Neural Correlates of Word Class Processing: An fMRI Study

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INTRODUCTION

Aphasic individuals often show impairments that are specific to word class. Most notable are (double) dissociations between noun and verb production (Miceli et al., 1984, 1988; Zingeser & Berndt, 1990).

Anomic aphasia: nouns more difficult than verbs

Agrammatic aphasia: verbs more difficult than nouns

VERBS AND ARGUMENT STRUCTURE

In fact, the verb production impairment in agrammatic aphasia is more than an across-the-board impairment for all types of verbs. It is sensitive to several factors, such as lexical frequency, imageability, and semantic factors. Most notably, agrammatic verb production is a function of a verb's *argument structure*.

VERB ARGUMENT STRUCTURE

argument ≈ participant in verb action

Possible argument structures [arguments in blue]:

1-place (intransitive) verb: John slept

2-place (transitive) verb: John punched Alex

3-place (ditransitive) verb: John gave money to Mary

For agrammatic speakers, verb production becomes more difficult as verb argument structures become more complex. That is, 3-place verbs are more difficult than 2-place verbs, which are more difficult than 1-place verbs (Figure 1). This finding has been reported in English (Thompson et al., 1997; Kim & Thompson, 2000, 2004; Thompson, 2003) as well as in other languages, such as Dutch (Jonkers & Bastiaanse, 1996, 1998), Italian (Luzzatti & Chierchia, in press), Hungarian (Kiss, 2000), and German (de Bleser & Kauschke, 2000).

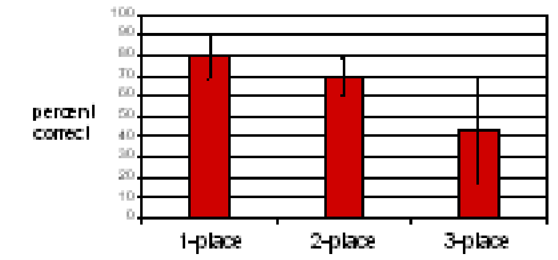

Figure 1. Aphasic production of verbs by argument structure.
(Kim & Thompson, 2000; cf. Thompson et al., 1997; Kim & Thompson, 2004)

This verb processing impairment seen in agrammatism suggests that anterior left-hemisphere regions are crucial for processing verbs and verb argument structure. Some data support this notion:

- Petersen et al. (1988) reported left frontal activation in a PET verb production task.
- Shapiro et al (2001) reported left frontal disruption of verb production but not noun production in a repetitive transcortical magnetic stimulation (rTMS) study.

However, posterior areas may participate in verb processing as well:

- Perani et al. (1999) compared, with fMRI, lexical decision of concrete and abstract nouns and verbs.

  Verbs compared to nouns = frontal and posterior perisylvian activation

- Grossman et al. (2002), using fMRI, examined:

  motion verbs (*run, walk*) – observable events
  cognition verbs (*think, know*) – non-observable events; complex argument structure

  Cognition minus motion verbs = posterior activation, including Wernicke's area

- Hadar & Palti (in press) reported greater Wernicke's area activation for verbs with more complex argument structures, in an fMRI study using a semantic judgment task.

HYPOTHESIS/EXPERIMENTAL DESIGN

QUESTION

Given these argument structure effects in aphasic populations as well as results from neuroimaging, what parts of the language network are recruited for verb argument structure processing?

HYPOTHESIS

We anticipated that increases in posterior perisylvian activation (e.g., Wernicke's area) would coincide with increases in verb argument structure complexity.

EXPERIMENTAL DESIGN

PARTICIPANTS

N = 15; 6 males, 9 females
Age range 20-30; mean = 25.2
Monolingual English speakers
Right-handed (Edinburgh Handedness Inventory); no familial left-handedness
No history of neurological/psychological problems

MATERIALS

Visually presented words/pseudowords: displayed for 1200 ms
followed by 300 ms ITI

Table 1. Experimental stimuli.

	Total number	Mean frequency*
Animal names	40	9.3
Tool names	40	9.1
1-place verbs	40	9.5
2-place verbs	40	9.3
3-place verbs	40	9.65
Pseudowords	50	---

* per million, from the CELEX database (Baayen, Piepenbrock, & van Rijn, 1993)

Null events = 1700 or 3400 msec
65% of stimuli were nulls
Stimuli appeared in two runs of 6 min 4 sec (including 6 initial dummy scans in each)
Order pseudorandomized using OPTSEQ (http://surfer.nmr.mgh.harvard.edu/optseq)

SCANNING PARAMETERS

3T scanner (Trio, Siemens)

T2-weighted functional scan	T1-weighted anatomical scan
Single-shot echo-planar imaging	3D FLASH sequence with saturation
24 slices parallel to AC-PC line	band inferior to image volume
TR=2 sec	TR= 2.1 sec
TE = 30 msec	TE = 4.38 sec
flip angle = 90°	flip angle = 20°
FOV = 220 mm	FOV = 220 mm
matrix = 64 x 64	matrix = 256 x 256
slice thickness = 3 mm	slice thickness = 1 mm

DATA ANALYSIS

All analysis used SPM2 (Wellcome Dept. of Imaging Neuroscience, Inst. for Neurology, University College London) running in a Matlab 6.5 environment (Mathworks Inc., Natick, MA). Functional scans were corrected for slice-acquisition timing and realigned to a mean functional image. The anatomical volume was coregistered to the mean image, and normalized to the MNI 152-subject template brain (ICBM, NIH P-20 project). The functional volumes were then normalized using the same transformation and were smoothed using a 10mm (FWHM) isotropic kernel. Resulting stereotactic coordinates, in MNI-space, were transformed into Talairach space using a script written by Matthew Brett (http://www.mrc-cbu.cam.ac.uk/Imaging/Common/mnispace.shtml).

RESULTS

Scan data from five of the 15 subjects were discarded because of excess noise or motion artifact. The remaining subjects showed a clear pattern of perisylvian activation under verb processing conditions. These subjects were analyzed as a group.

VERB AND NOUN ACTIVATION

For all verbs taken together, activation was seen in the inferior frontal gyrus (Brodmann's Area [BA] 44, 47) and in the superior temporal gyrus (BA 22) and superior temporal sulcus (BA 21/22). Additional activation was evident in the posterior-superior regions of the parietal lobe (see Figures 2 and 3, and Table 2). Nouns, however, elicited more widespread, and little perisylvian, activation (see Figure 2).

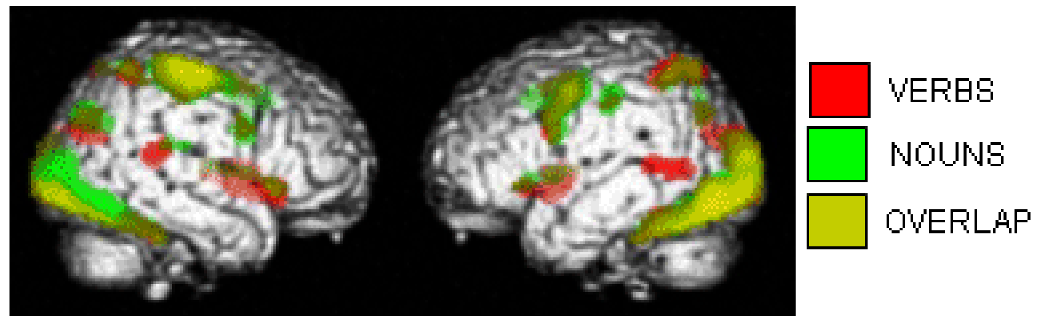

Figure 2. Lateral images showing activation for verb conditions and noun conditions. Verb conditions are red; noun conditions are green; overlap is yellow. Activations are significant at $p < .001$ (uncorrected) at a 3-voxel extent threshold.

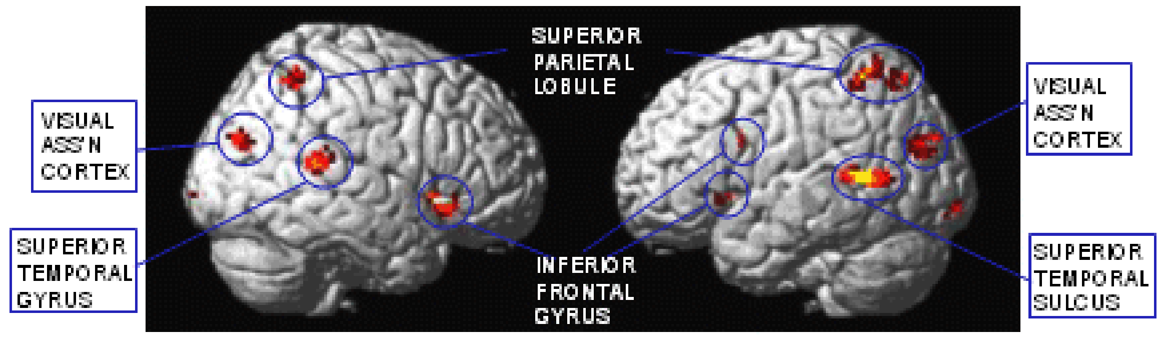

Figure 3. Lateral images showing activation for verb conditions as compared to activation for noun conditions. Activations are significant at $p < .001$ (uncorrected) at a 3-voxel extent threshold.

Table 2. Regions of statistically significant activation under verb processing conditions as compared to noun conditions.

Brain Region	BA	Side	Stereotactic Coordinates x	y	z	Z Value
Inferior Frontal Gyrus (Broca's Area)	44	Left	-56	10	22	3.32
Inferior Frontal Gyrus	47	Left	-30	21	4	3.31
	47	Right	33	21	4	4.83
Superior Temporal Sulcus (Wernicke's Area)	21/22	Left	-59	-52	8	4.36
Superior Temporal Gyrus (Wernicke's Area)	22	Right	65	-37	13	4.01
Fusiform Gyrus	37	Left	-36	-50	-10	3.98
Visual Association Cortex	19	Left	-27	-77	26	4.46
	19	Right	30	-74	29	4.34
Cuneus	17	Left	-15	-96	-3	4.54
	17	Right	9	-99	2	3.38
Precuneus	7	Left	-24	-47	52	3.46
Superior Parietal Lobule	7	Left	-33	-44	52	4.09
			-33	-52	58	3.67
			-24	-67	56	3.78
			-27	-62	50	3.38
		Right	42	-47	55	3.72
			33	-50	52	3.72

Note: BA = Brodmann's area. Voxel-wise (uncorrected) $p \leq .001$, cluster size = 3.

ARGUMENT STRUCTURE ACTIVATION

Comparison of activation for 3-place verbs to activation for both 1-place and 2-place verbs revealed activation in Wernicke's area (BA 22) bilaterally (Figure 4; Table 3). Similar activation was evident when 3-place verbs were compared to 1-place verbs, and when 3-place verbs were compared to 2-place verbs.

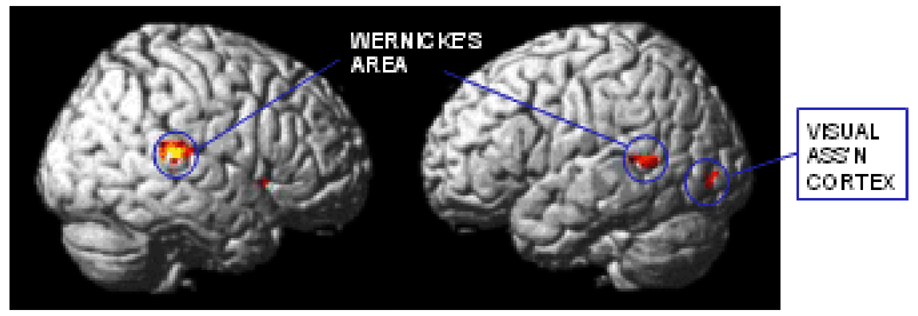

Figure 4. Lateral images showing activation for the 3-place verb condition compared to activation during 1- and 2-place verb conditions. Activations are significant at $p < .001$ (uncorrected) at a 3-voxel extent threshold.

Table 3. Regions of statistically significant activation under 3-place verb condition as compared to 1-place and 2-place verb conditions.

Brain Region	BA	Side	Stereotactic Coordinates x	y	z	Z Value
Middle Temporal Gyrus (Wernicke's area)	22	Left	-53	-49	11	3.37
Superior Temporal Gyrus (Wernicke's area)	22	Right	62	-34	16	3.87
Fusiform Gyrus	37	Left	-36	-44	-13	3.56
	37	Left	-27	-42	-18	3.19
	37	Right	30	-42	-18	4.11
Visual Association Cortex	19	Left	-27	-82	-4	3.64

Note: BA = Brodmann's area. Voxel-wise (uncorrected) $p \leq .001$, cluster size = 3.

DISCUSSION

Anterior perisylvian cortex (including Broca's area) and posterior perisylvian cortex (including Wernicke's area) were active in verb conditions but not in noun conditions. This role of Broca's area is consistent with results indicating processing of syntactic information associated with verbs (Friederici et al., 2000; Newman et al., in press; Perani et al., 1999; Warburton et al., 1996).

Activation of posterior regions, including Wernicke's area, is consistent with previous data suggesting that Wernicke's area is involved in verb processing (the aforementioned studies of Perani et al., Grossman et al., and Hadar & Palti). Most notably, the Hadar & Palti and Grossman et al. studies correlated Wernicke's area activation with increased verb argument structure complexity.

Patient studies provide another line of evidence. In several studies, Wernicke's aphasic subjects demonstrated inability to process aspects of argument structure information. McCann & Edwards (2000) found an inability to detect argument structure violations (e.g., *John gives a car*) in Wernicke's aphasic patients. Shapiro & Levine (1990) reported results of an online sentence processing task in which verb argument structure was manipulated. Wernicke's patients (but not Broca's patients) showed a lack of sensitivity to argument structure, suggesting that they were unable to access argument structure information. This in turn suggests that Wernicke's area is necessary for verb argument structure processing.

Together with these findings, our data indicate that posterior portions of the language network are essential for processing verb argument structure.

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