

FUNCTIONAL MRI OF LANGUAGE: New Approaches to Understanding the Cortical Organization of Semantic Processing

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■ **Abstract** Until recently, our understanding of how language is organized in the brain depended on analysis of behavioral deficits in patients with fortuitously placed lesions. The availability of functional magnetic resonance imaging (fMRI) for in vivo analysis of the normal brain has revolutionized the study of language. This review discusses three lines of fMRI research into how the semantic system is organized in the adult brain. These are (a) the role of the left inferior frontal lobe in semantic processing and dissociations from other frontal lobe language functions, (b) the organization of categories of objects and concepts in the temporal lobe, and (c) the role of the right hemisphere in comprehending contextual and figurative meaning. Together, these lines of research broaden our understanding of how the brain stores, retrieves, and makes sense of semantic information, and they challenge some commonly held notions of functional modularity in the language system.

INTRODUCTION

Over 150 years of research into the organization of language in the brain is based on a lesion deficit approach, which deduces the functional significance of a brain area through observation of deficit following either temporary or permanent brain lesions. These methods reveal brain areas that, when disrupted, produce a complete or near-complete breakdown in the patient's ability to perform a task, and by deduction, lead to models of the underlying functional role of the affected brain region. This fundamental philosophy has led neuroscientists toward what we may term a large-module conceptualization of functional organization, an approach in which rather widespread territories of cortex are deemed responsible for broad categories of function. A large-module philosophy is particularly prevalent within the realm of language research; texts and reviews describe the language system as composed primarily of two broad-domain regions: Broca's area in inferior frontal

cortex and Wernicke's area in the posterior superior temporal region. Consider, for instance, the commonly stated functions attributed to Broca's area [pars opercularis of the inferior frontal gyrus (IFG) according to Broca, but encompassing a broader territory within the IFG in most neuropsychological reviews]. Lesions to this area produce a wide range of deficits known collectively as Broca's aphasia, including those involving articulation, sequential production of speech, sentence production, syntax, naming, and comprehension of some complex syntactic structures. The corresponding argument—that Broca's area must therefore be responsible for executing these functions—appears unlikely given their scope; it is difficult to conceive of a set of neural computations complex enough to account for them all simultaneously. Large systems models have given rise to similarly phrased cognitive descriptions of brain systems, such as the semantic system, seeming in the same way to encompass extensive networks of meaning in a large centralized locale.

Small numbers of case reports over the years have suggested holes in this general philosophy, most notably the findings of some patients with category-specific memory or naming deficits, or the rare cases with specific deficits in certain syntactic constructions. Yet the small numbers and uncertain or inconsistent localization of these cases have made it difficult to generate comprehensive models of language organization that respect both the behavioral data and the available anatomical data. More recent studies using structural MRI to identify brain regions common to aphasia subtypes such as Broca's have found a great deal of variability on location of the critical lesion. In identifying MRI lesions with specific aspects of Broca's aphasia, Alexander et al. (1990) found different anatomical structures around the IFG correlated with different aphasic symptoms within the Broca's syndrome. Damage to the underlying white matter of all regions appears necessary to produce the complete syndrome. Similarly, resting metabolic studies using positron emission tomography (PET) indicate that brain regions far distal to the lesion site are affected in patients with diagnosed aphasia (Metter 1991). Taken together, the data have indicated increasingly that large modules do not adequately describe the organization of complex brain functions such as language, although few opportunities for testing alternative models had been available before the advent of functional neuroimaging.

Functional brain imaging, particularly activation PET and functional magnetic resonance imaging (fMRI), rely on a very different fundamental approach to understanding brain organization. These techniques reveal brain areas involved in, though not necessarily essential to, the ongoing performance of a task. Recent years have shown a tremendous increase in the number of imaging studies of language in the normal brain. From this corpus of research, several long-held notions of language organization are openly challenged, and new findings add substantial detail to our understanding of how language is organized and retrieved. In particular, it is apparent that large-module theories are clearly incorrect; rather, the language system is organized into a large number of relatively small but tightly clustered and interconnected modules with unique contributions to language processing. There is increasing evidence that language regions in the brain—even classic Broca's

area—are not specific to language, but rather involve more reductionist processes that give rise to language as well as nonlinguistic functions. Finally, functional imaging has indicated far greater involvement of the right hemisphere in some aspects of language processing than previously appreciated.

This review focuses on three areas of fMRI research in language organization: subdivisions within the IFG, emphasizing the role of the IFG in semantic processing; the nature of category-specific organization of semantic information in the temporal lobe; and contributions of the right hemisphere to language comprehension. The number of recent fMRI publications on language far exceeds what can be reviewed here; therefore, this review focuses on a few representative papers in each area. Advances in fMRI studies of language are by no means limited to these areas; in particular, there is now a large body of work on reading that has strongly supported the dual-route theory in reading and substantial, novel findings relevant to auditory comprehension in the posterior temporal parietal regions. A recent review by Price (2000) emphasizes both of these aspects of language research. In addition, progress in our understanding of semantic memory and how the brain accesses store verbal memories is described in recent reviews by Gabrieli et al. (1998) and Buckner & Wheeler (2001).

Functional Magnetic Resonance Imaging: Some Basic Principles

Activation PET and fMRI share fundamental similarities in that they measure blood flow changes during the performance of a cognitive task, in comparison with another task or condition. Blood flow serves as an indirect marker of neural activity, although the two are tightly coupled under most conditions. One key limitation of blood flow as a marker for neural activity is that the brain's vascular response is sluggish, beginning about 2 sec after onset of neural activity and peaking only after about 5–7 sec (Savoy et al. 1994, Cohen 1997). Thus, unlike unit recordings or evoked potentials, the temporal resolution of functional imaging under the most ideal conditions is quite slow compared to actual neural activity. fMRI carries the additional disadvantage of having no reliable means to quantify neural activity in an absolute sense. Unlike PET, which measures blood flow directly, fMRI measures blood flow indirectly by detecting susceptibility changes associated with the relative concentration of oxy- and deoxy-hemoglobin on the venous side of the capillary bed (see Cohen & Bookheimer 1994 for an introduction to fMRI). Measuring blood flow using fMRI requires at least two experimental conditions. Differences observed in the MRI signal between two cognitive states are therefore relative, and consequently, results from activation imaging experiments depend on skill with which one designs both the experimental and control task. Even in cases in which the experimental and control conditions appear well matched based on solid psychological grounds, subtle differences in task difficulty, response styles, and strategies can easily affect the magnitude, spatial extent, and even the location of brain regions in imaging experiments (Raichle et al. 1994).

Approaches to account for these problems include taking simultaneous behavioral measures, using multiple baseline conditions, and employing paradigm designs that minimize potential confounds. As none of these methods works perfectly, one must approach interpretations of fMRI results with a great deal of skepticism.

To describe increases in MRI signal intensity during task vs. control comparisons, I use the terms activation or increased brain activity, along with decreased brain activity in cases in which the MR signal intensity is lower in the experimental compared with the control task. Because MRI signal intensity changes are comparative by their nature, we cannot determine whether they represent an actual increase in blood flow for the experimental task or a decrease in the control or some combination. Thus, the term activation implies only relative changes in MRI signal intensity. Although this review emphasizes fMRI studies, I have included a review of important PET papers where fMRI data are lacking.

Recent Advances in Paradigm Design

Nearly all of the early PET activation studies prior to the advent of fMRI employed a hierarchical subtraction model for isolating cognitive operations. Petersen and colleagues' (1988) paper on single-word processing typifies this approach: A resting baseline is first attained and then subtracted from a sensory control, in this case, passive presentation of either visual or auditory words. This task is subtracted in turn from an output condition, reading or repeating the words, which is then subtracted from an association condition. The model makes several key assumptions, most importantly that brain activity in lower levels of the hierarchy remains constant across hierarchical levels and that passive presentation invokes primarily sensory regions, to name only a few. More recently, several new designs and analysis approaches that rely less on assumptions of hierarchical organization have begun to dominate the imaging literature. These include common baseline designs, in which all experimental tasks are compared to a single, simple baseline (Bookheimer et al. 1995); parametric designs (i.e., Price et al. 1992), in which the level or load of the dimension of interest is varied; and selective attention designs (e.g., Corbetta et al. 1990, Dapretto & Bookheimer 1999), in which subjects see identical or nearly identical stimuli but selectively attend to one or another feature within the stimulus set.

A new model possible only for fMRI research is the single-trial or event-related (ER) design (Savoy et al. 1994). The blocked designs listed above require that subjects enter a steady state in which they perform multiple trials of a particular task, usually in blocks of half a minute or more. The ER design presents one stimulus at a time, allowing the blood flow response to rise and fall for that particular item before presenting a second stimulus. Items of different categories (experimental vs. control items, e.g.) are presented randomly, making it impossible for subjects to develop an effective strategy for only one stimulus type. This design has additional advantages in that the blood flow response may ebb over time in a longer block, and thus the magnitude of the blood flow response may be preserved in

single-trial studies (though this has not been demonstrated formally). Also, ER designs distribute fatigue effects evenly across trials, whereas in blocked designs subjects may tire over the course of the experiment, affecting late-occurring conditions in particular. The original ER designs allowed time for the blood flow response to reach baseline (about 12–16 sec after each stimulus) before proceeding to the next, which greatly lengthens the task. In these designs the control state is rest, which most agree is not an adequate control. Newer approaches present stimuli more rapidly and perform direct contrasts of height epochs across stimulus types. This has the advantage of allowing far more trials in an imaging session at the cost of making additional assumptions about the linearity of the blood flow response when trials of the same type occur in succession, assumptions that also have not been validated. In practice, the ER designs are most important in studies in which strategies invoked by blocked paradigms would mar interpretation of the study results. For more detailed discussions of ER procedures and effective utilization of this approach, see D'Esposito et al. 1999 and Buckner et al. 2000. Whereas most of the fMRI studies of language continue to employ blocked designs, ER approaches have become increasingly popular and may be essential in cases where strategic effects of blocks could obscure effects due to different stimulus types.

The Universal Language of Brain Mapping

Nearly all fMRI and PET experiments report results in Talairach coordinate space (Talairach & Tournoux 1988). This system is based on the postmortem analysis of one person's brain and is published as an atlas, though newer atlases containing the average of several hundred brains are now accessible through this system. In the Talairach system, all locations within the three-dimensional space of the brain are represented as a number from left to right [x -dimension: -65 mm left hemisphere (LH) to $+65$ mm right hemisphere (RH)]; from anterior to posterior (y -dimension: $+70$ mm anterior to -90 posterior); and from inferior to superior (z -dimension: -40 mm inferior to $+65$ mm superior). In this system all brains are normalized to fit a template that is centered in z along the line connecting the anterior and posterior commissures, $x=0$ is at the midline and $y=0$ at the anterior commissure. In this way, a three-number coordinate defines the spatial location of any point in the brain, usually representing either the highest peak of activation in a region or the geometric center of a three-dimensional blob of activity. The coordinate system makes it possible for imaging investigators to compare the locations of brain activity across centers, imaging modalities, and subjects. They can compare the locations with reasonable certainty and in a common language that circumvents the need to agree on anatomical boundaries and naming conventions. All tables in this paper refer to the Talairach coordinate system; see Talairach & Tournoux 1988 for a more detailed description.

THE ROLE OF THE INFERIOR FRONTAL GYRUS IN SEMANTIC PROCESSING

Since Broca's original report of a patient with a motor speech disturbance, the IFG, especially Brodmann's area 44, has been attributed the role of producing language. Most models of Broca's area function refer to the role of the IFG in expressive speech. A strong challenge to this simple idea emphasizes the variability in location of Broca's area across individuals. In particular, Ojemann's cortical stimulation mapping studies (Ojemann et al. 1989) indicate striking variability in frontal temporal and parietal lobes for brain regions that disrupt object naming. Furthermore, the effects of language disruption in anterior vs. posterior language areas do not follow the classic posterior-comprehension, anterior-expression dissociation. Rather, particular within the frontal lobe, Ojemann found areas specialized for semantic processing and phonology as well as articulation. Luria (1966) noted that Broca's area patients made comprehension errors in syntactically complex sentences such as passive constructions. For instance, Broca's aphasics had difficulty answering the question "A lion was fatally attacked by a tiger. Which animal died?" but no problem with the active construction "The tiger fatally attacked the lion." Clearly, comprehension was intact at the word level, but meaning at the sentence level was lost under conditions in which function words or knowledge of the syntactic structure were essential for comprehension. Several anatomical correlation studies found little evidence for area 44's exclusive association with Broca's aphasia. Alexander et al. (1990), Dronkers (1996), and others have found evidence for functional heterogeneity in IFG for different deficits among Broca's aphasics including those in articulation, syntax, and naming. Rather than indicating a high degree of variability in lesion location, the data tend to show that multiple regions are involved in expressive language and that only disruption to all of them produces the catastrophic breakdown of language as revealed in aphasics. As Broca's aphasia patients have a variety of seemingly diverse impairments, it is likely that these skills have different neural representations.

In the past five years, an increasing number of fMRI studies have identified small brain regions within the IFG that respond to specific aspects of language. From the earliest language activation studies using PET, functional imaging studies consistently have demonstrated increased blood flow during tasks in which subjects did not make an overt verbal response (Gabrieli et al. 1998). In one such study using PET, we compared Broca's area activity in both silent and oral object naming and word reading (Bookheimer et al. 1995). Both silent and oral tasks produced Broca's area activity; indeed, in the case of reading, there was greater IFG activity for silent than for oral reading, a pattern also seen in posterior temporal cortex. This suggests that greater semantic processing in silent vs. oral reading produces greater IFG activity. As speaking produces head motion artifacts that contaminate fMRI pictures, covert verbal responses in fMRI studies of language are the norm. Wildgruber et al. (1996) used a covert speech paradigm to examine lateral differences in motor cortex during speech, finding ample activation in motor

cortex even though subjects did not actually speak. Studies comparing overt and covert speech have found differences represented primarily in magnitude of fMRI activation rather than in location, with the exception of motor areas (Palmer et al. 2001). Several investigations of sentence comprehension wherein covert pronunciation was unlikely have also shown IFG activity. One possible explanation is that strongly connected brain regions (i.e., Wernicke's and Broca's areas) jointly activate each other during language processing even if the neural activity is not critical to the process. However, increasing evidence suggests that, in addition to neural activity that might occur as a result of functional connectivity, activity in the IFG in the absence of speech production reflects functional activity in those regions specific for other aspects of language processing (Gabrieli et al. 1998). Recent fMRI research has identified at least three separate regions of functional specialization within the IFG separate from those involved principally in motor speech. These are syntax (reflecting both the production and comprehension of syntactic information), semantics, and phonology.

In their classic PET experiment, Petersen et al. (1988) identified a region of activity in the anterior, inferior portion of the IFG that was selectively engaged when subjects generated a semantic association to a presented noun. While at the time this conclusion generated considerable controversy, numerous studies using a variety of imaging methods and paradigm designs have consistently replicated this finding and elaborated on the role of the anterior IFG in semantic processing. This region lies in the junction between the pars triangularis and pars orbitalis of the left IFG in what is likely Brodmann's area 47. It appears to represent a unique brain region involved not in decoding meaning of individual words but in processing semantic relationships between words or phrases, or in retrieving semantic information. Evidence supporting this general idea has emerged from experimental designs that differ substantially in their specific task demands, input modality, and type of stimuli employed. This literature is now too extensive to review completely, but examples of recent fMRI and PET studies of this brain region using several different theoretical and experimental approaches follow below.

Priming Effects in the IFG

In the cognitive psychology literature, semantic priming paradigms have proven effective in identifying benefits in performance when subjects respond to a stimulus that follows a semantically related prime. In functional imaging research, the effect of priming in the brain is demonstrated by a decrease in the amount of brain activation for a stimulus that has been primed either by repetition or by following a semantically related stimulus. Demb et al. (1995) demonstrated semantic priming effects—a decrease in blood flow for repeated words during a semantic decision task—in the IFG, encompassing Brodmann's areas 45, 46, and 47. They varied the depth by which subjects encoded a word list. Increased semantic encoding (making a concrete vs. abstract judgment) was compared with making a case judgment or alphabetic order judgment on the typed words. The latter tasks differed

substantially from the experimental task in difficulty level with one more and one less difficult, which makes it possible to separate out difficulty effects from those most critical to the experimental task. Even though this study aimed principally at understanding the effects of deep vs. shallow encoding on memory, the results are relevant to language processing as well. Demb et al. (1995) found that deep semantic encoding produced increased fMRI activation in the lateral inferior prefrontal cortex; the exact location was not stated but was roughly centered around the anterior IFG. This finding was not due to increased task difficulty, as the more difficult, nonsemantic encoding task produced no significant blood flow changes in this region. Furthermore, when repeated items that were semantically encoded in a second task were presented, the same regions showed decreased activation. The authors have argued that this region may serve as a central executive for retrieving semantic information.

Wagner et al. (2000) used a similar repetition priming paradigm to differentiate priming effects in the anterior vs. posterior IFG. They varied task demands so that a list of words were processed at different levels of depth, i.e., either semantically or perceptually. In the perceptual or nonsemantic conditions, subjects determined whether letters in the target words were presented in upper- or lower-case. In semantic-processing conditions, they determined whether the words were concrete or abstract nouns. During the scans, subjects saw either novel or repeated words from the word lists and had to make either perceptual or semantic judgments. The stimuli were crossed such that items initially processed semantically could be repeated under either semantic or perceptual task instructions, and likewise for items initially encoded perceptually.

Although both the anterior and posterior portions of the IFG showed increased MRI activity during initial processing, Wagner et al. (2000) found an interaction between regions within the IFG and task-specific priming effects. In the posterior IFG, they found priming in both within-task and across-task repetitions, while in the anterior IFG, priming was specific for the task performed [i.e., items were primed only in the semantic task instructions when they had been initially encoded at a deep (semantic) level].

This study indicates that the priming effects in the IFG can not be explained as solely due to the identity of the individual stimuli, but must also involve a semantic analysis of those stimuli, which strongly implicates a primary role of the IFG in semantic processing. In a separate study, Wagner et al. (1997) examined whether different stimulus content (words vs. pictures) produced priming in the same area within IFG. It was found that anterior IFG region showed reduced activation for items that had been presented previously, regardless of whether they were presented as pictures or words.

Buckner and colleagues (2000) examined repetition priming effects across a series of experiments varying in their task demands and sensory input modality. They had subjects perform a visual word stem-completion task in which they saw several letters and had to generate a complete word, for example, 'bas—' (basket). The same stems were shown over four repeated trials, and fMRI analysis

identified those brain regions showing repetition priming effects, that is, reduced brain activation for repeated trials. They also had subjects generate a verb from a visually presented noun to identify those brain regions that were not task specific. In other words, if the priming effects are truly conceptual as opposed to perceptual in nature, both sets of task demands should reveal the same priming-related regional brain changes. Two regions in the IFG show repetition effects across tasks: one in superior, posterior IFG and another the anterior, inferior IFG. Buckner validated these results using auditory input in a word stem-completion paradigm. Here, subjects heard initial phonemes of possible words (e.g., *pur*) and had to generate a complete word (perfect). Comparing new word stems with those that were repeated, nearly identical regions in the IFG were found (see Table 1). The latter regions correspond well with the data of Demb et al. (1995) and others, whereas the former is more closely associated with phonological or articulatory processing (see below). Because the repetition priming effects were both item specific (unprimed items did not show priming) and were observed across task demands and input mode, the data provide support for the notion that these priming effects are conceptual in nature. Since repetition priming involves priming not only of the semantic content of the stimuli but also access to the motor plans for producing a response (either overtly or covertly), as well as the selection of a response (Thompson-Schill et al. 1997), the regions identified could reflect any of these components. Different experimental approaches, however, have tended to support the semantic retrieval hypothesis.

In the above studies, semantic information processing was deduced by observing a decrease in activation for repeated items. Other studies using paradigms not dependent on repetition priming have implicated the anterior IFG in semantic processing; these studies produce increases in functional activity. For instance, Poldrack et al. (1999) had subjects perform a semantic decision task and a phonological decision task in comparison with a perceptual control to differentiate areas within the IFG responsible for semantics and phonology, respectively. Task instructions involved either making a case judgment (perceptual task), counting syllables (phonological task), or judging whether the words were concrete or abstract (semantic task). This investigation revealed increased IFG activity in the anterior portion selectively during semantic processing, while other IFG regions showed less task specificity. Because the stimuli were matched across conditions, defining the critical variable in producing IFG increases must have been the semantic analysis required to make a decision. Gabrieli et al. (1998) note that the same region producing signal decreases in the priming tasks showed increases in the judgment task, which suggests that this region responds dynamically during semantic processing tasks.

Selective Attention to Meaning

Dapretto & Bookheimer (1999) modified a selective attention paradigm to differentiate syntactic and semantic aspects of sentence processing in a task in which

TABLE 1 Talairach coordinates of inferior frontal gyrus activations

First author	Task	Syntax	Semantics	Phonology
Moro 2001	Sentence judgment—acceptability	−28 34 8		
Friederici 2000	Function words	−45 12 6		
Dapretto 1999	Semantic vs. syntactic	−40 30 14	−46 30 −6	
	Sentence judgment	−52 10 28		
Stromswold 1994	Plausibility of syntactically complex sentences	−46 10 4		
Caplan 1998	Replication of Stromswold	−42 18 24		
Kang 1999	Detecting syntactic anomalies—noun-verb combinations	−50 15 12 −45 25 4		
Wagner 2000	Repetition priming Semantic judgment		−43 34 12	
Wagner 2001	Low association words— Semantic comparison		−45 27 −12 −51 21 −3	
Petersen 1988	Word generation		−33 32 −6 ^a −38 25 8 ^a	
Buckner 2000	Word stem priming—visual		−43 34 3	−43 9 34
	Word stem priming—auditory		−34 31 3	−43 6 25
Wagner 2001	Semantic priming: Weak associations vs. > strong		−45 27 −12	
Thompson-Schill 1997	Classification—hi vs. low selection		−49 8 30	
	Generation—hi vs. low selection		−38 15 30	
Thompson-Schill 1999	Generation—new vs. repeated		−44 15 22	
Muller 2001	Selection of a tone pattern		−42 27 −9	−48 0 33
Poldrack 1999	Phonological vs. case match		−47 20 −3	−47 28 16
	Semantic vs. case match			
Demonet 1992	Phoneme monitoring vs. tones			−50 18 20
Demonet 1994	Sequential/ambiguous phoneme detection			−42 6 28
Zatorre 1996	Phonetic monitoring			−44 8 27
	Phonetic discrimination			−35 20 21
Burton 2000	Phonological segmentation			−47 15 29
Zatorre 1992 ^b	Phonetic discrimination vs. speech			−48 3 24
	Vs. pitch discrimination			−56 6 29

^aTransformed to Talairach & Tournoux 1988 coordinates.

^b1996 reanalysis.

selection demands were minimal and held constant across conditions. In this study, subjects heard pairs of nearly identical sentences in which either a single word or the word order were varied, and they had to judge whether the meaning of the sentences remained the same or differed after this change. Although both tasks involve a semantic analysis of the sentences, additional semantic processing at the single-word level was required in the semantic condition in order to perform the task. Subjects were given the same set of instructions for both tasks and were not informed of the experimental manipulation, making it less likely that they used different strategies for performing the tasks. Both semantic and syntactic conditions activated a large network of regions in language areas principally in the left hemisphere. However, the semantic manipulation produced additional activity in anterior IFG, and the syntactic task produced a more posterior, superior area of selective MR activity. Because the selection demands across tasks were identical, as was task difficulty, the data are most consistent with the IFG's role in some aspect of semantic processing. Figure 1 illustrates the foci of the activations from Dapretto & Bookheimer (1999).

Controversies Over the Semantic Processing Hypothesis

While most have held that the anterior IFG is integral to some aspect of semantic processing, Thompson-Schill and colleagues (1997, 1999) have argued that the IFG performs the more general task of selective task-relevant stimulus attributes from amid a field of competing responses. To test this model, Thompson-Schill and colleagues (1997) performed an fMRI experiment in which subjects made a semantic decision in the face of smaller or larger competing demands. They presented a cue followed by two targets, and the subjects had to choose the one that was semantically related in a low-selection condition, vs. similar on a single-semantic dimension or feature in a high selection condition. Thompson-Schill et al. argue that the former task does not require selection because the comparisons made on the basis of global similarity do not require selection. If selection is the key variable influencing anterior IFG activity, then this condition should not elicit IFG activity, and they indeed found none. They also argue that a semantic account of IFG would predict more IFG activity when there are more semantic targets and that the region responds merely to the selection process. In a second experiment (Thompson-Schill et al. 1999), subjects performed a word generation task in which they generated a verb in response to a target noun. Words were primed with relevant or irrelevant information. If IFG depends on selection demands, the latter condition should show more activity in the primed condition relative to unprimed because the irrelevant information should increase the selection demands. They found significant priming in the same condition and a small increase in activity for primed vs. unprimed in the different condition, consistent with the selection hypothesis.

Intense debate on this issue continues, questioning whether semantic processing is a necessary component of anterior IFG activity. Wagner and colleagues (2000)

have noted that the region identified by Thompson-Schill et al. (1999) as important to selection falls significantly posterior to that indicated during semantic priming by Wagner et al. (1997), Poldrack et al. (1999), and others. In a second study, Wagner et al. (2001) argued that the anterior IFG is involved in controlled semantic retrieval, a process that could be prone to interference by competing alternatives but that is not dependent on selection. They varied the associative strength and the number of targets in a semantic decision task, in which subjects had to determine whether a word was globally related to a target, given a choice of either two or four words. If the semantic retrieval hypothesis is correct, one could predict that the IFG activation is modulated by both associative strength and number of targets. In contrast, if the selection hypothesis is correct, one would expect that neither factor should increase IFG activity. Wagner et al. (2001) found that weak associations, which should require more strenuous controlled semantic retrieval, activated the anterior IFG most strongly. The posterior IFG was active across all conditions, consistent with the predictions of Thompson-Schill and colleagues (1997, 1999). This posterior IFG region overlapped with that found in studies of phonological processing (see Table 1). Overall, Wagner's data help explain the disparate findings across studies relevant to the selection hypothesis and provide further support for the role of anterior IFG in semantic processing: specifically controlled semantic retrieval. Table 1 shows the coordinates in Thompson-Schill's studies (1997, 1999) in comparison to those of other groups; this is depicted graphically in Figure 2. Whereas the other studies reviewed show a tight cluster of activation foci in anterior, inferior IFG, the areas Thompson-Schill identifies as representing selection processes are located substantially more posterior and superior, supporting the spatial dichotomy suggested by Wagner and colleagues (2001).

Dissociations Among IFG Regions: Syntax

Several lines of evidence indicate that the anterior IFG region active during semantic processing is clearly different in both spatial location and function from other areas in the IFG responsible for other aspects of language processing (Fiez 1997). The most commonly dissociated processes are syntax and phonology.

Although rare, there have been several reports of patients with selective impairments in syntax or in some aspects of syntactic production or comprehension (Berndt & Caramazza 1980). fMRI investigations of syntax have largely supported the notion of a specialized region in IFG for processing syntactic aspects of sentence comprehension. PET studies by both Caplan et al. (1998) and Just et al. (1996) found increased activity in the IFG during additional resource allocation to syntactic complexity, though neither study differentiated among subregions within the IFG. Stromswold (1994) compared different manipulations of syntactic structure in a PET task. They compared right-branching sentences (e.g., The child spilled the juice that stained the rug) to the more difficult center-embedded structures (The juice that the child spilled stained the rug), finding increased activity in Brodmann's area 44 for the more complex constructions.

Caplan et al. (1998) varied the syntactic complexity of sentences using PET and the same stimuli as Stromswold (1994). The focus of activity in the IFG was close but did not precisely replicate their prior results; it is more in line with other studies of syntax. In a second experiment, they varied the number of propositions in sentences ("The magician performed the student that included the joke" vs. "The magician performed the stunt and the joke"). In this experiment, differences were found only in temporal lobe regions, not in IFG. Caplan et al. (1998) argue that in the latter experiment, the increased memory load is associated with the products of sentence comprehension, whereas in the former experiment, the load is with the "determination of the sentence's meaning." If so, this suggests that the frontal lobe contribution to syntactic comprehension may depend on an interaction with syntactic and semantic processes toward the determination of meaning. Such a view is supported by several other imaging studies of syntax.

For instance, Dapretto & Bookheimer (1999) contrasted syntactic with semantic aspects of sentence processing in an auditory sentence judgment task (see above) and had subjects make a semantic judgment of the form of the sentence. Subjects had to determine whether two sentences conveyed the same meaning. The sentences contained identical words but differed in word order. In each case, the novel word order combinations were grammatically correct and plausible, so that subjects had to rely solely on a comparison of the effect of word order on meaning to generate a correct response. The actual sentences and the syntactic complexity were matched across syntactic and semantic conditions so that activations depended not on the stimuli themselves but on the process of comparing the syntactic forms. They found an area in the superior portion of BA 45 that showed enhanced activation for the syntactic condition alone. The results from this study are illustrated in Figure 1.

In the Dapretto and Bookheimer (1999) study, subjects focused their attention on the effect of syntactic structure on meaning; that is, there was by design a strong relationship between syntactic variations and emergent meaning. One may question whether the brain regions reflect the attention to syntax alone, or the integration of syntactic and semantic information. One way to distinguish among these alternatives is to present syntactic information in the absence of semantic information. Friederici et al. (2000) used "Jabberwocky" sentences in comparison to normal sentences, word strings containing only content words, and nonwords. Jabberwocky sentences contain function words in appropriate placements between nonsense words taking the place of meaningful referents such as nouns and verbs ("Twas brillig, and the slithy toves. . ."). Subjects made a decision based on both semantic and syntactic grounds (subjects determined if there was a legal syntactic structure, or if there was a content word present). Regardless of whether sentences contained real or nonwords, those with normal placement of function words (normal sentences and Jabberwocky sentences) showed temporal lobe activation (Wernicke's area), and Jabberwocky sentences produced additional activity in area 44. Their results suggest this area is specific not simply for syntax, but for increased selective attention to syntactic structure. In contrast, the temporal

lobes, from Heschl's gyrus to the planum polare, show a relative increase for syntactic vs. nonsyntactic sentences types though all conditions produced significant activation. This suggests that the frontal lobe may play a more executive role in syntactic processing such as controlled retrieval of syntactic information, responding dynamically as the task demands require.

Furthering the notion that syntactic and semantic modules in the frontal lobe are mutually interactive, Keller et al. (2001) varied the cognitive load on syntactic and lexical processing. Using written sentences as stimuli, they varied the frequency of key words as well as the syntactic complexity of the sentences. Presumably, brain regions general to task difficulty should increase activity under both conditions, while those related solely to lexical semantics vs. syntactic processing should show task-specific regional activation. Because they used a region of interest approach and did not differentiate among regions within the IFG, and did not report results in Talairach coordinates, it is not possible to directly contrast their result with other studies dissociating among these processes. However, in the broadly defined IFG, they found an interaction between syntactic and semantic complexity, indicating increased engagement of IFG when both the syntactic and semantic demands of the task were greater. They argue that, even within a modularity framework, one must consider such modules to be highly interactive.

The above studies all used sentences as stimuli, presented either visually or auditorally. In several of these tasks, the more complex syntactic structures that produced IFG activation also were more difficult and involved greater working memory demands. Thus, the IFG activity associated with syntactic processing may reflect not the syntactic components of the task but rather working memory load or general difficulty, factors that may be independent from syntactic processing. Kang et al. (1999) used two-word, noun-verb combinations in the context of an event-related paradigm to differentiate brain regions associated with semantic vs. syntactic processes. Subjects saw these pairs printed and simply had to read them. Both semantic and syntactic anomalies were contained within the lists (e.g., "Grew heard" vs. "Ate suitcases") but most pairs were logical ("Wore glasses," "Broke rules"). Images associated with syntactic and semantic anomalies were averaged separately. Both stimulus types produced activity in the center of area 44, whereas syntactic anomalies produced additional activity in two other regions in the IFG (see Table 1). Whereas one of these regions is close to that most associated with semantic processing as described above, the second closely approximates regions found by other investigators for syntactic comprehension (see Table 1). The study did not require subjects to effortfully process the syntactic structure of the stimuli, and the anomalies occurred at low frequency. This suggests that at least some aspects of syntactic processing may be independent of executive functions including working memory, effortful attention, or retrieval of stimulus-specific information. However, the co-activation of anterior IFG suggests an interaction with processes relevant to semantic processing during the detection of syntactic anomalies.

Dissociations Among IFG Regions: Phonology

In addition to a general deficit in speech production, Broca's aphasia patients have specific problems in accessing, sequencing, and monitoring phonemes. Direct cortical stimulation of area 44 in patients undergoing surgical removal of the epileptic focus disrupts phoneme monitoring even when patients were not required to articulate (Ojemann & Mateer 1979). In an early PET study by Demonet et al. (1992) using PET, subjects performed a phoneme sequencing task in which they had to attend to the order of phonemes within nonwords in comparison to a tone control task. A second task asked subjects to monitor words for content (determine whether an adjective-noun combination was positive or negative in connotation). The area of activity selective for phoneme (vs. tone) comprehension lies in the superior portion of BA 44/45, while the word meaning task produced activity predominantly within the temporal lobes. A second study by Demonet et al. (1994) investigated the relative effects of perceptual ambiguity and sequence processing in a set of phoneme monitoring tasks. The tasks were designed to differentiate between two models of frontal lobe involvement in phonology: One holds that the IFG activity reflects rehearsal in working memory, corresponding to the articulatory loop proposed by Baddely (1992), while the other focuses on phonological processes directly, which may include phoneme sequencing or discrimination. Using nonwords as stimuli, they asked subjects to detect the presence of a letter occurring either at the beginning or within a word, either in isolation or if preceded by a second letter. Ambiguous stimuli were embedded in a group of consonants. They found increased blood flow in posterior IFG only in the condition in which subjects made the sequential judgment for embedded (ambiguous) phonemes. Simpler detection tasks produced temporal lobe activation only, as did sequencing tasks alone. They suggest that this part of the IFG likely performs sensorimotor encoding of auditory phonetic input, consistent with the rehearsal account.

Also using PET, Zatorre et al. (1992) identified a region in the posterior IFG selectively engaged when subjects made a phonological vs. a pitch discrimination on auditorally presented syllables. More recently, Zatorre et al. (1996) added an additional pair of tasks to differentiate frontal regions that may be involved primarily with working memory from those involved solely in phonetic analysis. Phonetic discrimination—in this case, determining whether real words ended in the same letter—produced activity in BA 44/45. Phoneme monitoring (detecting a target letter within a word) produced activity in posterior IFG. In comparison, lexical judgment did not show increases in this region, suggesting that the area 44 findings are specific to the phonetic processing demands of the task.

Other PET investigators reported similar results in Brodmann's area 44 on phonological tasks, including Paulesu et al. (1993) in a task of phonological recoding and rehearsal. Although it supports the critical role of the IFG in phonological processing, the PET technology may lack sufficient spatial resolution to test the hypothesis of a unique center for phonological processing in the IFG. Other fMRI studies have demonstrated increased IFG during phonological processing, but with

a region of interest approach that could not differentiate posterior IFG from the central IFG regions seen in most language tasks (e.g., Pugh et al. 1996). Poeppel (1996) argued on the basis of earlier PET work that the results in Broca's area for phonological tasks did not replicate well. However, more recent work with higher resolution PET (Zatorre et al. 1996) and with fMRI has generally supported the role of posterior IFG in phonological processing.

Several paradigms sensitive to phonological processing but using approaches differing substantially from the earlier works by Zatorre (1992), Demonet et al. (1992), and others have demonstrated posterior IFG activity. For instance, Friederici and colleagues (2000) report increased posterior IFG activity in sentence processing tasks that involved either Jabberwocky sentences, sentences composed of content but no function words, and pseudoword lists. The left hemisphere junction of the inferior frontal sulcus and inferior precentral sulcus showed increased activity for all conditions compared to normal sentences. This result could merely represent a general area for increased attention to any verbal stimuli but may reflect an increased need for attention to the word sequences or to articulate them covertly, which is consistent with the view that this area forms a part of the articulatory loop in a working memory circuit (Baddely 1992).

Although activations around posterior IFG appear frequently across laboratories and phonological processing tasks, some studies show activation in other portions of the IFG. In Zatorre et al.'s (1996) very similar tasks of phoneme discrimination and phoneme identification, for instance, the focus of activity in the former task was in the center of the IFG, whereas the centroid for discrimination was found in posterior IFG. Activation during phonological processing could interact with other task demands in the language system, producing new or overlapping activations in IFG or other brain regions. In the priming literature, for instance, lexical decision tasks can produce both semantic and phonological priming (Neely et al. 1989, Berent et al. 2001), although the priming effects may be independent (Cronk 2001). Poldrack et al. (1999) compared semantic with phonological processing by requiring subjects to count syllables in real words or pseudowords presented visually, and also to judge the case of the same words. They found IFG activity during the phonological tasks, most notably in the posterior, superior IFG during the pseudoword syllable counting condition. However, the same region was significantly more active in the semantic task. Because all tasks involved reading printed words, it is likely that phonological processing took place in all conditions, which would tend to minimize differences in direct task-task comparisons. Nonetheless, the results suggest that semantic processing automatically engages regions within the IFG responsible for phonological processing, at least during reading.

Activation of Left Inferior Gyrus in Nonlanguage Tasks

The most widely accepted theories posit separate modules for semantic, syntactic, and phonological processing, but how we interpret the basic functions of these regions is still a matter of considerable debate. In particular, arguments have centered

on how specific these subdivisions are to language processing vs. whether some more general processes may underlie language as well as nonlinguistic functions. Typically, in studying the properties of traditional language cortices, investigators employ tasks involving some component of language exclusively. A few studies have reported increased fMRI activation in Broca's Area for tasks that do not contain a language component. Such studies offer a unique perspective on the underlying properties of neurons in this region that give rise to language, though not necessarily exclusively, and cast doubt on the concept of the language-specific processing module.

Muller et al. (2001) examined the role of Broca's area in making tone discriminations. Specifically, subjects had to attend to 600 Hz tones that either remained stable, rose, or fell by 50% in a very brief duration (200 msec). Subjects listened to these tones and pressed a button whenever they heard the rising tone. In the comparison condition, subjects heard bursts of white noise and pressed a button whenever they heard the sound. Thus, the conditions differed in several ways; the quality of the sound, the duration over which the sound occurred, the nature of the task including monitoring a rapid temporal change, and selecting from among competing alternatives. Consequently, any of these features could have produced the results, although in no case could language processing account for any task-related activity. In the inferior frontal lobe, they found significant activation in the anterior, inferior portion of the IFG (areas 45/47), corresponding closely to the anterior IFG region demonstrated by Poldrack et al. 1999, Wagner et al. 2000, and others. These data may argue in support of the Thompson-Schill et al. (1997) model of anterior IFG function, which reflects selection from among competing responses as opposed to semantic processing. Muller et al. 2001 also reported a very large area of activity in the superior posterior portion of the IFG, a region more closely associated with phonological processing and verbal working memory.

Iacoboni and colleagues (1999) have performed a series of experiments on motor imitation that have produced increased fMRI responses in traditional Broca's area. Imitation is thought to represent a core, prerequisite skill for developing language; autistic children have notoriously poor imitative skills, but their ability to imitate oromotor movements appears to predict language acquisition. In this task subjects were asked to perform a simple finger movement either in response to a visual cue or an imitation of the same response; all other task parameters were held constant, including visual input. They found two brain regions that responded to imitated movements, specifically, the right parietal lobe and pars opercularis of the left IFG. This research argues for a neural basis of imitation that corresponds to similar neural responses seen in nonhuman primates. In addition, they suggest that motor imitation may underlie aspects of language acquisition. Binkofski et al. (2000) performed a detailed cytoarchitectonic analysis in combination with fMRI on a similar task in which imagery of motor movements was compared with imagery of observed hand movements. They found left hemisphere activation in area 44 when subjects imagined observing a movement, and right opercular activation when subjects imagined a moving target (a light point moving on a

screen). Studying the activity in these areas in spatially normalized histological sections, they found that these regions corresponded to cytoarchitectonic area 44; this area was clearly differentiated from nearby area 6 involved in motor planning. Thus, the authors conclude that area 44 of the left hemisphere plays a key role in the imagery of motion, which is thought to represent an efferent copy of a planned motor action, supporting the notion that human area 44 corresponds to the mirror neurons described in F5 of the monkey (Rizzolatti & Arbib 1998). Together, the data suggest that Broca's area retains function that is not directly related to language processing, but that neurons here have response characteristics that may give rise to imitation of complex motor behaviors including language. However, in a recent meta-analysis of studies involving imagery and observation of motor movements in comparison to speech, Grezes & Decety (2001) argue that this portion of Broca's area is only rarely activated during motor imagery; more commonly, activity is associated with silent speech processing. Indeed, that Grezes & Decety (2001) found activation in this area during observation of movement and not during observation made in order to imitate tends to contradict this hypothesis.

Summary of the IFG Hypothesis

In summary, recent fMRI research strongly supports the notion that there are separate subsystems within the IFG responsible for different aspects of language processing. In particular, there is strong support for the role of anterior IFG (Brodmann's area 47) in some aspects of semantic processing. By most accounts, the region is not modality specific, nor is there any evidence for specificity of content. Rather, this region appears important for executive aspects of semantic processing that involve semantic working memory, directing semantic search, or drawing comparisons between semantic concepts in working memory. While the argument that this region plays a general role in selection from among alternatives has not held up well, it remains quite possible that this region performs a more general function. It perhaps involves making comparisons or judgments among information held in working memory that underlies this aspect of semantic processing as well as other nonlinguistic processes. Other regions within the IFG appear to be specialized for syntactic and phonological processing as well. Figure 2 presents a summary of the studies reported here that directly contrast one of these processes with another (a more complete list of studies comparing phonological and semantic processing regions can be found in Poldrack et al. 2001). Of note, many of the regions shown to have greater activation for one process still demonstrate significant increases in the comparison tasks. In some studies (e.g., Keller et al. 2001), interaction effects between these distinctive processes suggest that regions within the IFG are highly connected, influencing both brain activity and processing efficiently for other language skills. Together, such a network of unique but highly interactive, compact modules should give rise to the tremendously complex language processing of which humans are capable. Perhaps a tight spatial and functional coupling of these small modules enables rapid, efficient processing of

language, but such an arrangement may also make us vulnerable to the catastrophic loss of broad-based language skills that comprise Broca's aphasia. Thus, we may characterize Broca's aphasia not as resulting from a lesion in a single Broca's area, but rather as a lesion affecting a family of Broca's areas, each contributing uniquely to one deficit but creating a whole syndrome that is far greater than the sum of its parts.

CONTENT-SPECIFIC ORGANIZATION OF SEMANTICS

Reports of patients with category-specific deficits in naming (Hart & Gordon 1992, Warrington & Shallice 1984), in addition to a large literature on semantic priming in both normal control subjects and patients with aphasia (Blumstein et al. 1982), suggest that the brain stores semantic information along categorical lines. While the frontal lobe semantic region appears to be both modality- and content-independent, there is increasing evidence to suggest that, in the temporal lobe, semantic content is highly organized and spatially segregated.

Living vs. Nonliving Categories

The most common categorical dissociation in the lesion literature separates living from nonliving entities. Several reports using functional imaging provide anatomical confirmation of this dissociation in the brain. The most common finding is increased occipital activation for animals compared with tools (Martin et al. 1996, Moore & Price 1999, Mummery et al. 1998, Perani et al. 1999). For instance, Perani et al. (1999) had subjects make a same-different judgment of objects that were either animals or tools while undergoing PET. In one experiment, they compared activation for pictures of objects. For direct task-task comparisons, animals showed specific activation in the fusiform and occipital gyrus, areas associated generally with object processing. Tools, in contrast, showed specific activation in the left hemisphere near principal language areas, namely BA 45/46 and 21/20. In a second experiment, subjects performed the same task in response to printed words. Areas replicated across experiments were the left fusiform gyrus for animals and the left middle temporal lobe (area 21) for tools.

A critical question in understanding the basis for category-specific semantic organization addresses the basis upon which these dissociations are made. One could, for instance, argue that they are generated by visual similarity (for instance, natural objects tend to have no straight lines or sharp edges, whereas manmade objects do). Several investigators have probed this issue. Mummery and colleagues (1998) contrasted living things and artifacts (tools) in two tasks: In one case they determined if the objects depicted by two words shared a perceptual characteristic (the same color); in another, they judged whether two words were associated (usually found in the same locations). A control task had subjects count the syllables in each word. Relatively large differences were found in contrasting the operation

performed on the stimuli (location vs. color), whereas smaller activations represented category-specific stimuli. In particular, no significant effects for living things were found that spanned task demands. This suggests that the retrieval task performed in accessing categorical information is at least as important as the category itself in defining focal brain activation.

Chao et al. (1999) tested this hypothesis by comparing categorical stimuli (animals, tools, houses, and faces) when presented as either pictures or words. Across tasks, several regions showed specific activation for animals and tools under different task conditions (viewing pictures, naming objects, matching pictures, or reading the names of objects). Reading produced the least replicable results, whereas other conditions showed relative consistency across tasks. Animals tended to show increased activity in bilateral medial and inferior occipital cortex, lateral fusiform gyrus, and superior temporal sulcus (near Wernicke's area). Tools appeared to activate the medial fusiform and the middle temporal gyrus in a region most often associated with visual motion perception. Both the lateral fusiform and superior temporal sulcus regions were also significantly activated for faces, which suggests a more general response to living things, whereas the medial fusiform showed a preference for nonliving things (though animals showed smaller levels of activation here as well). Within these categories, however, there were finer distinctions in the precise location of activation peaks that suggested a more refined separation of specific categories of objects. Similar dissociations have been demonstrated using these and other categories of objects (Moore & Price 1999, Okada et al. 2000, Smith et al. 2001, Spitzer et al. 1995).

Do category-specific findings in imaging necessarily imply unique modules for each entity? Ishai et al. (1999), using fMRI, found specific activations for several categories of objects, including chairs and houses. Within subjects, activation of separate regions for each category was very reliable. However, when examining the hemodynamic response across all stimulus types, they noted increased brain activity for other categories as well. Their model argues that, rather than representing distinct, independent modules for a single category, the neural representations of categorical information overlap, forming a continuous representation of information across the cortex, potentially represented as attributes or shared features.

A critical question in interpreting category-specific effects concerns whether such dissociations reflect organization based on critical features of those objects or categories (such as visual features, associations with visual motion, etc.) or semantic knowledge about those objects or categories (for a complete review of theoretical accounts of category specificity, see Caramazza et al. 1990). Likely, object knowledge reflects an amalgam of information widely distributed in the brain and includes feature information, as well as associative information. However, there is increasing evidence that, at least in the temporal lobe, the organization of semantic categories is not random, but may tie directly to critical features of the categories, for instance, as tools are associated with reaching and nonbiological movement (Martin et al. 1996). For instance, Chao & Martin (2000) had subjects view or name tools in comparison to animals, faces, and houses, imaging regions

in the frontal and parietal lobes associated with reaching and grasping in monkeys (e.g., Rizzolatti & Arbib 1998). Both of these areas (intraparietal sulcus and ventral premotor cortex) show specific activation for tools compared with all other categories, suggesting that one aspect of object knowledge includes associations with sensorimotor correlates of their use.

Using PET, Moore & Price (1999) addressed the question of whether category-specific effects were due to features of physical similarity between objects. This was done in two ways: First, they compared nonobjects (realistic-looking drawings that were not actual objects) to real objects; second, they varied the amount of available perceptual information by comparing black-and-white vs. colored objects as well as object complexity. This comprehensive study examined two categories of natural objects (animals and fruit) and two categories of manmade objects (vehicles and tools). Further, they used two separate tasks (naming and word-picture matching) to evaluate the effect of task demands on category-specific organization.

Right hemisphere occipital and temporal occipital/fusiform cortex show a preference for more visually complex objects in all categories. As in other studies, the left posterior temporal region showed increased activation for tools, but this was also seen for nonobjects. The authors suggest that, at least in the right occipital and fusiform cortices, reports in the literature implicating these areas in category-specific representations may have measured only an aspect of visual complexity (objects with multiple components like animals and complex tools).

The left posterior temporal region appeared to show category specificity for manmade vs. natural objects, but the finding that nonobjects activate the same area casts doubt on whether the region can be regarded as semantically based. The left anterior temporal cortex specificity for natural objects was found only for black-and-white objects, although the authors argue this is consistent with the semantic category-specific hypotheses. Overall, the data are consistent with the notion that natural objects are organized on the basis of shared perceptual information, while manmade objects are organized along the lines of functional information.

The authors also report, but do not interpret, one result that may be inconsistent with a clear dichotomy in these categories. They found increased activity in the posterior sensory cortex at the junction of the intraparietal cortex for fruit and for simple tools. This brain region is strongly associated with reaching for objects (see Binkofski et al. 1998, Johnson et al. 1996). Both fruit and simple tools are easily graspable objects, which might have caused co-activation here. One would not necessarily argue for the presence of a new category, reachable objects, nor do the data support a single structural/functional dichotomy for natural vs. manmade objects, respectively. Rather, both recognized objects may automatically activate shared associations with similar motor movements as well as having other distinctive features (perceptual and functional) on which they differ. This interpretation suggests that there is no single, unifying feature that allows for a dissociation between these categories, nor for a single anatomical locus for category-specific representations. Rather, categorical differences may be expressed in multiple, nonoverlapping areas in the brain. Such a model is consistent with a diffusely organized semantic

system based on multiple features, both perceptual and functional and likely involving other bases of similarity as well.

Body Parts

Ample clinical data implicate the parietal lobes in spatial representation, including representations of one's own body and manipulation of numbers. Le Clec'H et al. (2000) used a combination of blocked and event-related designs to identify brain regions active for these categories that were independent of sensory input modality. In the numerals condition, they asked subjects to compare a target number to a specified amount (larger, smaller, or equal); in the body parts condition, they asked subjects whether a target body part was higher, lower, or at the same level as the shoulders. For both conditions, stimuli were presented either verbally or visually. Although each task produced activation in numerous brain regions, those that responded to both input modalities were more specific: the right inferior parietal region for numbers, the left parietal lobe and left premotor cortex for body parts. The latter network is essentially the same as that identified in monkeys for reaching and maintaining plans for motor actions (Iacoboni et al. 1999). It is also close to that identified by Martin et al. (1996) for tools. This provides further evidence that categorical organization of semantic information may have emerged from nonlinguistic representations of sensory and motor behavior.

Word-Specific Effects: Concreteness

Several fMRI studies have investigated the cortical representations of different categories of words, including function (e.g., nouns vs. verbs), regularity (for instance, in past-tense production), and concreteness among nouns. By some theoretical models, concrete nouns can be represented both visually and auditorally, whereas abstract nouns can be represented only auditorally. Early accounts by Paivio (1986) and others suggested a left-hemisphere verbal-right hemisphere visual distinction would predict lateralized effects for both word types, though neuroanatomical data on word processing do not support a laterality model (Price et al. 1994, Bookheimer et al. 1995). Keihl et al. (1999) tested this model directly by using fMRI while subjects performed a lexical decision task; in the task non-words were interspersed with concrete or abstract printed words. Both concrete and abstract words activated an extensive network of right and left hemisphere regions; in direct comparisons, however, only abstract words produced additional activation in the right temporal lobe, in a region corresponding to tip of the superior temporal gyrus. This region is anterior to primary auditory cortex and was the only region showing significant activity in direct task-task comparisons. One reason for the small differences between conditions may have been the choice of a lexical decision task; because this task involves no substantial semantic processing, differences between word types may have been missed. Mellet et al. (1998) had subjects listen to concrete vs. abstract nouns and, in the case of concrete nouns, generate a mental image. As in the Keihl study (1999), this task showed increased

right temporal lobe activity for abstract words, but also showed significant activity for concrete words throughout the inferior temporal/fusiform region, primarily in the right temporal lobe. These regions are the same as those involved in object recognition and naming (Bookheimer et al. 1995), and apparently reflect the visual imagery engaged by subjects. In addition, left hemisphere activation during concrete as opposed to abstract words may reflect the extent to which the words and their associations are verbalizable. No coherent models for right hemisphere specialization for abstract words have been brought forth, but such words may demand context for their comprehension. A right hemisphere role for linguistic context has been reported in the literature and is discussed at length in the next section. However, an event-related fMRI study by Jessen and colleagues (2000) did not replicate the concrete/abstract dissociation reported above. In their task, subjects read words and were told to remember them for later use, but did not have to judge their concreteness or perform any other task. In this case, concrete words produced increased activity in the left superior frontal sulcus and in the left inferior parietal cortex, while abstract words produced increased activity relative to concrete in the right lateral occipital lobe and left IFG. Note that no brain areas overlapped across studies.

Summary

While there are some inconsistencies in the literature regarding the loci of each of the categories of stimuli discussed, overall there appears to be agreement that, particularly within the individual, there are separate peak foci of activity in several brain regions for categories of objects and concepts. Regions of focal activity reflect several different dimensions of object naming and knowledge: visual features, associations with object uses, and associations with semantically related objects. Within each of these broad categories may lie many associated features, thus making complete object representations broadly distributed in the brain. How to conceptualize organization by content remains an extremely contentious topic in the literature (see Thompson-Schill et al. 1999 and Caramazza 2000 for a very lively discussion of this issue). One general principle, however, appears to emerge consistently regardless of which category is under study: Whether the task that subjects perform requires naming, generating an associate, or matching stimuli on perceptual or conceptual grounds, the brain regions identified do not appear randomly distributed, but rather spatially proximal to brain regions with strong sensory or motor associations with the conceptual category. Objects that are manipulable activate brain regions associated with reaching and grasping; objects that move show activation close to visual motion centers, and objects that must be discriminated from many exemplars of similar objects (like faces) activate visual form recognition areas. Martin & Chao (2001) argue for a gradient of detail in which posterior brain regions process information more generically, whereas increasing uniqueness (a specific face or unique object like the White House) is processed in anterior temporal lobe regions and suggest that anterior temporal lobe integrates

some aspects of visual information (see also Damasio et al. 1996). The available functional neuroimaging data do not clearly support one model of the functional architecture of the semantic system, but the technique holds promise for adding the data necessary for generating more plausible and comprehensive models than are available today.

Assuming that different aspects of sensory, conceptual, and associative semantic information have separate and diffuse organization in the brain, how do we then integrate such knowledge in the service of language? Martin & Chao (2001) argue that a good candidate model for this integration could be subserved by the left anterior IFG as discussed in detail above. This region is likely involved in the executive control of semantic information processing, including retrieving, integrating, comparing, and possibly selecting the diverse pieces of semantic information in the brain. Currently there is no clear evidence supporting or contradicting this model. Direct tests of this model could utilize functional connectivity approaches, which measure the correlated activity during brain activation across different brain regions (see Horwitz et al. 1999 for an excellent description of functional connectivity methods).

RIGHT HEMISPHERE CONTRIBUTIONS TO LANGUAGE COMPREHENSION

Language research, from the perspectives of both lesion-deficit and activation imaging approaches, has focused primarily on small units: speech sounds and words. Much of communication, however, relies on processing language at a level that goes well beyond information expressed by single words or in literal interpretations of words and sentences. Recent fMRI research has explored contributions to understanding language that emphasize metaphor, connotative meaning, prosody, and processes relevant to comprehending language at a level above that of literal meaning of words or sentences. Increasingly, this line of research has revealed a critical role for the right hemisphere in language that has received only a little attention in the lesion literature.

Figurative Language and Metaphor

The first major contribution in this field was made using (PET) by Bottini et al. (1994), who explored the role of the right hemisphere in processing metaphors. Metaphors depart from semantic rules in that one may be able to decode the sounds and apply meaning to each word (and correctly parse them syntactically) and yet not comprehend the meaning of the phrase or sentence. The correct meaning is implied through association and comparison of similarities between different experiences that are not stated explicitly; indeed, relying on interpretation of literal meaning destroys the true, connotative meaning of the metaphor. Our ability to reject literal meaning and accept an unspoken, connotative meaning requires both a

traditional linguistic analysis and a contextual analysis. To differentiate these processes, Bottini et al. had subjects listen to sentences and to random word strings, making either a plausibility judgment or a lexical decision (in the control task). Metaphoric, plausible sentences consisted of metaphors that either made sense (e.g., The investors were squirrels collecting nuts) or were implausible (The investors were trams). Plausibility, then, was determined by whether the metaphor was meaningful though not necessarily familiar. Literal sentences were also judged plausible or implausible, but this was based on the literal meaning and logical relations between specific words or phrases (e.g., "The boy used stones as paperweights" vs. "Tim used feathers as paperweights"). In both cases, a correct answer requires accurate knowledge about the words and concepts, but only the former required an understanding of connotative meaning and rejection of literal meaning.

The comparison of interest—making plausibility judgments of metaphoric vs. literal sentences—revealed a striking dissociation between right and left hemisphere activation, respectively. Metaphoric sentence judgments produced relatively greater activation in several areas in the right hemisphere, most notably in right IFG, right pre-motor cortex, and right posterior temporal cortex. The latter regions are roughly right hemisphere analogs of Broca's and Wernicke's areas.

Several very different processes may take place in making judgments about metaphors; the authors suggest that reference to long-term, episodic memories may be specifically required in judging metaphors, whereas no such reference is required in judging literal meaning. Frontal lobe activation may reflect the additional need to search long-term memories for information on which to compare meanings, or the activation may be involved in generating visual imagery to facilitate decision making. In general, though, metaphoric analysis may require emphasis on holistic aspects of language processing, whereas judging literal meaning requires only the sequential, one-to-one mapping of words with known literal meanings and not necessarily knowledge of the context.

An unfortunate problem with this study is that the metaphors were far more difficult for subjects, who performed significantly less accurately than in the literal meaning conditions. Unmatched level difficulty can produce changes in the magnitude, spatial extent, and location of brain activity in ways that may not relate closely to the process under study, and it is possible that the results reported by Bottini et al. (1994) reflect this alone.

Using PET, Nichelli et al. (1995) examined how subjects derived the figurative meaning of passages by asking them to monitor the moral of a story, in comparison with a semantic or syntactic detail of the story. Subjects listened to Aesop's fables and made a judgment about either the figurative or literal meaning of the fable. Although left hemisphere language regions were engaged in all cases, making a judgment regarding the moral of the story produced relative activity increases in right frontal and temporal regions. Because subjects always heard the same or similar stimuli and made a judgment in all cases, right hemisphere activity must have been due specifically to the process of drawing a figurative inference from the passage. Several underlying processes could be involved, however: These include making

an inference from limited or less apparent information, or attending to the context of the passage as opposed to individual elements of a passage. Several other studies have examined linguistic context and reasoning independently; these are discussed below.

Linguistic Context

Probably the most widely reported single paradigm in the language-imaging literature is the word or verb generation paradigm (e.g., Petersen et al. 1988, Cuenod et al. 1995, McCarthy et al. 1993, Rueckert et al. 1994). This paradigm has subjects generate a word or a list of words in response to a category cue or to a single-word cue (e.g., dog-bark), and has demonstrated activation in left frontal cortex consistently. Kircher et al. (2001) modified this basic design to have subjects generate a single word in response to a sentence cue, e.g., "These days the weather is rather—," such that subjects use the context of the whole sentence to generate a response. In comparison to control tasks in which subjects either chose one of two displayed responses or simply read a complete sentence, this generation task produced unique activity in the right temporal lobe, in cortex roughly homologous to Wernicke's area. In contrast, areas of the brain associated with production (typically the MFG in a generation task) were limited to the left hemisphere. The data suggest that subjects use the left hemisphere language system to access a verbal associate but used a right hemisphere system to analyze the spoken information. Since the right temporal region has not been reported in single-word generation studies, the RTL activation likely represents processing of the content of the sentence as a whole.

In the absence of a task requirement to actively synthesize contextual information or produce a response, increased right hemisphere activation appears limited to the temporal lobe. St. George et al. (1999) imaged subjects listening to a verbal passage with or without a title that oriented the reader to the context. In this case, the passage consisted of a set of instructions and tips on riding a horse. With the title provided, the paragraph makes perfect sense; without the title the paragraph is nearly incomprehensible. In this study, participants read paragraphs with and without titles, but made no decision or response. Titled paragraphs showed activity in standard language and reading areas: inferior frontal cortex, basal temporal region; and posterior temporal cortex, with a strong left lateralization. In contrast, reading untitled paragraphs showed overall greater activity in the right hemisphere, and was significantly greater than titled passages in the right temporal lobe. Since the actual content heard was identical across conditions (counterbalanced across subjects), right temporal lobe activation was likely due to the increased effort in attempting to place seemingly unrelated sentences in context to create a coherent presentation of the text. Thus, it is not simply sentence length comprehension that drives the right temporal lobe activation, but presumably the process involved in trying to make a passage coherent.

Is the critical variable in elucidating the RH contribution to semantic processing in sentences the duration over which the semantic information occurs? If so,

shorter phrases should not elicit RH activity. Kang et al. (1999) looked at simple noun-verb combinations in an event-related fMRI design in which subjects detected anomalies based on either semantics (ate-suitcases vs. broke-rules) or syntax (wore-glasses vs. grew-heard). In this case, the temporal durations were brief and the context minimal. While both conditions showed left hemisphere activity in traditional BA (44), the semantic task showed additional activation in anterior, inferior pars triangularis of the right hemisphere. The data suggest that reliance on semantic context, rather than temporal duration, underlie the right hemisphere contributions to language comprehension.

Reasoning and Logic

Several studies demonstrate that deriving meaning from text relies on right hemisphere structures, but drawing logical inferences from text is an exception. Goel et al. (2000) tested the hypothesis that deductive reasoning relies on syntactic aspects of language—that knowledge of the structural properties of words and phrases underlies logical deduction—making it an inherently linguistic process. Using event-related fMRI, they compared congruent and incongruent phrases with and without semantic content (e.g., All pets are poodles; all poodles are vicious; thus, all pets are vicious) vs. the similarly framed arguments without semantic content (e.g., All B are C). They compared these phrases with matched sets in which all sentences were unrelated, or in which only the first two were related; subjects had to judge the validity of the conclusions. Both types of stimuli engaged primarily left hemisphere regions associated with language processing (BA 44/45 and 21/22) though the stimuli with less semantic content also engaged bilateral parietal and premotor cortex (BA6). However, in right hemisphere analogs of language regions, no conditions showed preferential activation. While this paper argues for parallel systems in drawing logical conclusions depending on whether subjects relied on content vs. spatial processing, it also provides a contrast to other studies of text comprehension that show primarily right hemisphere activation. In the Goel et al. (2000) task, logical inference relied exclusively on the serial position of individual statements. In contrast, in studies by Bottini et al. (1994), St. George et al. (1999), and others, subjects could derive meaning from passages as a whole, regardless of the strict serial order of sentences or elements within sentences. This suggests that inference per se does not determine lateralization but may depend instead on whether the context as a whole must be preserved to reach a conclusion.

In a recent study, Caplan & Dapretto (2001) examined different aspects of reasoning separately to evaluate right vs. left hemisphere contributions to logical inference. They predicted that whereas the left hemisphere was important in assessing logic in discourse, the right hemisphere participated in the implicit assessment of topic maintenance. To test this, they had subjects make judgments about whether pairs of sentences made sense. In each case, the sentences were presented as questions with responses. “Do you believe in angels?” “Yes, I have my own special angel” (on topic response); “Yeah, I like to go to camp” (off topic response).

To test logic they asked: “Do you like having fun?” “Yes because it makes me happy” (logical); “No, because it makes me happy” (illogical). The subjects thus heard the same types of stimuli and in every case made a judgment response, and they were unaware of the experimental manipulation. In direct comparisons of topic maintenance with logic reasoning, the logic task produced significantly greater activity in the left hemisphere language areas (BA 44/45 and 22). In contrast, the topic maintenance condition produced a right hemisphere bias in both homologous regions in addition to other cortical areas (dorsal prefrontal cortex, angular gyrus, and supplementary motor area). Their data suggest that, in making sense in a conversation, both hemispheres participate but do so uniquely; the right hemisphere appear to play a specific role in integrating semantic information into the context as a whole, while the left hemisphere may implicitly sense the sequential logic of a conversation. Figure 3 illustrates the areas of increased activation for topic maintenance vs. logic conditions in the Caplan & Dapretto (2001) study.

Cohesion and Repair

Several imaging studies have examined the brain’s response to linguistic anomalies—incorrect groups of words or phrases. How the brain responds to these anomalies differs depending on whether the anomalies are based in syntax or semantics; and how the task demands that subjects respond to these anomalies. In the Kang et al. (1999) study, in which subjects passively heard but did not make an overt or covert response to semantic anomalies in word pairs (e.g., heard-shirts), only right frontal lobe activity for semantic anomalies was found. However, the investigators did not report on brain regions showing an early hemodynamic rise, which is more characteristic of temporal lobe responses, so it is possible that such activations may have been overlooked. Further, when subjects make no behavioral response, it is difficult to know how well they are attending to the stimuli and what cognitive operations are in effect.

In discourse and text, we tend to join sentences together with cohesive ties that help to build on the coherence of the passages as a whole. Such ties may reflect causality of agents and actions, facilitating comprehension. Ferstl & von Cramon (2001) used fMRI to examine brain activity while subjects judged whether pairs of sentences were related to one another pragmatically. Four types of sentence pairs were presented: (a) coherent and cohesive sentences both maintained a logical relationship and contained cohesive ties (Mary’s exam was about to start. Therefore, her palms were sweaty); (b) incoherent and cohesive ties (Mary’s exam was about to start. Her friends remembered her birthday); (c) similarly constructed without cohesive ties (e.g., Mary’s exam was about to start. The palms were sweaty); and (d) nonword sentences served as a control. Sentence pairs in general activated traditional anterior and posterior language areas in the left hemisphere. In addition, cohesive ties in the context of incoherent sentence pairs produced left frontal lobe

activation, particularly in areas 44 and 44/6, but no regions were increased for incohesive or incoherent pairs relative to cohesive and coherent pairs. These regional activations were likely due to increase effort in resolving the apparent conflict between the logic of the sentences and the cohesive ties. Unlike similar studies that use auditory input, the Ferstl & von Cramon (2001) study used printed sentences in both activation and control tasks. The role of the right hemisphere in judging coherence may not be apparent in tasks using printed text alone, given the strong left hemisphere bias for reading.

“Repair” refers to the act of fixing anomalies in speech. A study by Meyer et al. (2000) had subjects repair anomalies in sentences. They presented subjects sentences auditorally that were either grammatically correct or contained an error in one of several ways, such as case disagreement or word order violation. Both groups of subjects had to determine whether a sentence was grammatically correct; one group of subjects had the additional job of silently repairing the incorrect sentences. In judging whether or not the sentences were correct, activation was reported bilaterally in anterior, middle, and posterior temporal portions of the superior temporal gyrus (STG); however, when subjects had to repair those anomalies, significant increases were seen in the right middle temporal gyrus and the right frontal lobe (44/45). In contrast, the posterior STG showed bilateral activation for all conditions. Possibly, greater right hemisphere activity for repair vs. detection of anomalies, may reflect the greater demands placed on processing the context or global intent of language.

Prosody

Information about intent, connotative meaning, and some aspects of the form of speech can be expressed through intonation and emphasis in discourse that is irrespective of the semantic content of the words themselves. Prosody in speech comprehension encompasses a range of features, including intonations relevant to emotion, importance (e.g., stress or accents), and linguistic forms (questions vs. imperatives) that are associated with right hemisphere function.

Emotional prosody refers to changes in stress and intonation in either sentences or words that convey information about the speaker’s emotional state, such as anger, surprise, sadness, or happiness. Buchanan et al. (2000) compared brain activity in normal subjects when listening to a set of four rhyming words differing in the initial phoneme, which were presented in each of the above four emotional intonations. In two verbal conditions subjects monitored words for the appearance of one of the initial phonemes; in the prosody condition, subjects monitored words for one of two emotional states. Thus, this design follows the selective attention approach in which subjects always receive the same sensory input and perform the same type of decision and output, but the design differs in the processes that give rise to the subjects’ response. Looking exclusively at both prosody conditions independent of conveyed emotion, they found that activity in

the right IFG and right inferior parietal regions was greater than that in the verbal tasks. In comparison, attention to the initial phoneme of the same stimuli produced left hemisphere activity in the anterior IFG (47) and in posterior temporal cortex. In comparison to a resting baseline, both verbal and prosody conditions produced activation in bilateral temporal cortex; in the posterior portions of auditory cortex, all conditions showed greater right than left temporal lobe activity. Possibly, prosodic information is processed automatically and preferentially in the right temporal lobe and is less affected by selective attention than frontal lobe regions. Interestingly, the location of the right temporal lobe region is very close to that reported by Burton et al. (2000) for tone discrimination vs. speech and close to the region for integrative meaning in metaphors and discourse (Bottini et al. 1994, St. George et al. 1999). An earlier study using PET to identify brain areas involved in detecting emotional prosody (George et al. 1996) in sentences also reveals a right prefrontal activation similar to the Buchanan et al. (2000) study. The right prefrontal cortex has a well-documented role in processing emotion generally; for instance, imaging studies of emotional face processing also reveal right frontal lobe activity (Hariri et al. 1999), and emotional deficits among RH damages patients span not only comprehension and expression of affective prosody but also interpretation and expression of facial affect (Montreys & Borod 1998).

Friederici (2001) also reports on a study contrasting normal sentences, Jabberwocky sentences, and sentences filtered so that subjects could detect the intonations, but not the actual content, of spoken sentences. Subjects had to determine whether the sentences had an active or passive construction. In this case, the attention to prosodic features was based on linguistic, as opposed to affective, prosody. The investigators found bilateral activity in both frontal and temporal regions, with additional right frontal activity during the prosodic condition in the right pars opercularis. In this study the experimental conditions likely differ in their difficulty (behavioral data not reported), and it is thus difficult to determine what brain changes, if any, are due solely to the general effect of task difficulty and increased effort. Nonetheless the data are consistent with the notion that increased attention to the syntactic content of sentences produces increases deep in the frontal operculum. Unfortunately, the authors do not provide coordinates of the region of interest centers, making comparison across studies difficult.

In examining the loci of right hemisphere activations across studies, there is striking consistency in the center of mass. Table 2 presents the centers of activation in the frontal and temporal lobes for studies reported here. In the frontal lobe, the right IFG activations occur primarily in Brodmann's area 45, and are homologous to Broca's area activity seen in traditional language tasks; in temporal lobe, the activations appear analogous to the posterior superior temporal sulcus area specific to auditory word processing (Wise et al. 2001) experiment four: -64, -34, 2. The right IFG appears particularly important in tasks in which subjects are required to make a decision or judgment about information, as opposed to passive comprehension, although this is not universal.

TABLE 2 Talairach coordinates of right hemisphere activation in fMRI studies of language and logic

Author	Task	Frontal	Temporal
	Reasoning		
Goel et al. 2000	Deductive reasoning— language control	−52 14 20	−50 −42 2
Caplan & Dapretto 2001	Logic vs. topic maintenance judgment	−50 14 12 −54 24 4	−54 −34 4
	Figurative Language		
St. George et al. 1999	Discourse/integration Comprehension/passive		r. posterior temporal
Bottini et al. 1994	Metaphors vs. sentences Comprehension/judgment	40 28 8	56 −38 0
	Linguistic context		
Kang et al. 1999	Semantic vs. syntactic anomalies passive	40 23 4	
Kircher et al. 2001	Generate word to complete a sentence; reading control		58 −8 9 58 −36 9
Caplan & Dapretto 2001	Topic maintenance vs. logic judgment	44 20 28 40 24 −6 44 12 18	52 −14 2 46 −30 −2
	Cohesion and repair		
Meyer 2000	Repair of incoherent sentences	48 11 10	51 −19 9
Ferstl 2001	Cohesive ties/ coherent sentences Judgment	−46 20 19 −46 28 5	
	Prosody		
Buchanan et al. 2000	Prosody vs. verbal attention Prosodic stimuli vs. rest (COM) ^a	44, 20, 16	49 −42 12 ^a
	Tones		
Demonet et al. 1994	Tone vs. phonemes	46 4 28	48 −42 20 50 −62 0
Burton et al. 2000	Tone discrimination vs. speech		62 −42 15

^aCalculated center of mass in the defined ROI.

Summary

Across studies, we can identify three large clusters of right hemisphere activity during a wide range of tasks that measure aspects of language relevant to figurative, contextual, or connotative meaning. In posterior temporal lobe, these regions cluster most strongly around cortex that is roughly contralateral to Wernicke’s area, while an additional cluster more anterior in the STG is closer to primary auditory cortex. The posterior temporal region overlaps with that involved in making judgments about tones, which clearly requires no language interpretation. Thus,

we can presume that the nature of the right temporal lobe neurons gives rise to a variety of processes that can be used in the service of language as well as other processes. Many of the tasks showing RH activation require subjects to integrate information over time in order to reach a correct conclusion. This general principle can apply to language tasks from the paragraph level as in Bottini et al. (1994) to the word level as in Buchanan et al. (2000), but it may also apply in the case of nonlanguage tasks including tone-discrimination tasks. In contrast, sentence level tasks involving processes like sequential logic or cohesion may not require integration over the whole set of information but rather require one to extract individual, relevant elements of information from the whole to make a decision; such tasks tend to show left hemisphere activity. In other ways, right hemisphere activity during language tasks appears analogous to the homologous left hemisphere regions: Tasks that involve analyzing sensory input generally produce more posterior activity, and those that require making an active response or judgment, or generating a solution give rise to frontal lobe activation. Taken as a whole, the fMRI data add anatomical detail to the growing acceptance of the crucial role the RH plays in language comprehension.

GENERAL CONCLUSIONS

This review has emphasized three primary results from fMRI research into language. First, the broadly defined terms Broca's area and Wernicke's area do not correspond with the reality of how language processes are organized in the brain. Rather than demonstrating that large brain regions (like the IFG) are responsible for several different functions, the data suggest that within a large brain area are small, compact zones with relatively narrow functions, but which may interact to a high degree with one another. While this review discusses only three of these functions within the IFG, other regions in this area also have specialized functions relevant to language, and a similar organization in Wernicke's area is also likely (Wise et al. 2001).

Second, the concept of either a single system for semantic information or an organizational structure formed along strictly categorical lines, cannot be supported by the imaging data. Rather, information about natural categories and about specific—environmentally and perhaps culturally specific—categories is spread diffusely in sensory and cortical association areas. However, the organization is not random but rather reflects associations with visual or other sensory features, associations with use or actions, and associations with linguistic attributes. Likely, these diverse and diffuse representations are bound together by an executive system in the frontal lobe that is relatively specific for semantic information processing.

Third, the right hemisphere makes a substantial contribution to many aspects of language comprehension, though not at the single-word level. Whereas the right hemisphere appears to lack both the one-to-one mapping of information with words and the sequential analysis in discourse that the left hemisphere performs

with ease, the right hemisphere appears to make unique contributions to keeping track of the topic, drawing inferences from text and in conversation, and integrating prosodic information into a complete representation of meaning and intent, aspects of language that are critical to social communication.

Finally, a few tidbits of new imaging data suggest that each of the regions critical for language processing may in fact have some more general underlying function, bringing us closer to understanding language in basic neural terms.

While many imaging studies of language have aimed to confirm theories already suggested by lesion-deficit research, fMRI has added anatomical precision and a level of complexity unavailable to lesion-based methods. The principal new findings emerging from fMRI investigations of semantic organization in the brain highlight the complexity of this organization, reflecting not only a high degree of specialization for specific aspects of language, but also a high degree of interactivity and interdependence. While this review has focused primarily on semantics, it is striking to note how broadly regions contributing to semantic processing are distributed in the brain. This is clearly at odds with the standard neurological models on language comprehension, which continue to teach that comprehension is completed in Wernicke's area, as well as with the cognitive psychological models positing a central semantic store.

As brain imaging data are nearly always presented in terms of focal centers of task-related activity, it is commonly assumed that all brain imaging research assumes a strict interpretation of the principles of modularity as detailed by Fodor (1983). fMRI research easily lends itself to that interpretation, but researchers are increasingly utilizing new techniques that go beyond this account. In particular, the use of functional connectivity techniques in image processing reveal patterns of mutual engagement of different brain areas; new analysis tools allow for greater use of interactions among the data, and paradigm designs that rely less on assumptions of hierarchical organization of cognitive processes have become the norm. New approaches such as these will undoubtedly accelerate advances in language research. Also the wide availability of MRI scanners and the noninvasiveness of this technique guarantees that our understanding of how language is organized in the brain will continue to burgeon in the coming years.

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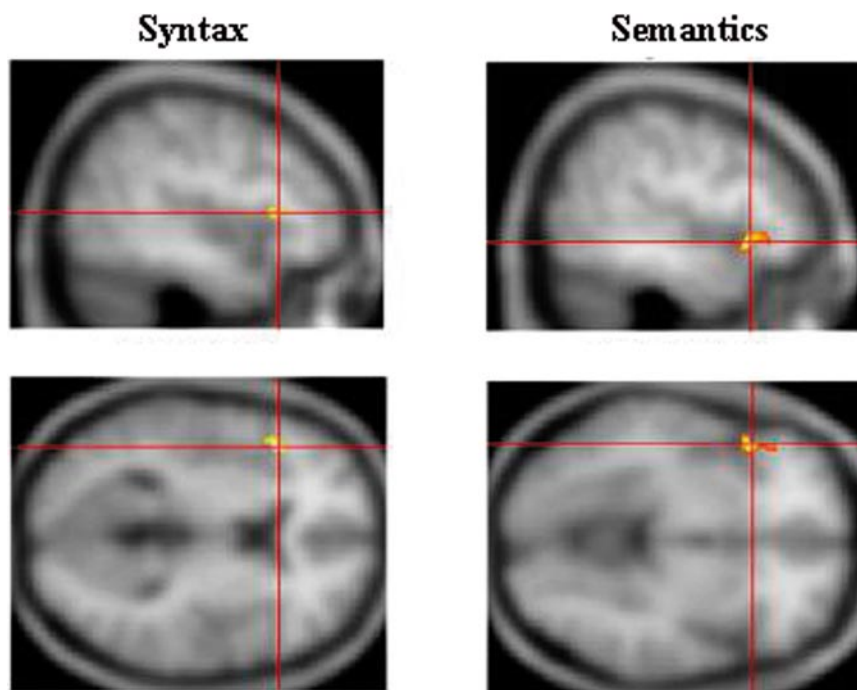


Figure 1 Activation in the inferior frontal gyrus (IFG) for semantic and syntactic aspects of sentence processing, from Dapretto & Bookheimer (1999). For both tasks, subjects determined whether two sentences conveyed the same meaning. In the semantic condition, a single word was changed; in half of the trials, the word was a synonym and in half the word was unrelated (e.g., “The boy went to the store.” “The boy went to the market” vs. “The boy went to the school”). In the syntactic condition, the words remained constant, but the word order was changed to make a syntactically plausible sentence. In half the cases, the meaning remained the same and in half the meaning differed (“The city is west of the lake.” “The lake is west of the city” vs. “West of the city is the lake”). Syntactic complexity was matched across conditions. Results here show direct comparisons of semantics vs. syntax (revealing the anterior, inferior IFG–pars orbitalis) and syntax vs. semantics (showing the middle IFG area 45–pars triangularis).

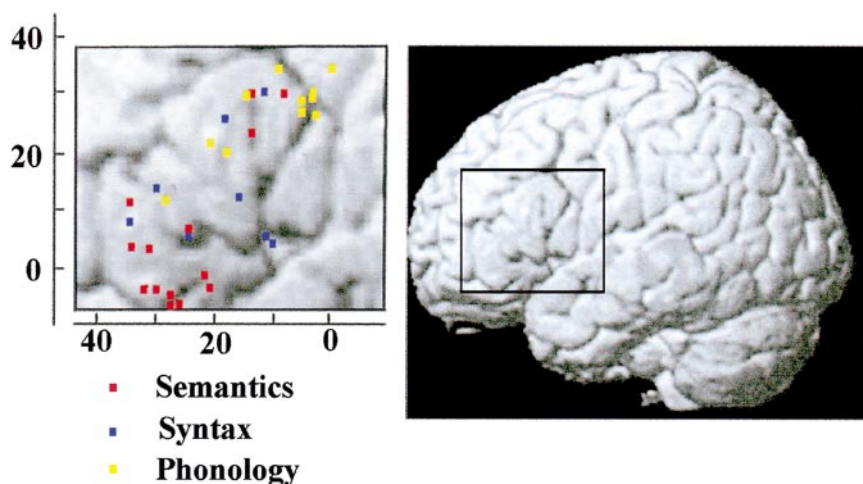


Figure 2 Summary of inferior frontal gyrus (IFG) activations across studies. Table 1 shows the list of studies and centers of activation for semantic, syntactic, and phonological processing experiments showing significant activity in the left IFG. Semantic areas (shown in *red*) cluster around the anterior, inferior IFG (pars orbitalis); phonological regions center around the posterior superior IFG at the border of Brodmann's areas 44 and 6; syntax regions fall in the center near middle IFG in pars triangularis, area 44/45.

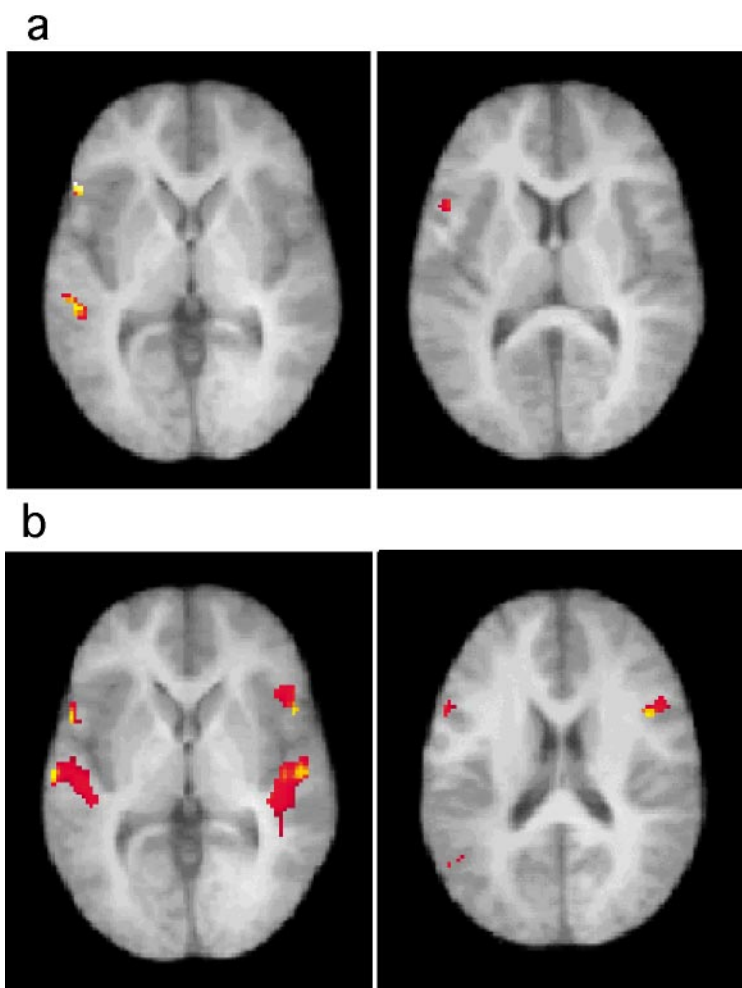


Figure 3 FMRI activation during logical reasoning and topic maintenance from Caplan & Dapretto (2001). (*a*) shows areas of increased MR signal for logic compared with topic maintenance; (*b*) shows the reverse comparison.

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