Brain Activation Modulated by Sentence Comprehension

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The comprehension of visually presented sentences produces brain activation that increases with the linguistic complexity of the sentence. The volume of neural tissue activated (number of voxels) during sentence comprehension was measured with echo-planar functional magnetic resonance imaging. The modulation of the volume of activation by sentence complexity was observed in a network of four areas: the classical left-hemisphere language areas (the left laterosuperior temporal cortex, or Wernicke's area, and the left inferior frontal gyrus, or Broca's area) and their homologous right-hemisphere areas, although the right areas had much smaller volumes of activation than did the left areas. These findings generally indicate that the amount of neural activity that a given cognitive process engenders is dependent on the computational demand that the task imposes.

This study examines what it means to be "thinking harder" in the course of sentence comprehension, in terms of functional magnetic resonance imaging (fMRI)–measured brain activation. One of the challenges of brain science is to relate the dynamics of higher level cognition to the equally dynamic activity of brain-level events. A possible meeting ground between these two levels is the modulation in the amount of neuronal activity (at the brain level) in a given task, measured as a function of the amount of computational demand that the task places on cognitive resources (*1*). In particular, we examined whether sentences that were more computationally demanding also engender more brain activation (*2*, *3*).

At the cognitive level, sentence comprehension requires combining information from a sequence of words and phrases, computing their syntactic and thematic relations, and using world knowledge to construct a representation of the sentence meaning. These processes require the consumption of computational resources to perform the comprehension operations and also to maintain the representations of the component word meanings, propositions, and relational structures in an activated state during the processing (*1*).

At the brain level, sentence comprehension entails activation in a network of cortical areas, most prominent of which are the left laterosuperior temporal cortex (Wernicke's area) (*4*) and the left inferior frontal gyrus (Broca's area) (*5*). In addition, another set of areas sometimes observed to be activated during sentence comprehension are the right-hemisphere homologs of these two classical language areas (*6*). Although the left hemisphere is usually the primary site of language comprehension and production in right-handed people, the right-hemisphere homologs may be recruited in times of high demand. The amount of brain activation in these four areas was examined as a function of the amount of processing demand imposed by the comprehension of different sentence structures.

We manipulated comprehension demand by using three types of sentences that differ in structural complexity but are superficially similar, containing two clauses and the same number of words, as shown below.

1) Active conjoined (no embedded clause): "The reporter attacked the senator and admitted the error."

2) Subject relative clause: "The reporter that attacked the senator admitted the error."

3) Object relative clause: "The reporter that the senator attacked admitted the error."

The three sentence types increase in complexity from type 1 to 3, by several measures. Type 1 sentences contain active clauses that are simply conjoined, whereas the somewhat more complex type 2 sentences contain a relative clause that interrupts a main clause. Finally, in type 3 sentences with object relative clauses, not only is the main clause interrupted, but the first noun plays two different roles, as the subject of the main clause and the object of the relative clause. Also, the most complex type (Object Relative) produces longer reading times, higher comprehension error rates, and larger pupillary responses in adults than do subject relatives (*7*). A similar ordering arises from the processing indices (processing time, error probability, and resource consumption) in a computational model of human comprehension (*8*). Thus, several criteria suggest an ordering in processing demand from the least complex sentence (actives that are simply conjoined), through subject relatives, to the most complex (object relatives).

Fifteen college-age participants (*9*) read sets of four to five successive sentences of the same linguistic type (each such set will be referred to as an epoch), and after each sentence, answered true or false (with a manual response by use of two hand-held push buttons) to a comprehension probe, such as "The reporter attacked the senator, true or false?," of one of the two clauses. The response terminated the sentence display, which was viewed on a rear-projection screen at 45 cm away. Unlike the three sample sentences above, the stimulus sentences varied in content, all involving concrete, familiar nouns and actions. Another condition, to control for the visual components of the task, involved scanning consonant strings (such as, "Pws ntkgqrfm zjkjrng kwtdc sbfght swn mjrdbxq kgt mxbtq"), followed by a nonword target to be matched to one of two other nonwords. There were four instances of each type of epoch (Active, Subject Relative, Object Relative, Consonant), along with five instances of a rest control epoch, in which the participant fixated a centered asterisk for 24 s without performing any task. The order of the 21 epochs was pseudorandomized to balance order effects, and successive epochs were separated by 6 s of rest (*10*).

We also obtained behavioral indices of sentence complexity (mean processing time and error probability) for the last 12 of the 15 participants while they were being scanned. The indices increased monotonically with sentence complexity [analysis of variance (ANOVA), $F(1,11) = 71.94$, $P < 0.01$ for the processing times].

The central result is that all four areas showed an increase in the amount of brain activation as the demand on the language processing system increased from the simplest to the most complex sentence structures (Fig. 1). The mean number of significantly activated voxels in the left laterosuperior temporal cortex differed reliably across the three sentence conditions, as indicated by a one-way (ANOVA) [$F(2,28) = 11.37$, $P < 0.01$ (*11*)], and the pairwise increase in the number of activated voxels between adjacent conditions

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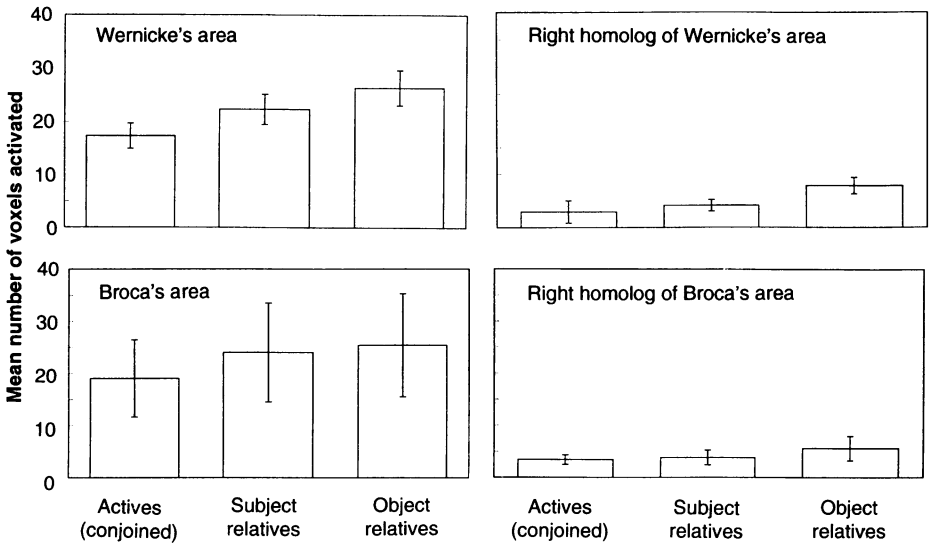

Fig. 1. The top panels indicate the mean number of voxels activated per condition in the left (Wernicke's area) and right laterosuperior temporal cortex (and standard errors of the means over 15 participants). The bottom panels indicate the mean number of voxels activated per condition in the left (Broca's area) and right inferior frontal cortex (and standard errors of the means over only five participants).

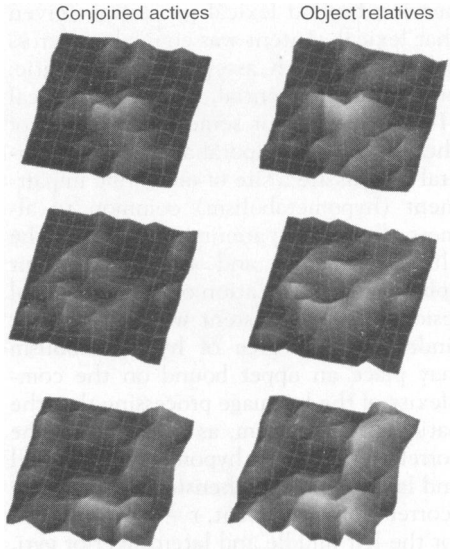

Fig. 3. The three-dimensional plots depict the *t* values of the activated and surrounding voxels from an axial slice of the left temporal region (the anterior region is at the top of each image; the medial region is at the left). The *t* value is a proxy for the voxel's activation increase over the rest condition that controls for variance. The three rows of plots depict data from three different participants.

was also reliable [all three pairwise Student $t(14)$ values >2.4, all P values <0.03] (*12*). The precise area that was activated within the left temporal region of interest (ROI) corresponds to the superior temporal gyrus and superior temporal sulcus in most participants and the middle temporal gyrus in the remainder, areas that correspond to Brodmann's areas 22 and 42, and sometimes area 21 (*13*). The modulation of the activation volume in the left inferior frontal gyrus (Brodmann's areas 44 and 45) was similar. However, the activation in the frontal gyrus was difficult to evaluate precisely, given the locations of the axial scans. Therefore, the last five participants were additionally scanned in an ancillary study using coronal slices and presenting comparable sentences (Fig. 1, bottom panels). To compensate in the statistical analysis for the small number of participants, we used a more sensitive design to compare the mean percent change in signal intensity (relative to the rest condition) across the three conditions in the voxels that were activated in any of the sentence conditions in any of the five participants. This analysis indicated a highly reliable difference [$F(2,304) = 8.97$, $P < 0.01$] in an ANOVA in which voxels were nested within participants. The mean percent change in signal intensity increased from 1.8% in the Active condition to 1.97% in the Object Relative condition.

The right-hemisphere homologs of Wernicke's and Broca's areas were also activated but at lower levels, with only 26% as many voxels in the right homolog as in Wernicke's area and 22% as many voxels in the right homolog as in Broca's area. Importantly, both right homologs showed a modulation in activation as a function of demand. For 13 participants (excluding two who had only a left temporal coil), the number of voxels that was activated in Wernicke's homolog increased with sentence demand [$F(2,24) = 4.20$, $P < 0.05$] (Fig. 1, top right). (Two participants, one male and one female, were unlike the rest in that they showed almost as much activation in the right temporal cortex as in the left.) Similarly, the right homolog of Broca's area produced reliable differences in the percent changes in signal intensity among the activated voxels in the three sentence conditions for the five participants [$F(2,62) = 3.40$, $P < 0.05$].

As Fig. 2 suggests, the processing of the three sentence types recruits an increasing number of voxels from overlapping pools, as opposed to recruiting three disjoint sets of voxels. The additional voxels that became activated only when the sentences were more complex were spatially contiguous or proximal to those voxels activated during the processing of simpler sentences within each area. This topographic property is illustrated in the pairs of three-dimensional plots in (Fig. 3), depicting the *t* values for voxels in the axial slice with the largest number of activated voxels in Wernicke's area for each of three participants. That the surrounding voxels in these unthresholded graphs remain unaffected indicates that the activation is spatially selective.

In addition to their roles as part of a functional system, each area may have an affinity for certain types of more specialized processing. The left temporal region may be involved in some level of compre-

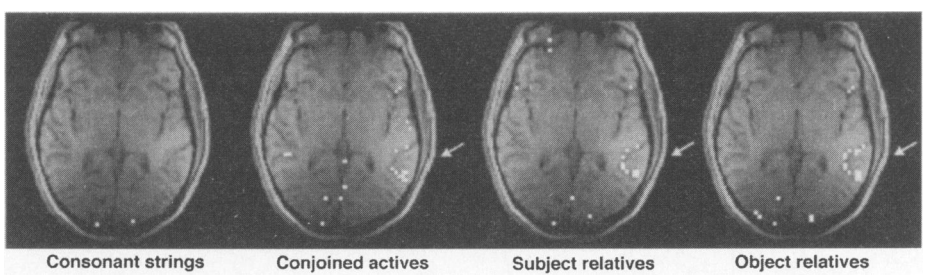

Fig. 2. Thresholded fMRI brain activation images (superimposed on structural images) for only the most activated slice from one participant. The number of activated voxels (shown in white) in the left laterosuperior temporal cortex (Wernicke's area, indicated by white arrows) generally increases with sentence complexity.

hension beyond lexical processing (given that lexical content was equivalent across conditions), such as syntactic, thematic, pragmatic, referential, or phonological (*14*) processing, or some combination of these. The left temporal and temporoparietal regions are a site of metabolic impairment (hypometabolism) common to almost all aphasic patients regardless of the clinical category and severity of their aphasia and the location of their structural lesions (*15*). Consistent with the present findings, the degree of hypometabolism may place an upper bound on the complexity of the language processing that the patients can perform, as indicated by the correlation between hypometabolism level and language comprehension performance (correlation coefficient, $r = 0.60$ and 0.44 for the left middle and laterosuperior gyri, respectively).

Although the precise role of Broca's area in comprehension is not known, it has been suggested that the area might be the generator of sound-based or articulatory codes (*16*) or the area might be involved in syntactic processing (*5*) or a combination of both. Finally, the current data implicate the right homologs in literal processing, with the involvement dependent on the sentence difficulty, rather than their being associated only with the processing of figurative meaning (*6*, *17*) and prosodic processing.

The reading of the consonant strings (which were arranged in sentence-like configurations) succeeded in producing occipital activation similar to that produced by reading the sentences, as well as a small amount of activation in the left temporal area and left inferior frontal gyrus and produced 37% and 24% of the number of activated voxels in these two areas, respectively, that were activated in response to the simplest sentence types.

The dorsolateral prefrontal cortex (ROIs of three adjacent coronal slices containing the middle frontal gyrus, bounded by the limiting sulci) showed bilateral activation for three of the five participants who were scanned coronally; the activation increased with sentence complexity. This area has been shown to be activated in tasks requiring planning and executive control (*3*, *18*) processes evoked by the more demanding conditions for some, but not all, participants.

The answer to the question of how the brain responds to increased comprehension demand is that it recruits more neural tissue in each area of a network of cortical areas. Thus, any mapping between brain site and cognitive function is a variable function between two levels of description of a dynamic system, modulated by the demand of the task, and so cannot be a static cartography of brain anatomy.

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9. Informed consent with a protocol approved by the University of Pittsburgh Institutional Review Board was obtained from 10 male and 5 female right-handed native English speakers, who were college students or graduates, aged 18 to 30.
10. The gradient echo, resonant echo-planar fMRI used BOLD (blood oxygen level–dependent) contrast [S. Ogawa *et al.*, *Biophysical J.* **64**, 803 (1993)] in a 1.5-T GE Medical Systems scanner at the Magnetic Resonance Research Center of the University of Pittsburgh Medical Center. Images were acquired at a repetition time (TR) of 1500 ms in each of seven adjacent axial planes covering the superior and medial portions of the temporal lobe, with time to echo (TE) of = 50 ms, flip angle = 90°, and voxel sizes of 3.125 mm by 3.125 mm by 5 mm. The surface coils were 12.7-cm bitemporal general purpose coils for 12 of the 15 participants, a left temporal coil for two participants, and a whole head coil for one. In the ancillary experiment, seven coronal slices covered the frontal lobes. In both experiments, the field of view was 400 mm by 200 mm, a 128 by 64 acquisition matrix, 5-mm slice thickness, and a 1-mm gap. The structural images for anatomic localization were high-resolution T1-weighted spin echo images, TR = 400 ms, TE = 11 ms, 256 by 256 acquisition matrix, 5-mm slice thickness, and a 1-mm gap.
11. Image preprocessing was as described [W. F. Eddy, M. Fitzgerald, C. R. Genovese, A. Mockus, D. C. Noll, in *Proceedings in Computational Statistics*, A. Prat, Ed. (Physica-Verlag, Heidelberg, in press)]. The mean of the maximum head motion per participant was 0.1 voxel, and it never exceeded 0.4 voxels; data sets with more motion were discarded. To accommodate the rise and fall time of the hemodynamic response [P. A. Bandettini *et al.*, *Magn. Reson. Med.* **25**, 390 (1992)], we discarded data from the first 6 s of each epoch and the 6 s rest interval between epochs, leaving approximately 61 images per condition per participant. A voxel was considered activated in a condition if a t test comparing its activation in that condition to its level during rest epochs reached a threshold value of $t > 4.5$, which corresponds to a chance probability of $P < 1.6 \times 10^{-5}$ for a 61-image comparison and is more conservative than the Bonferroni correction for $P < 0.01$. The activation effects are believed to reflect changes in the microvasculature induced by changes in cortical neuronal activity rather than in larger veins because (i) regions of activation map to gray matter rather than to spaces occupied by cerebrospinal fluid in which such vessels are found; (ii) the same effects were observed with one of the participants who was tested a second time at 3 T with an asymmetric spin echo pulse sequence that is less sensitive to large vessels [R. M. Weisskoff, C. S. Zuo, J. L. Boxerman, B. R. Rosen, *Magn. Reson. Med.* **31**, 601 (1994)]; (iii) the nonlinear distribution of activation confined to a discrete volume within the imaging space does not represent the known venous drainage pattern of the temporal lobe; and (iv) we excluded from analysis 1.9% of voxels showing greater than 6% change in signal intensity that might have possibly arisen from blood vessels. Finally, the problem of blood vessel artifacts in fMRI primarily affects the absolute localization of function, rather than the measurement of the relative volume of activation across conditions. Variations in epoch durations in the three sentence conditions had little effect on the results, as indicted by a separate analysis that truncated each participant's epochs to the duration of the shortest epoch type.
12. The magnitude of the activation response for the activated voxels in this set was approximately a 2% change in signal intensity above the rest condition, which is the usual magnitude in many fMRI studies of the association cortex at 1.5 T. There was some deactivation—an average of four voxels per participant in the left temporal ROI (compared with the rest condition)—although its interpretation is unclear [J. Sergent, *Trends Neurosci.* **17**, 221 (1994)].
13. Four ROIs were anatomically defined a priori for each participant with reference to coregistered structural images in the axial and in the sagittal planes. The temporal ROIs were three adjacent axial slices (subtending 17 mm) that best covered the laterosuperior and middle temporal gyri. The frontal ROIs were three adjacent coronal slices that best covered the inferior frontal gyrus. Both ROIs were bounded in-plane by the limiting sulci of the gyri. Anatomical localization of Wernicke's area activation in one participant, scanned a second time at 3 T, indicated activation in both the superior temporal gyrus and sulcus, with Talairach coordinates spanning the ranges: x, −50 to −65; y, −21 to −44; and z, 3 to 19.
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