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Recruitment of Anterior and Posterior Structures in Lexical-Semantic Processing: An fMRI Study Comparing Implicit and Explicit Tasks

Ilana Ruff[1], **Sheila E. Blumstein**, **Emily B. Myers**, and **Emmette Hutchison**[2]
Department of Cognitive and Linguistic Sciences, Brown University

Abstract

Previous studies examining explicit semantic processing have consistently shown activation of the left inferior frontal gyrus (IFG). In contrast, implicit semantic processing tasks have shown activation in posterior areas including the superior temporal gyrus (STG) and the middle temporal gyrus (MTG) with less consistent activation in the IFG. These results raise the question whether the functional role of the IFG is related to those processes needed to make a semantic decision or to processes involved in the extraction and analysis of meaning. This study examined neural activation patterns during a semantic judgment task requiring overt semantic analysis, and then compared these activation patterns to previously obtained results using the same semantically related and unrelated word pairs in a lexical decision task which required only implicit semantic processing (Rissman et al., 2003). The behavioral results demonstrated that the tasks were equivalent in difficulty. FMRI results indicated that the IFG and STG bilaterally showed greater activation for semantically unrelated than related word pairs across the two tasks. Comparison of the two task types across conditions revealed greater activation for the semantic judgment task only in the STG bilaterally and not in the IFG. These results suggest that the pre-frontal cortex is recruited similarly in the service of both the lexical decision and semantic judgment tasks. The increased activation in the STG in the semantic judgment task reflects the greater depth of semantic processing required in this task and indicates that the STG is not simply a passive store of lexical-semantic information but is involved in the active retrieval of this information.

Keywords

semantic processing; fMRI; semantic judgment; lexical decision

1. Introduction

There has been considerable interest in and research on the neural systems underlying the processing of meaning. While results from the lesion literature implicate the left superior temporal gyrus (STG), i.e. Wernicke's area, in such processing, results from the neuroimaging literature suggest that there is a distributed network encompassing both anterior structures including the inferior frontal gyrus (IFG) as well as posterior structures including the superior

Corresponding author: Prof. Sheila E Blumstein, Brown University, Department of Cognitive and Linguistic Sciences, 190 Thayer Street, Box 1978, Providence, RI 02912, Sheila_Blumstein@brown.edu, 401-863-2849 (office), 401-863-2255 (fax).
[1]now at Northwestern University School of Medicine
[2]now in the Department of Neuroscience, Brown University

(STG) and middle (MTG) temporal gyri. It has generally been assumed that there is a functional distinction between these areas with the posterior areas involved in the storage of semantic meanings and the frontal areas involved in executive processes necessary to act on these meanings (for review and discussion see Noppeney et al. 2004). Nonetheless, it has been difficult to show empirically a functional dissociation between these areas since similar changes in modulation of activation have been reported in both anterior and posterior structures as a function of the nature and difficulty of the task (Gabrieli et al. 1996; Kapur et al. 1994), semantic attributes of the stimuli (Demb et al. 1995; Roskies et al. 2001; Tyler et al. 2001), selection demands of the task (Thompson-Schill et al., 1997), and modes of processing (Jansma et al. 2001).

Most of the neuroimaging studies examining the processing of word meaning have used explicit tasks in which participants are asked to make judgments about particular semantic attributes of the stimuli. Such tasks have included decisions based on semantic category membership (Demb et al. 1995; Roskies et al. 2001; Tyler et al. 2001), functional attributes of words (Petersen et al., 1988), and semantic relatedness of nouns and verbs (Muller et al. 2003; Wagner et al., 2001). Although a number of these studies have shown significant activation in both the IFG and the STG or MTG (Mueller et al., 2003; Roskies et al., 2001; Thompson-Schill et al., 1999; Tyler et al., 2001), the focus of discussion has largely been on the significant activation shown in the IFG and its potential role in semantic processing. To this end, a series of studies has examined whether the increased activation in the left IFG (LIFG) reflects executive decisions relating to task difficulty as determined by reaction time latencies or to semantic processing itself. These studies have shown that even when controlling for task difficulty, there is still greater activation in the LIFG in semantic tasks, thus implicating the IFG in semantic processing.

Although IFG activation has been shown in explicit semantic tasks, investigations of the processing of meaning using implicit tasks have failed to show consistent activation in this area. In implicit semantic tasks, participants are required to attend and respond to an attribute of the stimulus other than its meaning. For example, subjects may be asked to decide about the lexical status of a stimulus which may be preceded by a word which is either semantically related or unrelated to it. Performance, as measured by reaction-time (RT) latencies, is influenced by the semantic relatedness of the stimuli. Subjects show faster RT latencies to a target stimulus preceded by a semantically related word than to either a semantically unrelated word or a nonword.

FMRI results show modulation of activation as a function of semantic relatedness of word pairs in a lexical decision task. In general, there is greater activation for word pairs that are semantically unrelated compared to word pairs that are semantically related (Kotz et al. 2002; Rissman et al. 2003; Rossell et al. 2003), consistent with the view that semantically related pairs activate a common lexical-semantic network and hence require less neural processing. Nonetheless, a few studies have shown more activation in some neural areas for related than unrelated word pairs (Rossell et al. 2001; Rossell et al. 2003). The neural areas that show modulation of activation as a function of semantic relatedness include posterior structures, i.e. the STG (Rissman et al., 2003) and the left anterior medial temporal cortex (Rossell et al., 2003), and frontal structures, i.e. the middle frontal gyrus (MFG) (Rissman et al., 2003; Kotz et al., 2002) and precentral gyrus (Rissman et al., 2003). However, of importance, Rissman et al. (2003) and Rossell et al. (2001, 2003) both failed to show modulation of activation in the IFG, while Kotz and colleagues (2002) did find such modulation in the inferior frontal cortex. Taken together, the literature provides mixed evidence of IFG activation as a function of semantic relatedness in an implicit lexical decision task.

That there is consistent IFG activation only in explicit semantic judgment tasks raises the possibility that the functional role of this area is related to those processes needed to make a semantic decision rather than to semantic processes involved in the extraction and analysis of meaning. In nearly all of the studies that used an explicit task, both tasks and stimuli differed between the experimental and control conditions making it difficult to know for certain whether the differences that emerged in IFG activation reflected the different cognitive operations used in processing the experimental and control stimuli, e.g. words vs. letters, and/or in performing the tasks, e.g. discrimination of meanings of word pairs vs. discrimination of colored asterisks.

The current experiment is designed to address this question by comparing activation patterns in a semantic judgment task to those in a lexical decision task using the same semantically related and unrelated word pairs. We first investigate whether there is modulation of activation for semantically related versus unrelated word pairs in a semantic judgment task. It is hypothesized that consistent with earlier research using explicit tasks there will be modulation of activation in both the IFG and STG with increased activation in semantically unrelated compared to semantically related word pairs. We then compare the activation patterns in the semantic judgment task, a task which requires overt analysis of meaning, to previously obtained results using the same semantically related and unrelated word pairs in a lexical decision task, a task which does not require overt analysis of meaning. In this way, we will be able to assess whether differences in modulation of activation as a function of semantic relatedness will emerge solely on the basis of task demands. A semantic judgment task requires overt analysis of the meaning of the stimuli whereas the lexical decision task does not. That is, subjects must retrieve the meaning of the stimulus pairs, consciously compare their meanings and decide whether they are semantically related or not. In contrast, in the lexical decision task the meanings of the stimulus pairs are implicitly accessed, and subjects do not need to overtly analyze the stimulus pairs for their meaning. As a consequence, we hypothesize that comparison of activation patterns between the two tasks will show increased activation in both the IFG and the STG for the semantic judgment task compared to the lexical decision task.

2. Methods

2.1. Participants

Eight female and seven male volunteers ranging in age from 19 to 31 (mean age 21.4) were recruited from the Brown University community. All fifteen participants were native speakers of English, reported normal neurological function and absence of bodily ferromagnetic materials, and were confirmed to be strongly right-handed by the Edinburgh Handedness Inventory (Oldfield, 1971). After explanation of the study, each participant gave written informed consent and was assured of confidentiality according to guidelines established and approved by the Human Subjects Committees of both Brown University and Memorial Hospital of Rhode Island. Participants received monetary compensation for their time and effort.

2.2. Materials

Stimuli used in the experiment were the same as the related and unrelated pairs used by Rissman and colleagues (2003) in their lexical decision experiment. Results of the Rissman et al. (2003) study indicated strong semantic priming effects for the prime-target pairs. All stimuli were matched for stimulus duration and lexical frequency. Stimuli were recorded by a phonetically trained male speaker and were digitized at a sampling rate of 22,050 Hz to produce a 16-bit digital sound file.

Each trial consisted of a prime followed by a target with a 50 ms interstimulus interval (ISI). Participants were asked to make a push-button response using their right hand to indicate if the stimuli were related or unrelated. A total of 80 real word stimulus pairs (either semantically related or unrelated) were presented. In the related condition, the target was preceded by a semantically related prime, e.g. *petite-small*. In the unrelated condition, the target was preceded by a semantically and associatively unrelated prime, e.g. *construct-small*. The experiment was divided into two runs containing 40 trials with equal numbers of related and unrelated stimulus pairs. Run order was held constant across participants.

2.3. Procedure

Stimuli were presented during the scanning session through a pair of sound attenuating headphones (Resonance Technologies ™, Northridge, California). Experimental presentation and response collection was conducted using the BLISS software suite (Mertus, 1989) running on an IBM Thinkpad. Responses were scored for both reaction time latency (measured from the onset of the target word) and accuracy. All participants were instructed to make a “Related/ Unrelated” judgment by pressing the appropriate button. The button mapping was counterbalanced across participants. Participants were asked to respond as quickly and accurately as possible, to remain still during scanning, and to keep eyes closed to avoid visual and eye movement artifacts.

The temporal onset asynchrony (TOA) was varied in 8 quarter intervals of the 3.6 s TR (2.7s, 3.6s, 4.5s, 5.4s, 6.3s, 7.2s, 8.1s and 9.0s) with an average TOA of 5.85s. This resulted in an effective sampling rate of 900 ms. TOAs were distributed equally across runs and were randomized within the run.

2.4. Image Collection

Functional and Anatomical images were collected using a 1.5 Tesla Symphony Magnetom MR system (Siemens Medical Systems, Erlangen, Germany.) Anatomical images were collected prior to the acquisition of functional data (TR=1900ms, TE=4.15 ms, TI = 1100 ms, 1 mm^3 isotropic voxels, 256×224mm FoV and 160 slices and sagittal acquisition). Functional echo-planar (EP) images using the BOLD contrast (TR=3600ms, 45 slices, 3 mm^3 isotropic voxels, TE=38ms, 64mm^2 matrix and a FoV of 192 mm) were collected while participants performed the semantic judgment task. A total of 138 functional volumes were collected (69 in each run).

2.5. Data Analysis

All images were processed and analyzed using AFNI (Cox 1996,Cox & Hyde, 1997). The first four EP volumes of each run were excluded from the analysis to remove T1 saturation effects. The anatomical and functional datasets for each participant were co-registered using positioning information from the scanner. Functional datasets were corrected for motion using a six-parameter rigid body transformation (Cox & Jesmanowicz, 1999). Anatomical images were normalized to the Talairach and Tournoux template (1988) as implemented in AFNI and motion-corrected functional datasets were registered to the normalized anatomical dataset. Normalized functional datasets were smoothed using a 6mm^3 full-width at half-maximum Gaussian kernel. A brain mask dataset which defined area of brain tissue was created from each participant’s normalized, motion-corrected and blurred functional dataset. Voxels which were imaged in at least 13 of 15 participants were included in subsequent group analyses. This threshold was chosen rather than requiring that all voxels be imaged in all subjects due to small differences in the alignment of the functional volumes for two subjects, which would have decreased the size of the analyzed volume by approximately 5,000 voxels. Nonetheless, in the areas of interest (i.e. inferior and middle frontal areas, superior and middle temporal areas), data from all subjects contributed to the analysis.

Vectors containing stimulus onset times for each condition, with errors included as a separate vector, were created for each participant and convolved with a gamma-variate function to create reference functions for each condition. Reference functions and the blurred functional dataset were then submitted to deconvolution analysis to estimate the hemodynamic response during performance of each condition on a voxel by voxel basis. The six parameters of the motion correction algorithm were included in the deconvolution analysis as additional reference waveforms. Estimated coefficients for each condition were normalized to the participant's average experiment-wise signal intensity to convert intensity into percent signal change.

Group analysis for the Semantic Judgment experiment was accomplished by submitting percent change datasets to a two-factor analysis of variance (ANOVA) using stimulus condition (fixed effect) and participant (random effect) as independent variables. For each condition (Related and Unrelated) mean statistical maps were calculated, and a contrast between the two conditions was also performed.

The activation patterns obtained in the current experiment were then compared to those obtained from the Rissman et al. (2003) study. In this experiment, 15 participants performed a lexical decision task, in which a target word was preceded by either a semantically related or semantically unrelated prime. As in the current experiment, there was a 50 ms ISI between the stimulus pairs. Comparison of the two tasks was accomplished by performing a second deconvolution analysis on both sets of data, using only voxels present in a minimum of 28 out of 30 participant's brain masks. Deconvolution analysis conducted on datasets from both studies otherwise matched the procedure stated above.

Between-experiment analysis was accomplished by submitting percent change datasets to a three-factor ANOVA using experiment (fixed effect), stimulus condition (fixed effect) and participant (random effect) as independent variables. This analysis allowed for comparison between the two experiments across conditions (Semantic Judgment vs. Lexical Decision), comparison of the two conditions across experiments (Related vs. Unrelated) and for an interaction between Experiment and Condition.

Monte-Carlo simulations were run on the group brain mask to obtain corrected, cluster level thresholds. For the ANOVA outputs a voxel-level threshold of $p<0.01$ and a corrected, cluster-level threshold of $p<0.05$ was used (36 contiguous voxels for the semantic judgment task alone and 35 contiguous voxels for the comparison between the semantic judgment task and the data from the Rissman et al. (2003) lexical decision study).

3. Results

3.1. Behavioral Results

As anticipated, the majority of subjects (fourteen of the fifteen) exhibited semantic priming in the semantic judgment task by responding more quickly to the semantically related stimulus pairs than the unrelated stimulus pairs. The mean error rate was one error for related pairs and 0.6 errors for the unrelated pairs. Mean reaction-time latencies (RT) for correct responses were 859 ms (S.E. = 36 ms) for the related condition and 1008 ms (S.E. = 43 ms) for the unrelated condition. A one-way ANOVA comparing the RT latencies in the related and unrelated conditions resulted in a significant effect of stimulus condition ($F(1,14) = 31.707$, $p < 0.001$).

Comparison of the RT latencies between the semantic judgment task and the Rissman et al. (2003) lexical decision task showed similar results. The RT latencies in the lexical decision task were 890 ms for semantically related word pairs and 1052 ms for the semantically unrelated pairs. A 2-way Experiment X Condition ANOVA with Experiment as a between-subject factor and Condition as a within subjects factor revealed a main effect for Condition ($F(1,56) =18.35$, $p < .001$) indicating a significant effect of priming. All other comparisons were non-significant.

3.2. FMRI Results

Table 1 shows the results for the Unrelated vs. Related contrast in the semantic judgment task. The only significant cluster observed in this comparison showed greater activation for the Unrelated than for the Related stimuli and the maximum intensity for that cluster was located in the L IFG (see Figure 1). No significant clusters were observed in which Related > Unrelated in the semantic judgment task.

Results of the comparison between related and unrelated conditions across both the semantic judgment and lexical decision tasks revealed a number of significant clusters (see Table 2). There was greater activation in the unrelated than the related condition in the IFG, the left STG, the right superior temporal sulcus (STS) extending into the STG, the insula bilaterally, the left postcentral gyrus, the left MFG, and the cerebellum bilaterally (see Figure 2). Greater activation emerged for the related than the unrelated condition in both the left inferior parietal lobule and the left cingulate gyrus (see Table 2 and Figure 2).

In the comparison of the two task types across conditions, there was greater activation only for the semantic judgment task compared to the lexical decision task. These clusters emerged in the STG bilaterally and the left medial frontal gyrus extending into the cingulate (see Table 2 and Figure 3).

Several regions were found to exhibit an interaction between experimental task (semantic judgment or lexical decision) and condition (related or unrelated) (see Table 2). These interactions were observed in the right caudate, the right inferior parietal lobule and the right medial frontal gyrus and were due to greater activation for unrelated than related word pairs in the lexical decision task and greater activation for related than unrelated word pairs in the semantic judgment task.

4. Discussion

It was the goal of the current study to examine the neural systems underlying lexical semantic processing with a focus on potential functional differences between posterior areas, e.g. STG, MTG, and anterior areas, e.g. IFG. Results of the analysis of the semantic judgment task taken alone showed modulation of activation in the LIFG with greater activation for semantically unrelated than related word pairs. The presence of semantically-modulated activation in this area is consistent with earlier studies showing increased frontal activation in explicit semantic tasks (Demb et al., 1995; Spitzer, 1996) and is consistent with the view that the IFG is particularly involved in lexical semantic processing and in the retrieval and analysis of word meaning.

The locus of activation in the IFG included both BA 45 and 47. Earlier research has suggested a different functional role for these two areas with activation in BA47 (pars orbitalis) involved in accessing stored conceptual representations and BA45 (pars triangularis) involved in resolving competition among activated representations (Badre and Wagner, 2007; Miller and Cohen, 2001, cf. also Petrides, 2005). Because both BA45 and BA47 were activated, we are unable to uncouple the relative contribution of each area to the semantic judgment task. Nonetheless, it is worth noting that the semantic judgment task requires that stored semantic representations be activated and overt comparisons between these representations be made to determine whether the stimuli are semantically related or not. Presumably accessing words that share conceptual properties require fewer processing resources than accessing those that do not. The findings of greater activation for semantically unrelated words compared to semantically related words are consistent with the role of BA47 in accessing the conceptual representations of words.

The role of BA45 in the semantic judgment task is less clear. The semantic judgment task does not require selecting one meaning from among a set of competing alternatives, but rather evaluating the potential semantic overlap between two words. In principle, semantically related pairs are in competition with each other because they share semantic properties. Were activation patterns in BA45 attributable to competition between meanings, one would expect to see more activation for related than unrelated pairs. However, this was not the case in the current study. Of interest, using a lexical decision task, Kotz et al. (2002) showed, similar to the current experiment, decreased activation for related than for unrelated word pairs in BA44/45. Neither the semantic judgment task nor the lexical decision task requires the selection of a single word from a set of semantic competitors. Thus, it appears as though BA45 has lexical-semantic functions that extend beyond simply resolving competition.

The failure to show a modulation effect in the semantic judgment task in temporal areas as well as the IFG was surprising. However, further examination of the activation patterns by relaxing the voxel-level threshold value in the cluster analysis from $p<.01$ to $p<.025$ revealed a significant cluster in the STG as well as in the IFG. Thus, modulation effects appear in both the STG as well as in the IFG with greater activation for semantically unrelated than related word pairs in the semantic judgment task.

Turning to the comparison between the semantic judgment and lexical decision tasks, it is worth noting that although a significant interaction effect emerged as a function of task and condition, this effect emerged in areas other than the IFG and STG. In particular, they emerged in right hemisphere structures including the caudate, inferior parietal lobule, and medial frontal gyrus. Thus, the patterns of activation that emerged for the IFG and STG were limited to the effects of stimulus condition (related vs. unrelated) and task (semantic judgment vs. lexical decision). Let us turn to these findings.

Both the LIFG and STG bilaterally showed greater activation for semantically unrelated than related word pairs across the two tasks. As discussed above, this pattern of results is consistent with the view that semantically related words activate a similar lexical-semantic network and hence require less neural processing than words which have no semantic relationship (Demb et al., 1995; Rissman et al., 2003). It is possible that the extent of activation in either the STG or the IFG is related to the degree of overlap in the lexical-semantic network activated by each word in the word pair. In this view, unrelated words activate different semantic fields, and hence activate the semantic system to a greater degree than do related words, which activate overlapping semantic fields.

It is worth observing that there was a high degree of overlap (42 of 52 voxels) between the inferior frontal cluster revealed in the comparison of unrelated and related stimuli in the semantic judgment task alone, and the larger inferior frontal cluster activated in the comparison between unrelated and related stimuli across both tasks. This overlap occurred in BA 45 and 47, areas which as described above have been previously linked to automatic access of conceptual representations and to resolution of competition further supporting the notion that these inferior areas are involved in both accessing semantic information and automatically resolving competition irrespective of task. In addition to this area of overlap, the inferior cluster revealed in the comparison of unrelated versus related stimuli across both tasks extended into posterior and superior portions of the IFG and into BA 44. Given that this more posterior area was not activated in the semantic judgment task, it seems likely this more posterior area of activation arises largely due to increases in activation for unrelated vs. related stimuli in the lexical decision task. It may be the case that as subjects make word and non-word decisions in the lexical decision task, attentional resources are focused on aspects of phonological-lexical form. As such, these results are consistent with the view that posterior portions of the LIFG

(BA44) are involved in access and manipulation of phonological representations (Burton, 2001).

Comparison of the two task types across conditions revealed greater activation only in the STG bilaterally and not in the IFG as originally predicted. The behavioral results as measured by reaction time latencies demonstrated that the tasks were equivalent in difficulty. These results showed a significant main effect for priming but neither a main effect for task nor an interaction between task and condition. Thus, differences in the activation patterns between the two tasks reflect differences in task demands, but not differences in task difficulty. Greater activation in the STG for the semantic judgment task compared to the lexical decision task is not surprising. Unlike the lexical decision task, the semantic judgment task requires overt analysis of meaning, and hence a greater 'depth of processing' (Craik & Lockhart, 1972). Thus, increased activation in the STG may be indicative of greater utilization of semantic resources in order to perform this task. These findings indicate that the STG is not only a passive store of meaning but is actively involved in its processing (cf. also Rissman et al., 2003; Noppeney et al.,2004; Gold et al., 2006).

What is surprising is that there was not a similar modulation of activation in the IFG as a function of task demands. After all, the semantic judgment task required retrieval of the meanings of both stimulus pairs, holding them in working memory, and assessing whether the word pairs were semantically related or not. In contrast, the lexical decision task required that a response be made only on the lexical form (not the meaning) of the target. It did not require overt analysis of either form or meaning of the prime stimulus nor did it require overt resolution of meaning competition between the prime and target stimulus. Nonetheless, there were differences not only in the stimuli but also in the nature of the two experimental tasks that could have contributed to the failure to show differences between the two tasks. In particular, the stimuli in the lexical decision task included nonword targets, whereas there were only word targets in the semantic judgment task. Moreover, although the semantically related pairs in both the semantic judgment and lexical decision tasks required 'yes' responses, the semantically unrelated pairs required a 'yes' response in the lexical decision task (since the target stimulus was a word) and a 'no' response in the semantic judgment task (since the stimulus pairs were semantically unrelated). And although both tasks included an equal number of 'yes' and 'no' responses, the proportion of related trials was 1/3 in the lexical decision task and ½ in the semantic judgment task. These differences make it difficult to assess potential differences in the executive processes and the computational resources needed to do the two tasks.

In fact, consideration of the *similarities* between the two tasks may provide an explanation for why no differences emerged in activation patterns in the IFG. In particular, both tasks required similar aspects of cognitive control in the service of accomplishing a goal (cf. Miller and Cohen, 2001; Badre and Wagner, 2007). Both required a decision on a target word, in one case about lexical form, in the other about lexical meaning. In both tasks, there was the automatic activation of lexical-semantic representations as evidenced by greater activation for semantically unrelated compared to related stimulus pairs. And because the related and unrelated stimulus pairs were the same, competition of these activated representations was equivalent. As a consequence, no differences emerged in the IFG when comparing activation patterns to the same stimuli in the in the two tasks.

As expected, increased activation in the medial frontal gyrus extending into the cingulate suggests that there were greater response demands in the semantic judgment task than in the lexical decision task (cf. Ridderinkohf, et al., 2004). That is, there was greater response conflict in the former task since subjects needed to determine the extent to which two words were similar in meaning, and on that basis, decide whether they were related or not. Thus, a more qualitative judgment was required than in the lexical decision task where a given target word was either a lexical item or it was not.

As discussed in the introduction, those studies which have attempted to separate out the role of task demands from semantic processing have compared activation patterns between semantic and non-semantic tasks and as a consequence have had to use different stimuli. Although behavioral measures in these studies suggested no differences in task difficulty, it is difficult to know for certain whether the differences that emerged in IFG activation reflected the different cognitive operations used in processing the different stimuli, and/or in performing the tasks with these stimuli. The current study attempted to control for this difficulty this by changing the task demands while comparing activation patterns associated with the processing of the same semantically related and unrelated stimulus pairs. The failure to show differences in activation in the IFG between the semantic judgment and lexical decision task provides support for the view that the IFG is involved in semantic processing irrespective of potential differences in the processing demands between the lexical decision and semantic judgment tasks.

Evidence from the lesion literature is consistent with this view. In a series of studies examining lexical-semantic processing using both auditory and visual modalities (Blumstein et al., 1982; Milberg & Blumstein, 1981), both Broca's and Wernicke's aphasics performed a lexical decision task and a semantic judgment task using the same stimuli. Although both groups of patients had extensive lesions, the Broca's aphasics had lesions that were primarily frontal and included the LIFG and the Wernicke's aphasics had lesions that were primarily temporal and included the STG. The results were analogous to those found in the current study. Namely, both groups of patients demonstrated semantic priming effects with faster RT latencies to semantically related compared to semantically unrelated word pairs. However, it was the Wernicke's aphasics, not the Broca's aphasics who showed impairments in the semantic judgment task. Thus, the Wernicke's aphasics had deficits in performing a task which required a deeper semantic analysis of the stimuli.

In sum, the results of this study suggest that both left frontal and posterior areas are involved in lexical-semantic processing. Both the L IFG and the STG bilaterally show sensitivity to the semantic relationships between words, whether accessed in an explicit semantic judgment task or an implicit lexical decision task. However, there was greater activation in the temporal lobes bilaterally when the task required controlled access to the semantic properties of words than when it required access only to lexical form.

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References

Badre D, Wagner AD. Left ventrolateral prefrontal cortex and the cognitive control of memory. Neuropsychologia. 2007in press

Blumstein SE, Milberg W, Shrier R. Semantic processing in aphasia: evidence from an auditory lexical decision task. Brain and Language 1982;17:301–15. [PubMed: 7159838]

Burton MW. The role of inferior frontal cortex in phonological processing. Cognitive Science 2001;25:695–709.

Cox RW. AFNI: Software for analysis and visualization of functional magnetic resonance neuroimages. Computers and Biomedical Research 1996;29:162–173. [PubMed: 8812068]

Cox RW, Hyde JS. Software tools for analysis and visualization of fMRI data. NMR in Biomedicine 1997;10:171–178. [PubMed: 9430344]

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Cox RW, Jesmanowicz A. Real-time 3D image registration for functional MRI. Magnetic Resonance in Medicine 1999;42:1014–1018. [PubMed: 10571921]

Craik FIM, Lockhart RS. Levels of processing: A framework for memory research. Journal of Verbal Learning and Verbal Behavior 1972;11:671–684.

Demb JB, Desmond JE, Wagner AD, Vaidya CJ, Glover GH, Gabrieli JDE. Semantic encoding and retrieval in the left inferior prefrontal cortex: A functional MRI study of task difficulty and process specificity. Journal of Neuroscience 1995;15:5870–5878. [PubMed: 7666172]

Gabrieli JDE, Desmond JE, Demb JB, Wagner AD. Functional magnetic resonance imaging of semantic memory processes in the frontal lobes. Psychological Science 1996;7:278–283.

Gold BT, Balota DA, Jones SJ, Powell DK, Smith CD, Andersen AH. Dissociation of automatic and strategic lexical-semantics: Functional magnetic resonance imaging evidence for differing roles of multiple frontotemporal regions. The Journal of Neuroscience 2006;26:6523–6532. [PubMed: 16775140]

Jansma JM, Ramsey NF, Slagter HA. Functional anatomical correlates of controlled and automatic processing. Journal of Cognitive Neuroscience 2001;13:730–743. [PubMed: 11564318]

Kapur S, Rose R, Liddle PF, Zipursky RB, Brown GM, Stuss D, Houle S, Tulving E. The role of the left prefrontal cortex in verbal processing: semantic processing or willed action? Neuroreport 1994;5:2193–2196. [PubMed: 7865775]

Kotz SA, Cappa SF, von Cramon DY, Friederici AD. Modulation of the Lexical-Semantic Network by Auditory Semantic Priming: An Event-Related Functional MRI Study. Neuroimage 2002;17:1761–1772. [PubMed: 12498750]

Milberg W, Blumstein SE. Lexical decision and aphasia: evidence for semantic processing. Brain and Language 1981;14:371–85. [PubMed: 7306789]

Miller EK, Cohen JD. An integrative theory of prefrontal cortex. Annual Review of Neuroscience 2001;24:167–202.

Muller R, Kleinhans N, Courchesne E. Linguistic theory and neuroimaging evidence: an fMRI study of Broca's area in lexical semantics. Neuropsychologia 2003;41:1199–1207. [PubMed: 12753959]

Noppenney U, Phillips J, Price C. The neural areas that control the retrieval and selection of semantics. Neuropsychologia 2004;42:1269–80. [PubMed: 15178178]

Oldfield RC. The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologia 1971;9:97–113. [PubMed: 5146491]

Petersen SE, Fox PT, Posner MI, Mintun M, Raichle ME. Positron emission tomographic studies of the cortical anatomy of single-word processing. Nature 1988;331:585–589. [PubMed: 3277066]

Petrides M. Lateral prefrontal cortex; architectonic and functional organization. Philosphical Transactions of the Royal Society B 2005;360:781–795.

Price C, Friston K. Degeneracy and cognitive anatomy. Trends in Cognitive Science 2002;6:416–421.

Ridderinkhof KR, van den Wildenberg WPM, Segalowitz SJ, Carter CS. Neurocognitive mechanisms of cognitive control: The role of prefrontal cortex in action selection, response inhibition, performance monitoring, and reward-based learning. Brain and Cognition 2004;56:129–140. [PubMed: 15518930]

Rissman J, Eliassen JC, Blumstein SE. An event-related fMRI investigation of implicit semantic priming. Journal of Cognitive Neuroscience 2003;15:1160–1175. [PubMed: 14709234]

Roskies AL, Fiez JA, Balota DA, Raichle ME, Petersen SE. Task-dependent modulation of regions in the left inferior frontal cortex during semantic processing. Journal of Cognitive Neuroscience 2001;13:829–843. [PubMed: 11564326]

Rossell SL, Bullmore ET, Williams SCR, David AS. Brain activation during automatic and controlled processing of semantic relations: a priming experiment using lexical decision. Neuropsychologia 2001;39:1167–1176. [PubMed: 11527554]

Rossell SL, Price CJ, Nobre AC. The anatomy and time course of semantic priming investigated by fMRI and ERPs. Neuropsychologia 2003;41:550–564. [PubMed: 12638581]

Spitzer M, Belleman ME, Kammer T, Friedemann G, Kischka U, Maier S, Schwartz A, Brix G. Functional MR imaging of semantic information processing and learning-related effects using psychometrically controlled stimulation paradigms. Cognitive Brain Research 1996;4:149–161. [PubMed: 8924044]

Talairach, J.; Tournoux, P. A co-planar stereotaxic atlas of a human brain. Stuttgart, Germany: Thieme; 1998.

Thompson-Schill SL, D'Esposito M, Aguirre GK, Farah MJ. Role of left inferior prefrontal cortex in retrieval of semantic knowledge: A reevaluation. Proceedings of the National Academy of Sciences USA 1997;94:14792–14797.

Tyler LK, Russell R, Fadili J, Moss HE. The neural representation of nouns and verbs: PET studies. Brain 2001;124:1619–1634. [PubMed: 11459753]

Wagner AD, Pare-Blagoev EJ, Clark J, Poldrack RA. Recovering meaning: Left prefrontal cortex guides controlled semantic retrieval. Neuron 2001;31:329–338. [PubMed: 11502262]

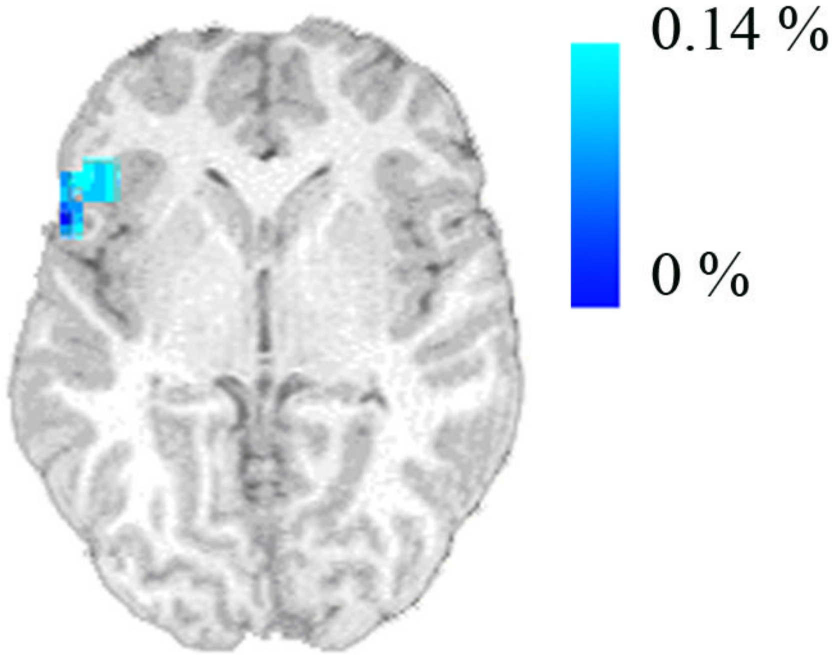

Figure 1.
Axial view (z = 1) of the cluster in the inferior frontal gyrus with significantly greater activation (p < .05 corrected) for the unrelated than the related stimulus pairs in the semantic judgment task. Color scale represents differences in % signal change between the 2 conditions.

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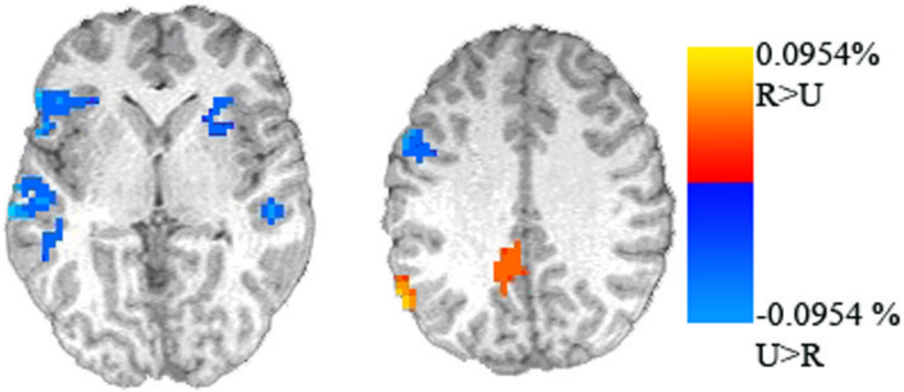

Figure 2.

Clusters showing significant differences (p < .05 corrected) in activation patterns for related compared to unrelated stimulus pairs across the two experimental (semantic judgment and lexical decision) tasks. Clusters showing greater activation for unrelated pairs are in blue and clusters showing greater activation for related pairs are in red. The axial view on the left (z = 2) shows increased activation for unrelated compared to related stimulus pairs in the left IFG extending into the insula, the right insula, the left STG and the right STS. The axial view on the right (z=32) shows greater activation for unrelated compared to related in the left IFG and greater activation for the related compared to the unrelated in left inferior parietal lobule and the left cingulate gyrus (see Table 2). Color scale represents differences in % signal change between the 2 conditions.

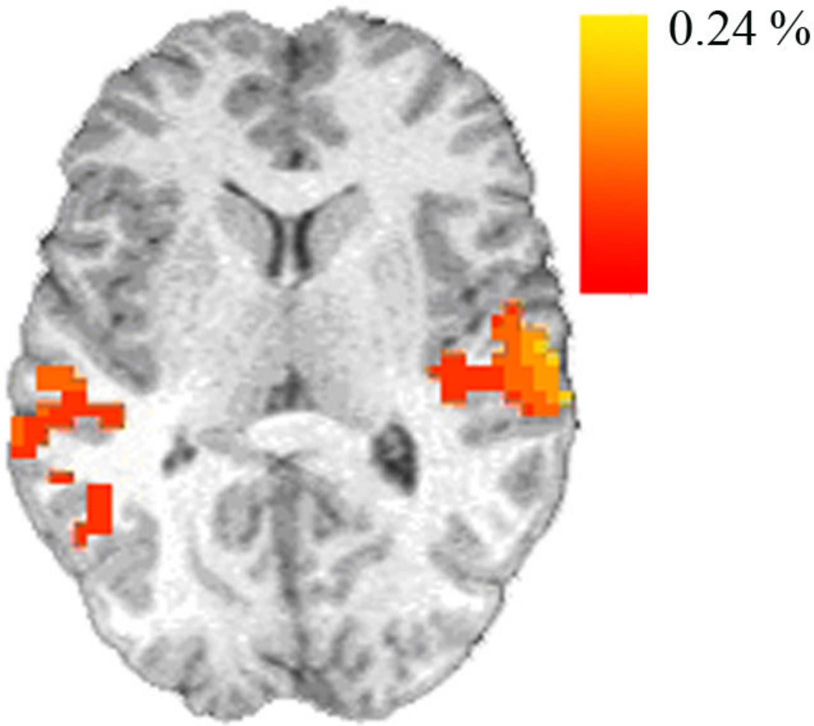

Figure 3.
Clusters showing significantly greater activation (p < .05 corrected) for the semantic judgment task compared to the lexical decision task across the stimulus conditions. The axial view (z = 7) shows increased activation in the STG bilaterally. Color scale represents differences in % signal change between the 2 conditions.

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Table 1

Areas of activation significant in comparison of related and unrelated conditions in the semantic judgment task, clusters significant at a corrected level $p<0.05$ (voxel-level correction, $p<0.01$; ≥ 35 contiguous activated voxels.). Coordinates indicate the maximum intensity voxel for that cluster. All coordinates are in Talairach and Tournoux space.

Anatomical Region	Maximum Intensity			Number of activated voxels	Mean Difference in % Signal Change (Std Err)
	x	y	z		
Unrelated > Related					
Left Inferior Frontal Gyrus	−49.5	+16.5	−3.5	52	0.1403 (0.0046)

Table 2

Results of comparison of Condition (Related vs Unrelated), Task (Semantic Judgment vs Lexical Decision) and Condition x Task Interaction, clusters significant at a corrected $p<0.05$ (voxel-level correction, $p<0.01$; ≥ 35 contiguous activated voxels.)

Anatomical Region	Maximum Intensity x	y	z	Number of activated voxels	Mean Difference in % Signal Change (Std. Err.)
Unrelated > Related					
L IFG	−49.5	22.5	20.5	328	0.0954 (0.0013)
L STG	−61.5	−7.5	−0.5	168	0.0919 (0.0018)
R Insula	28.5	25.5	5.5	67	0.0701 (0.0016)
R STS	49.5	−22.5	2.5	65	0.0735 (0.0018)
L Cerebellum	−7.5	−73.5	−27.5	59	0.0762 (0.0022)
R Cerebellum	13.5	−40.5	−18.5	50	0.0650 (0.0013)
L Insula	−40.5	−28.5	−0.5	48	0.0657 (0.0011)
L Postcentral Gyrus	−52.5	−19.5	47.5	47	0.0759 (0.0025)
R Middle Frontal Gyrus	49.5	19.5	26.5	37	0.0954 (0.0025)
Related > Unrelated					
L IPL	−52.5	−52.5	44.5	93	0.0960 (0.0023)
L Cingulate Gyrus	−1.5	−40.5	26.5	61	0.0825 (0.0022)
Semantic Judgment > Lexical Decision					
R STG	61.5	−13.5	5.5	212	0.2440 (0.0072)
L STG	−58.5	−19.5	11.5	187	0.1950 (0.0041)
L Medial Frontal Gyrus extending into cingulate	−1.5	13.5	47.5	88	0.1745 (0.0043)
Interaction Condition X Task					
R Caudate	7.5	−1.5	14.5	83	0.3145 (0.007)
R IPL	43.5	−37.5	56.5	76	0.3280 (0.0066)
R Medial Frontal Gyrus	1.5	31.5	32.5	38	0.2878 (0.0088)