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Activation of Broca's Area by Syntactic Processing Under Conditions of Concurrent Articulation

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Abstract: Regional cerebral blood flow (rCBF) was measured with positron emission tomography (PET) when 11 subjects made plausibility judgments about written sentences that varied in their syntactic complexity. While making their judgments, subjects uttered the word "double" aloud at a rate of one utterance per second to inhibit their ability to rehearse the sentences. Blood flow increased in Broca's area when subjects made judgments about the more complex sentences. This result replicates and extends previous findings that blood flow increases in this region when subjects process complex syntax under no interference conditions. The results of this experiment provide strong evidence that the increase in blood flow seen in Broca's area in association with processing syntactically complex structures is not due to subvocal rehearsal of those structures, but rather results from processing syntactic forms themselves. *Hum. Brain Mapping 9:65–71, 2000.* © **2000 Wiley-Liss, Inc.**

Key words: syntactic processing; localization of syntax

INTRODUCTION

Comprehending language involves assigning the syntactic structure of a sentence and using that structure to determine the propositional content of the sentence [Frazier and Clifton, 1996; MacDonald et al., 1994]. The neural basis for syntactic processing has been studied through deficit-lesion correlational analyses, observations of event-related potentials (ERPs), and functional neuroimaging.

There is very strong evidence from deficit-lesion correlational analyses that the assignment of syntactic form is largely carried out in the dominant perisylvian association cortex [Caplan et al., 1996]. Some researchers have argued that one aspect of syntactic processing—relating the head noun of a relative clause to its position in the relative clause—is affected only by lesions in Broca's area and that lesions in this region affect only this syntactic process [Zurif et al., 1993; Swinney et al., 1995; Grodzinsky, 1999], but others disagree that the data from aphasia can be interpreted this way [Caplan, 1995, 1999; Berndt and Caramazza, 1999]. The claim that relating the head noun of a relative clause to its position in the relative clause

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involves Broca's area is consistent with the occurrence of a "left anterior negativity (LAN)" wave associated with processing more complex relative clauses [Kluender and Kutas, 1993a, b]. However, the exact location of the generator(s) of the LAN is not known.

Functional neuroimaging studies using PET and fMRI are beginning to provide data regarding the localization of syntactic processing in sentence comprehension. Studies that have compared reading and listening to sentences with processing words have found activation in a relatively wide region of the perisylvian cortex, extending into the anterior temporal lobe [Mazoyer et al., 1993; Bavelier et al., 1997; Chee et al., 1999]. However, this widespread pattern of rCBF reflects many differences between processing words and sentences and does not necessarily isolate syntactic processing. Controlled experiments have focused more narrowly on syntactic processing. One approach has been to have subjects make plausibility judgments about sentences with the same words and meaning that vary in their syntactic complexity. These studies have shown that processing syntactically more complex sentences leads to increases in rCBF in Broca's area [Stromswold et al., 1996; Caplan et al., 1998, 1999]. Another approach has been to have subjects read sentences that vary in syntactic complexity and verify assertions about their meanings. This approach has documented increases in rCBF in both Broca's area and Wernicke's area [Just et al., 1996; Dapretto et al., 1998], as well as in the homologous regions of the right hemisphere [Just et al., 1996]. The region of activation common to all these well-controlled studies of syntactic processing is Broca's area; the differences across studies may reflect differences in operations such as retaining a sentence for a short period of time in memory while answering a question about its meaning.

One important reservation about these more controlled functional neuroimaging studies is that the increases in rCBF they report may be due to one or more operations associated with processing syntactically more complex sentences, rather than that associated with syntactic processing itself. The leading candidate for such an operation is subvocal rehearsal. Subjects recode written sentences into phonological form in comprehension [Pollatsek et al., 1992], and written comprehension is affected by concurrent articulation that interfers with rehearsal [Waters et al., 1987]. It is possible that subjects rehearse more complex sentences more than simple ones. This alternative analysis is particularly important to consider because there is considerable evidence that rehearsal involves Broca's area [Zatorre et al., 1993; Smith et al., 1998]. It thus could be that the increased rCBF seen in Broca's area when sentences with more complex syntax are processed is a result of that region being involved in subvocal rehearsal, not syntactic processing per se.

We tested this possibility by examining syntactic processing while inhibiting subjects' abilities to rehearse by having them engage in a concurrent repetitive simple articulation task. Concurrent articulation interferes with rehearsal, as is seen by its effect on word length effects in span tasks. In the absence of a concurrent task, subjects have longer spans for shorter words [Baddeley et al., 1975] and the magnitude of the word length effect correlates with articulatory rate [Waters et al., 1992]. Concurrent articulation eliminates the word length effect in span tasks [Baddeley et al., 1975]. This pattern of performance has been taken as evidence that the word length effect is largely due to rehearsal, which allows more short words than long words to be recalled, and that concurrent articulation interferes with, or even eliminates, rehearsal (Baddeley, 1986). Accordingly, differences in rCBF associated with subjects' processing more complex syntactic structures that persist under concurrent articulation conditions are not likely to be due to differences in rehearsal in the more and less syntactically complex conditions. It is considerably more likely that any such differences are due to abstract psycholinguistic operations associated with structuring and interpreting complex syntactic structures. In the experiment reported here, we had subjects accomplish the plausibility judgment task reported in Stromswold et al. [1996] and Caplan et al. [1998] under conditions of concurrent articulation.

METHODS

Subjects

Eleven monolingual English-speaking college students, 5 males and 6 females, mean age 25.8 years (range: 19–35 yr), mean years of education 17 (range: 13–20 yr) participated after having given informed consent. All were strongly right-handed and had no first-degree left-handed relatives. All had normal vision and hearing and no history of neurological or psychiatric disease.

Procedure

Subjects were scanned during two experimental conditions. The two conditions were presented in blocked format, with each subject being presented each condition three times. Each block contained 24

items. The order of presentation of blocks was counterbalanced across subjects in order to eliminate any effect of order of presentation on behavioral or PET data.

Sentences in the two conditions contained the same words and propositions and differed only in their syntactic structure. Sentences in condition 1 contained subject-object, center-embedded relative clauses (e.g., *The juice that the child enjoyed stained the rug*) and sentences in condition 2 contained object-subject, right-branching relative clauses (e.g., *The child enjoyed the juice that stained the rug*). These sentences were chosen as stimuli in this and previous experiments because results from previous psycholinguistic research indicate that normal subjects reliably make more errors and take longer to process sentences that contain center-embedded relative clauses sentences than sentences that contain right-branching relative clauses [e.g., King and Just, 1991; Waters et al., 1987]. This is thought to result from the memory load associated with holding the matrix subject NP in a parsing buffer until it is assigned a thematic role [Berwick and Weinberg, 1984], or with the combination of this memory load and the operation of structuring the relative clause [Just and Carpenter, 1992].

All sentences contained verbs that required that a noun in either subject or object position be either animate or inanimate. Half of the sentences in each condition were semantically plausible sentences that obeyed this restriction, and half were semantically implausible sentences that violated this restriction (e.g., the center-embedded sentence, *The child that the juice enjoyed stained the rug,* or the right-branching sentence, *The juice enjoyed the child that stained the rug*).

A number of controls and counterbalances were introduced to ensure that the three conditions differed only on the dimension(s) outlined above and to ensure that subjects did not adopt alternative strategies for judging the sentences. The following factors were controlled for in the design of the stimuli and the experiment.

1. Sentences were based on scenarios. There were a total of 144 scenarios (such as the scenario involving a child staining a rug by spilling juice onto it), and each scenario appeared in each condition equally often across subjects. Because each scenario appeared in each condition equally often, differences in semantic goodness of scenarios, frequency of words, word choice, etc., could not be responsible for any differences in rCBF between the conditions. No verb appeared in more than one scenario and no subject judged any scenario more than twice.
2. The animacy of subject and object noun phrases and the plausibility of the sentences were systematically varied within block by sentence type. Thus, e.g., the semantically plausible sentence, *The patient that the drug cured thanked the doctor,* and the semantically implausible sentence, *The girl that the miniskirt wore horrified the nun,* both contained an animate noun phrase, followed by an inanimate noun phrase, followed by an animate noun phase. Animacy type, acceptability, and sentence type were counterbalanced within subjects. This feature of the design was included to ensure that subjects could not make plausibility judgments on the basis of the sequence of animacy of the nouns.
3. All noun phrases were singular, common, and definite. This feature of the design was included to ensure that subjects would not be influenced by discourse effects.
4. Sentences became implausible at various points in the relative clauses and the main clauses. This feature was included to increase the variability of the stimuli each each block. Some anomalies occurred at the end of the sentence to ensure that subjects read each sentence in its entirety before they could decide if it was plausible. Overall, the point at which center-embedded sentences became implausible was earlier than the point at which right-branching sentences became implausible. This feature was included to eliminate the possibility that the advantage enjoyed by right-branching sentences was attributable to right-branching sentences becoming implausible at an earlier point than center-embedded sentences.

PET scans were taken as subjects read and judged the goodness of sentences presented visually in whole sentence format on a Macintosh Classic II computer screen. The computer screen rested on a shelf 12″ from the subject's eyes. After a 300 msec fixation point, a whole sentence appeared on a single line, subtending a visual angle of 20–25°. This sentence remained on the computer screen until the subject responded via keypresses with two fingers of the left hand. After a response, the screen was blank for 700 msec, followed first by the 300 msec fixation point, and then by the next sentence to be judged. Reaction time and error rate data were collected during PET scanning and subjects were told to make acceptability judgments as quickly as possible without making errors.

TABLE I. Accuracy and RT results for right branching and center-embedded sentences

	Right branching Object-subject		Center embedded Subject-object	
	Plausible	Implausible	Plausible	Implausible
Mean percent errors/subject	7.8	7.8	18.3	12.2
Mean RT (sd) in msec	4,373 (1,215)	4,237 (1,176)	5,168 (1,683)	5,215 (1,685)

Subjects repeated the word "double" at a rate of 1 utterance per sec, timed with a metronome, while doing the plausibility judgment task. Subjects received practice in doing the plausibility task with simple active sentences (e.g., *The child licks the lollipop, The lollipop licks the child*) while repeating "double" in the psychology lab prior to the scanning session. They began to repeat "double" prior to the experiment and were given additional practice trials before the first block.

A General Electric Scanditronix PC4096 15 slice whole body tomograph was used in its stationary mode to acquire PET data in contiguous slices with center-to-center distance of 6.5 mm (axial field equal to 97.5 mm) and axial resolution of 6.0 mm FWHM, with a Hanning-weighted reconstruction filter set to yield 8.0 mm in-plane spatial resolution (FWHM). Subjects inhaled ^{15}O-CO_2 gas by nasal cannulae within a face mask for 90 sec, reaching terminal count rates of 100,000–200,000 events per sec. Each PET data acquisition run consisted of 20 measurements, the first three with 10 sec duration and the remaining 17 with 5 sec duration each. Scans 4–16 were summed after reconstruction to form images of relative blood flow. The summed images from each subject were realigned using the first scan as the reference using a least-squares fitting technique [Alpert et al., 1996]. Spatial normalization to the coordinate system of Talairach and Tournoux [1988] was performed by deforming the contour of the 10 mm parasagittal PET slice to match the corresponding slice of the reference brain [Alpert et al., 1993]. Scans were filtered with a two-dimensional Gaussian filter, full width at half maximum set to 20 mm. Data were analyzed with SPM95 (Wellcome Dept. of Cognitive Neurology, London). The PET data at each voxel was normalized by the global mean and fit to a linear statistical model with cognitive state (i.e., scan condition) considered as a main effect. Hypothesis testing was performed using the method of planned contrasts at each voxel [Worsley et al., 1996]. It was decided a priori that a change in rCBF in Broca's area would be considered significant if it exceeded the z-score threshold significance for that region at the $P < .01$ level as described by Worsley et al. [1996]. Other regions of interest (ROIs) were also examined for changes in rCBF that exceeded the thresholds for particular regions described by Worsley et al. [1996].

RESULTS

Behavioral results are shown in Table I. Responses were longer and less accurate for center-embedded than right-branching sentences. Analyses of variance by subjects and items with syntactic structure and plausibility as factors yielded a main effect of sentence structure ($F_{subjects,\ RT}(1,\ 10) = 18.0,\ P < .001$; $F_{Items,\ RT}(1, 284) = 36.8, P < .001$; $F_{Subjects,\ Errors}(1, 10) = 13.6, P < .01$; $F_{items,\ Errors}(1, 284) = 17.3, P < .001$), and no other significant main effects or interactions.

rCBF results are shown in Table II and Figure 1. The hypothesis that rCBF would increase in Broca's area

TABLE II. Areas of increased rCBF for subtraction of PET activity associated with right branching sentences from center embedded sentences

1. *Broca's region in which an increase in rCBF was predicted*

Location	Max Z-score	Number of pixels (z > 3.1)	Location {X, Y, Z}
Broca's area (Brodmann 45)	3.6	112	−46, 36, 4

2. *Regions in which z-scores exceeded the threshold for significance for the individual region but not for multiple comparisons across all brain regions*

Location	Max Z-score	Number of pixels (z > 3.1)	Location {X, Y, Z}
Left thalamus (centromedian nucleus)	3.4	62	−14, −20, 4
Cingulate gyrus (Brodmann 31)	3.4	158	−10, −36, 40
Medial frontal gyrus (Brodmann 10)	3.2	113	0, 56, 8

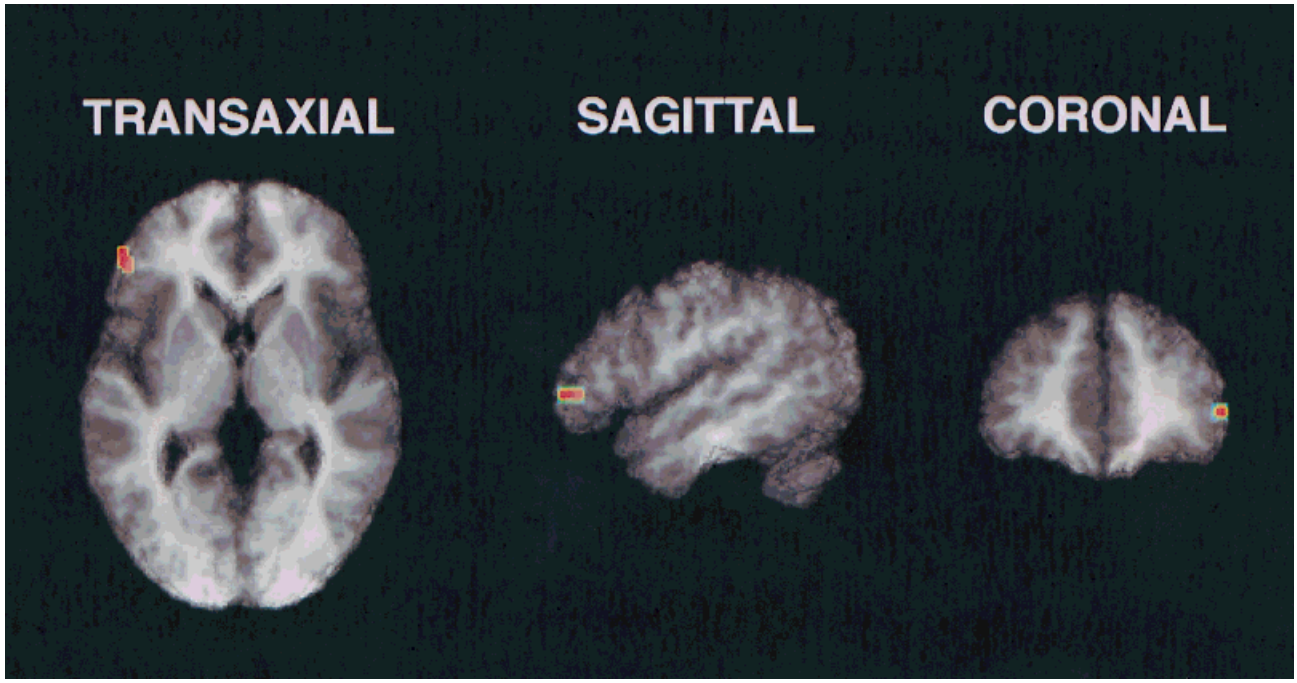

Figure 1.
Statistical parameter mapping (SPM) image showing an increase in rCBF in Broca's area when subjects processed syntactically more complex sentences under conditions of concurrent articulation.

when PET activity in condition 1 (center-embedded sentences) was contrasted with PET activity in condition 2 (right-branching sentences) was confirmed. Three other regions showed increases in rCBF that exceeded the thresholds for significance of those regions given by Worsley et al. [1996]: the centromedian nucleus of the left thalamus, the medial frontal gyrus, and the posterior cingulate gyrus. None of these activations reached the threshold for significance required for multiple comparisons across all brain regions.

DISCUSSION

The increase in rCBF in Broca's area reflects the demands of processing the more complex syntactic structure. Since rehearsal was likely to be substantially reduced, perhaps eliminated, under concurrent articulation conditions, this increase in rCBF is not likely due to increased rehearsal of the more complex sentences.

There are several operations that might occur in parsing subject-object center embedded sentences that differ from those involved in parsing object-subject right-branching sentences that might give rise to these behavioral and rCBF effects. One is that assigning the noun phrase encountered within the subject-object relative clause as the subject of the relative clause may require constructing more intermediate products of computation than are constructed in assigning the noun phrase encountered within the object-subject relative clause as the object of the clause [Just and Carpenter, 1992]. It is, however, not clear that the phrase markers associated with subject-object and object-subject sentences differ in this way. A second is that the head of a subject-object relative clause must be maintained in a memory buffer until it is assigned a thematic role in the *main* clause, and this is not required in object-subject sentences. It is unlikely that this mechanism accounts for either the behavioral or rCBF differences associated with processing subject-object vs. object-subject sentences, however, because the same behavioral and rCBF effects occur with cleft-object and cleft-subject sentences [Caplan et al., 1994, 1999], which do not make these different memory demands. A third is that the head of relative clause must be maintained in a memory buffer until it is assigned a thematic role in the *relative* clause, and this occurs later in the subject-object than in the object-subject clauses, adding to the memory load associated with processing these object-relativized sentences

[Berwick and Weinberg, 1984; Gibson, 1998]. This seems to us to be the most likely source of both the behavioral and rCBF effects found here and in previous studies.

The memory system involved in this process has been conceptualized in two ways: as part of a general verbal working memory [Just and Carpenter, 1992] and as a specialized working memory system related to syntactic processing and other first-pass psycholinguistic operations in the comprehension process [Caplan and Waters, 1999]. The present results support this latter view, because the region of the brain in which activation was seen in this experiment is caudal to that activated in other working memory studies in which conscious, controlled verbal processing was required [Petrides et al., 1993].

The exact location of the peak increase in rCBF within Broca's area differs from that in studies by Stromswold et al. [1996] and Caplan et al. [1998], who reported increased rCBF centered in the pars opercularis (Brodmann's area 44), but is consistent with results reported by Caplan et al. [1999], who found increased rCBF centered in the pars triangularis (Brodmann's area 45) in an auditory paradigm. The spatial extent of all these activations extends over both Brodmann areas 44 and 45, however. Just et al. [1996] also reported activation in their study in both the pars opercularis and the pars triangularis. At this point, it appears that despite their histological differences [Amunts et al., 1999], both these areas can be activated by syntactic processing. Whether the exact localization of peak rCBF reflects different functional specializations of these two areas remains to be investigated.

The rCBF effects in the left centromedian nucleus, the medial frontal gyrus, and the posterior cingulate gyrus deserve comment. One may discount these effects since they were not predicted and are only reliable if we do not consider them in the context of blood flow throughout the entire brain, but we prefer to bring them to readers' attention because increases in rCBF have been found in the cingulate and medial frontal gyrus in some previous studies [Caplan et al., 1999]. These increases in rCBF may therefore reflect neural activity reliably associated with processing the subject-object compared to the object-subject sentences in this paradigm. Our interpretation of increases in rCBF in the cingulate and medial frontal gyrus in previous studies has been to attribute them tentatively to roles these structures play in attentional and control processes [Posner et al., 1987, 1988]. The presence of activity in left centromedian nucleus may have a similar explanation, since CM is connected to the reticular activating system [Nauta and Kuypers, 1958] and projects widely across cortex through collateral fibers [Jones and Leavitt, 1974]. We are tentative in this analysis because, as pointed out by an anonymous reviewer of this report, the evidence for a role for these structures in nondomain-specific attentional processes is limited.

In conclusion, this study provides evidence that one syntactic operation in sentence comprehension relies at least in part on the neocortex in Broca's area.

REFERENCES

Alpert N, Berdichevsky D, Weise S, Tang J, Rauch S. 1993. Stereotactic transformation of PET scans by nonlinear least squares. In: Uemura K, editor. Quantifications of brain functions: tracer kinetics and image analysis in brain PET. New York: Elsevier, p 459–463.

Alpert NM, Berdichevsky D, Levin Z, Morris ED, Faschman AJ. 1996. Improved methods for image registration. NeuroImage 3:10–18.

Amunts K, Schleicher A, Bergell U, Mohlberg J, Uylings HBM, Zilles K. 1999. Broca's region re-visited: cytoarchitecture and intersubject variability. J Comp Neurol (in press).

Baddeley AD. 1986. Working memory. New York: Oxford University Press.

Baddeley AD, Thompson N, Buchanan M. 1975. Word length and the structure of short-term memory. J Verbal Learning Verbal Behavior 14:575–589.

Bavelier D, Corina D, Jezzard P, Padmanabhan S, Clark VP, Karni A, Prinster A, Braun A, Lalwani A, Rauschecker JP, Turner R, Neville H. 1997. Sentence reading: a functional MRI study at 4 Tesla. J Cognitive Neurosci 9:664–686.

Berndt R, Caramazza A. 1999. How "regular" is sentence comprehension in Broca's aphasia? It depends on how you select the patients. Brain and Language (in press).

Berndt R, Mitchum C, Haendiges A. 1996. Comprehension of reversible sentences in "agrammatism": a meta-analysis. Cognition 58:289–308.

Berwick RC, Weinberg A. 1984. The grammatical basis of linguistic performance: language use and acquisition. Cambridge: MIT Press.

Caplan D. 1995. Issues arising in contemporary studies of disorders of syntactic processing in sentence comprehension in agrammatic patients. Brain and Language 50:325–338.

Caplan D. Lesion location and aphasic syndrome do not tell us whether a patient will have an isolated deficit affecting the co-indexation of traces. Behavioral Brain Sci (in press).

Caplan D, Waters GS. 1999. Verbal working memory and sentence comprehension. Behavioral Brain Sci 22:114–126.

Caplan D, Hildebrandt N, Waters GS. 1994. Interaction of verb selectional restrictions, noun animacy and syntactic form in sentence processing. Language Cognitive Processes 9:549–585.

Caplan D, Hildebrandt N, Makris N. 1996. Location of lesions in stroke patients with deficits in syntactic processing in sentence comprehension. Brain 119:933–949.

Caplan D, Alpert N, Waters G. 1998. Effects of syntactic structure and propositional number on patterns of regional blood flow. J Cognitive Neurosci 10:541–552.

Caplan D, Alpert N, Waters G. 1999. PET studies of sentence processing with auditory sentence presentation. Neuroimage 9:343–351.

Chee MWL, Caplan D, Soon CS, Sriram N, Tan EWL, Thiel T, Weekes B. 1999. Processing of visually presented sentences in mandarin and English studied with fMRI. Neuron 23:127–137.

Dapretto M, Bookheimer YS, Strojwas M, Cohen MS. 1998. An fMRI study of syntactic processing using a selective attention paradigm. Neuroimage 7:S1.

Frazier L, Clifton C. 1996. Construal. Cambridge:MIT Press.

Gibson E. 1998. Syntactic complexity: locality of syntactic dependencies. Cognition 68:1–76.

Grodzinsky Y. The neurology of syntax: language use without Broca's area, Behavioral Brain Sci. (in press).

Hagoort P, Brown C, Groothusen J. 1993. The syntactic positive shift (SPS) as an ERP measure of syntactic processing. Language Cognitive Processes 8:485–532.

Jones EG, Leavitt RY. 1974. Retrograde axonal transport and the demonstration of nonspecific projections to the cerebral cortex and striatum from thalamic intralaminar nuclei in the cat, rat, and monkey. J Comp Neurol 154:349–378.

Just MA, Carpenter PA. 1992. A capacity theory of comprehension: Individual differences in working memory. Psychological Rev 99:122–149.

Just MA, Carpenter PA, Keller TA, Eddy WF, Thulborn KR. 1996. Brain activation modulated by sentence comprehension. Science 274:114–116.

Kluender R, Kutas M. 1993a. Bridging the gap: evidence from ERPs on the processing of unbounded dependencies. J Cognitive Neurosci 5:196–214.

Kluender R, Kutas M. 1993b. Subjacency as a processing phenomenon. Language Cognitive Processes 8:573–633.

King J, Just MA. 1991. Individual differences in syntactic processing: the role of working memory. J Memory Language 30:580–602.

MacDonald MC, Pearlmutter NJ, Seidenberg MS. 1994. Lexical nature of syntactic ambiguity resolution. Psychological Rev 101: 676–703.

Mazoyer B, Tzourio N, Frak V, Syrota A, Murayama N, Levrier O, Salamon G. 1993. The cortical representation of speech. J Cognitive Neurosci 5:467–479.

Nauta WJH, Kuypers HGJM. 1958. Some ascending pathways in the brain stem reticular formation. In: Jaspers et al, editors. Reticular formation of the brain. Boston: Brown, p 3–30.

Petrides M, Alivisatos B, Meyer E, Evans A. 1993. Functional activation of the human frontal cortex during the performance of verbal working memory tasks. Neurobiology 90:878–882.

Pollatsek A, Lesch M, Morris RK, Rayner K. 1992. Phonological codes are used in the integration of information across saccades in word identification and reading. J Exp Psychol 18: 148–162.

Posner MI, Inhoff AW, Friedrich FJ, Cohen A. 1987. Isolating attentional systems: a cognitive-anatomical analysis. Psychobiology 15:107–121.

Posner MI, Peterson SE, Fox PT, Raichle ME. 1988. Localization of cognitive operations in the human brain. Science 240:1627–1631.

Smith EE, Jonides J, Marshuetz C, Koeppe RA. 1998. Components of verbal working memory: evidence from Neuroimaging. Proc Natl Acad Sci 95:876–882.

Stromswold K, Caplan D, Alpert N, Rauch S. 1996. Localization of syntactic comprehension by positron emission tomography. Brain and Language 52:452–473.

Swinney D, Zurif E, Prather P, Love T. 1996. Neurological distribution of processing resources underlying language comprehension. J Cognitive Neurosci 8:174–184.

Talairach J, Tournoux P. 1988. Co-planar stereotaxic atlas of the human brain. New York: Thieme.

Waters G, Caplan D, Hildebrandt N. 1987. Working memory and written sentence comprehension. In: Coltheart M, editor. Attention and performance XII. London: Erlbaum, p 531–555.

Waters GS, Rochon E, Caplan D. 1992. The role of high-level speech planning in rehearsal: Evidence from patients with apraxia of speech. J Memory and Language 31:54–73.

Worsley KJ, Marrett S, Neelin P, Vandal AC, Friston KJ, Evans EC. 1996. A unified statistical approach for determining significant signals in images of cerebral activation. Hum Brain Mapp 4:58–73.

Zatorre RJ, Evans AC, Meyer E, Gjedde A. 1992. Lateralization of phonetic and pitch discrimination in speech processing. Science 256:846–849.

Zurif E, Swinney D, Prather P, Solomon J, Bushell C. 1993. An on-line analysis of syntactic processing in Broca's and Wernicke's aphasia. Brain and Language 45:448–464.