie	Corkscrew (Open-Cork)
Cavalletta Easel	Granoturco	Corn (Corn-Turkish)	Scavalcare Climb over	Attaccapanni	Coat rack (Hang-Clothes)
Scoiattolo Squirrel	Arcobaleno	Rainbow (Arc - Flash)	Specchiarsi Mirror	Scaldabagno	Boiler (Heat-Bath)
Molletta Pincer	Astronave	Starship (Star-Ship)	Pettinare Comb	Paraurti	Bumper (Parry-Impact)
Lavagna Blackboard	Autoradio	Car radio (Car-Radio)	Assaggiare Taste	Cacciavite	Screwdriver (Pull out-Screw)
Staccionata Fence	Melograno	Apple-Corn Seed	Abbaiare Bark	Reggiseno	Bra (Hold- Breast)
Serranda Blind			Palleggiare Bounce		
Spazzolino Tooth brush			Allacciare Fasten		
Carrozzina Pram			Calciare Kick		
Barattolo Can			Inseguire Pursue		
Stampella Crutch			Asciugare Dry		
Pala Shovel			Scodinzolare Wag		
Scarafaggio Beetle			Spaventare Scare		
Damigiana Demijohn			Arrestare Arrest		
Pannolino Nappy			Applaudire Clap		
Immondizia Garbage			Inginocchiare Kneel		
Seggiolone High Chair			Sbucciare Peel		
Spazzolone Scrubbing Brush			Abbronzarsi Tan		
Pescatore Fisherman			Pattinare Skate		
Balcone Balcony			Starnutire Sneeze		
Rastrello Rake			Scolpire Carve		

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