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Prefrontal Cortical Response to Conflict during Semantic and Phonological Tasks

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Prefrontal Cortical Response to Conflict during Semantic and Phonological Tasks

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Abstract

■ Debates about the function of the prefrontal cortex are as old as the field of neuropsychology—often dated to Paul Broca’s seminal work. Theories of the functional organization of the prefrontal cortex can be roughly divided into those that describe organization by process and those that describe organization by material. Recent studies of the function of the posterior, left inferior frontal gyrus (pLIFG) have yielded two quite different interpretations: One hypothesis holds that the pLIFG plays a domain-specific role in phonological processing,

whereas another hypothesis describes a more general function of the pLIFG in cognitive control. In the current study, we distinguish effects of increasing cognitive control demands from effects of phonological processing. The results support the hypothesized role for the pLIFG in cognitive control, and more task-specific roles for posterior areas in phonology and semantics. Thus, these results suggest an alternative explanation of previously reported phonology-specific effects in the pLIFG. ■

INTRODUCTION

Theories of the functional organization of the prefrontal cortex can be roughly divided into those that describe organization by process and those that describe organization by material. For example, one prominent debate concerns whether dissociations between dorsal and ventral regions of the lateral prefrontal cortex are attributable to differences in the content of working memory (e.g., verbal, spatial) or in the operations performed on that content (e.g., maintenance, manipulation) (Cadoret, Pike, & Petrides, 2001; D’Esposito, Postle, & Rypma, 2000; Levy & Goldman-Rakic, 2000; D’Esposito, Postle, Ballard, & Lease, 1999; Courtney, Petit, Haxby, & Ungerleider, 1998). In recent years, a similar debate has emerged with regard to the left ventrolateral prefrontal cortex generally, and of the posterior region of the left inferior frontal gyrus (pLIFG) more specifically. Hypotheses about the function of this region are as old as the field of neuropsychology (often dated by the publication of Paul Broca’s seminal paper about the role of this region in speech production), and they run the gamut from response inhibition (Matsubara, Yamaguchi, Xu, & Kobayashi, 2004), to action imitation (Hamzei et al., 2003), to verbal rehearsal (Cohen et al., 1997), to a specific syntactic transformation (Grodzinsky, 2000) (for a discussion, see Thompson-Schill, 2006). Here, we consider two specific hypotheses about the functions of the LIFG: one that describes functional specialization of

the pLIFG for the specific domain of phonology and the anterior LIFG (aLIFG) in semantic processing (e.g., Burton, Diamond, & McDermott, 2003; Burton, 2001), and another that describes a more general function of the LIFG in guiding selection among competing alternatives, by, for example, inhibiting task-irrelevant stimulus attributes (Barde & Thompson-Schill, 2002; Thompson-Schill, D’Esposito, Aguirre, & Farah, 1997). The goal of the present study is to evaluate the extent to which seemingly domain-specific effects in the LIFG might instead reflect a more general cognitive control process.

There are numerous reports of increased activation in the pLIFG during phonological as compared to semantic processing. For example, deciding whether “chair” and “bear” rhyme is associated with greater pLIFG activation than is deciding whether they mean the same thing. None of these studies reveal a clear, robust functional division between the pLIFG and the aLIFG on semantic and phonological tasks. Rather, three studies (Devlin, Matthews, & Rushworth, 2003; Price, Moore, Humphreys, & Wise, 1997, with a lowered threshold; Turriziani, Caltagirone, Tomaiuolo, Capasso, & Miceli, 2001) found higher phonological than semantic activation in the pLIFG and a trend in the opposite direction or no effect in the aLIFG, whereas two (Burton et al., 2003; Mummery, Patterson, Hodges, & Price, 1998) found higher semantic than phonological activation in the aLIFG and a trend in the opposite direction or no effect for the pLIFG. Several studies have reported greater semantic than phonological activation in both the pLIFG and aLIFG (Gold & Buckner, 2002; Roskies, Fiez, Balota, Raichle, & Petersen, 2001; Poldrack et al.,

1999). Additionally, one study found higher semantic than phonological activation throughout most of the LIFG, with a phonological advantage only in a very posterior area including the premotor cortex (McDermott, Petersen, Watson, & Ojemann, 2003), whereas one study (Martin, Wu, Freedman, Jackson, & Lesch, 2003) reported no significant differences between semantic and phonological conditions in the LIFG. In a recent study, Gold, Balota, Kirchoff, and Buckner (2005) showed activation and functional magnetic resonance imaging adaptation effects in both the aLIFG and pLIFG when subjects performed semantic and phonological tasks which emphasized controlled processing. The semantic verb-generation task produced higher activation and greater adaptation than did the phonological regularization task.

Why the discrepancies? One possibility, which we explored in the present study, is that some comparisons of phonological and semantic retrieval tasks may have revealed pLIFG activity related to cognitive control demands, and not domain-specific processing. We considered the hypothesis that the automatic retrieval of semantic information (cf. Macleod, 1991) during phonological judgments—for which information about word meaning is irrelevant and potentially distracting—may engage pLIFG regions purported to be involved in selecting among competing sources of information. If the comparison task for these phonological word tasks does not also tax similar cognitive control mechanisms, activation related to a general regulatory mechanism could masquerade as a domain-specific phonology effect. In particular, domain-specific interpretations of pLIFG activation during phonological judgments about real words become suspect.

In the current study, we evaluated this hypothesis by contrasting semantic and phonological tasks with either high or low semantic conflict (Figure 1). If the function of the pLIFG is best described as part of a domain-specific phonology system, activation would be expected to be greater in both phonological conditions compared to both semantic conditions, with no effect of the conflict manipulation. On the other hand, evidence for conflict effects in the absence of differences between phonological and semantic conditions would support cognitive control accounts of pLIFG function. We evaluated domain-specific and cognitive control response profiles not only in the LIFG but also in three posterior cortical regions that have been linked to either phonological (i.e., left supramarginal gyrus, left ventral precentral gyrus) or semantic (i.e., left middle temporal gyrus) processing.

Within each region of interest (ROI), three contrasts were of paramount importance: the comparison of the high-conflict and low-conflict phonological conditions, the comparison of the high-conflict semantic and phonological conditions, and the comparison of the high-conflict semantic condition to the low-conflict

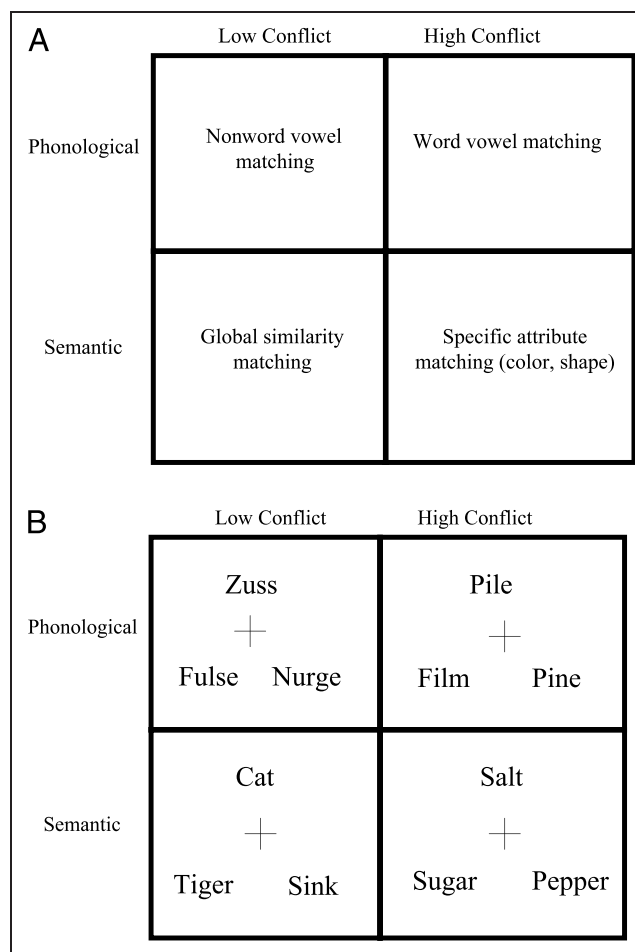


Figure 1. Experimental design and example items. (A) The current study investigated the roles of task type and cognitive control demands by using semantic and phonological tasks with high and low inhibition demands. The organization-by-process hypothesis predicts increased activation with high versus low inhibition demand in the pLIFG and aLIFG, regardless of whether the task is semantic or phonological. (B) In a blocked design, subjects selected which of two targets best matched a probe. Instructions before each block informed subjects of how to make judgments on that block. For the phonological tasks (word and nonword), this decision was made based on vowel sound. For the semantic task, subjects were instructed to base their decision on overall similarity (global), shapes or color (specific). There was also a false-font baseline task.

phonological condition. Predictions about each of these contrasts depend on the following assumptions: First, both phonological conditions (word and nonword) require more phonological processing than does the high-conflict semantic condition. Therefore, any area deemed to be phonology-specific will exhibit greater activity in both phonological conditions than in the high-conflict semantic condition. The amount of phonological processing in the word and nonword conditions is assumed to either be equal, or greater in the nonword condition where the orthography to phonology mapping is less well practiced. Second, retrieval of semantic information will be greatest in the high-conflict semantic condition

(where detailed semantic facts are required for the task), less so for the high-conflict phonological (word) condition (where some semantic content may be automatically retrieved when the word is read), and least for the low-conflict phonological (nonword) condition (where there is no strongly associated referent). The response profile for a semantic-specific area should reflect this ordering. Third, cognitive control demands will reflect the extent to which task-irrelevant information is retrieved. Thus, within the domain of phonology, increased cognitive control should be reflected by a greater response to words than to nonwords (high- vs. low-conflict phonological tasks). There is no clear basis for making assumptions about the relative extent of cognitive control demands between the high-conflict phonological and semantic tasks, a point that we will return to in the Discussion. Nonetheless, the presence of a word–nonword effect in the absence of the preceding two domain-specific effects is the predicted pattern for a cognitive control region. In sum, these three contrasts allow us to evaluate the response properties of any given cortical area.

METHODS

Subjects

Fourteen right-handed subjects (10 women, 4 men, mean age 24.5 years, range 18–30 years) from the University of Pennsylvania community participated in the study. Subjects were excluded if they were not native English speakers, had a history of neurological conditions or head injury, or were taking any psychoactive medication. All subjects gave informed consent and were treated in accordance with procedures approved by the University of Pennsylvania Institutional Review Board.

Design

We created four experimental conditions by crossing the factor of task domain (semantic, phonological) with the factor of level of conflict (high, low). For the two semantic tasks, subjects evaluated the similarity of the meaning of words. Conflict was manipulated by varying the need to inhibit competing semantic information. In the semantic-specific condition, subjects made a color or shape judgment, which often required picking a target that was otherwise less similar to the probe. In the semantic-global condition, subjects made an overall similarity judgment with stimuli that created minimal conflict, and thus, which required little cognitive control. In the phonological conditions, subjects made a vowel sound judgment on words (higher conflict with meaning) or nonwords (lower conflict with meaning). This design allowed us to evaluate the effects of varying degrees of conflict independently of the effects of task domain.

Stimuli

The stimuli consisted of 336 one- to three-syllable regular and irregular English nouns (mean length 4.94 letters, mean Kucera–Frances frequency 41.37), 168 pronounceable nonwords (mean length 4.58 letters) (drawn from Seidenberg, Plaut, Petersen, McClelland, & McRae, 1994), and 168 false-font strings matched in length. False-font strings were created using the font Wingdings (e.g., $\text{O} \bullet \text{O} \blacklozenge \blacklozenge$), and were included as a baseline because they require perceptual matching without linguistic processing.

Probe and target words in all conditions were matched on average string length and, for conditions with words, frequency. All stimuli were presented in white type on a black background and were viewed through a prism mirror apparatus within the scanner. The experiment was programmed and run using E-Prime (Psychology Software Tools, Pittsburgh, PA).

Procedure and Tasks

In each trial, subjects viewed three stimuli: At the onset of the trial, a probe item appeared. After 500 msec, two target words appeared under it for 3000 msec. A fixation cross then appeared for 500 msec before the onset of the next trial. Subjects were instructed to select the target that best matched the probe in vowel sound (phonological conditions), overall similarity (semantic-global condition), shape or color (semantic-specific conditions), or which was identical to the probe (false-font baseline). Seven trials in each of these conditions were grouped into blocks, and instructions at the beginning of each block indicated the task to be performed. The correct target appeared on the right and left an equal number of times. Subjects selected the correct target by pressing the left or right button on a fiber-optic button box.

To familiarize subjects with the pronounceable nonword stimuli, they completed a self-paced training session, either the day before or earlier on the day of scanning. Nonwords were presented on a computer screen one at a time, and the subject was instructed to read the nonword out loud however he or she thought it should sound. Each nonword was presented four times, in random order. Subjects also completed four practice items in each condition before entering the scanner.

During data acquisition, subjects completed eight blocks each of semantic (four global + four specific), word phonological, nonword phonological, and baseline items. In the specific semantic condition, the incorrect target was globally more similar to the probe than the correct target on 70% of trials (e.g., a lime is closer in color to moss than to an otherwise more similar lemon). On the remaining 30%, an unrelated target was used to prevent subjects from adopting the strategy of always picking the globally less similar target. Because words

with irregular grapheme to phoneme mappings (e.g., pint) may require more complete semantic access in order to complete a phonological task than do regular words (e.g., cat) (e.g., Plaut, McClelland, & Seidenberg, 1996), the phonological word task was further subdivided into four regular and four irregular word blocks for exploratory analyses. Thus, each subject completed 32 blocks for a total of 224 trials. Blocks were presented in the following order for half the subjects: (1) false-font baseline, (2) regular word phonological, (3) semantic-specific, (4) nonword phonological, (5) false-font baseline, (6) irregular word phonological, (7) semantic-global, (8) nonword phonological, repeated four times. For the other half of the subjects, the sequence of the blocks was reversed for counterbalancing of condition order. The entire session, including informed consent and demographic forms, training, testing, and debriefing, lasted 90 min. Subjects were paid US\$20 as compensation for their participation.

Image Acquisition

Imaging was performed on a 3-Tesla Siemens Trio scanner (Siemens, Erlanger, Germany) equipped with a Siemens body coil and a four-channel head coil. High-resolution axial T1-weighted structural images were collected from each subject prior to the collection of experimental data. A gradient-echo, echo-planar sequence (TR = 3500 msec, TE = 30 msec) was used to acquire data sensitive to BOLD signal. Resolution was 3 mm × 3 mm in-plane, with 3-mm-thick axial slices. Twenty-eight seconds of gradient and radio-frequency pulses preceded the actual data acquisition in each scan to allow tissue to reach steady-state magnetization. Prospective motion correction was done on-line with a PACE sequence.

Data Analysis

Off-line data processing was performed using VoxBo software (www.voxbo.org). The data were realigned, thresholded, and smoothed with an 8-mm full-width half-maximum (FWHM) Gaussian filter. The data were also reoriented to give coronal, as well as the original axial, slices. Data were analyzed using the general linear model as implemented in VoxBo, including an empirically derived $1/f$ noise model, regressors to account for global signal variations, and nuisance regressors to account for differences between scans (Aguirre, Zarahn, & D'Esposito, 1997; Zarahn, Aguirre, & D'Esposito, 1997). Each stimulus condition was modeled as a boxcar function convolved with a canonical hemodynamic response function.

For the whole-brain analysis, the data were first normalized using the Montreal Neurological Institute (MNI) template using a set of affine and smoothly nonlinear transformations as implemented in SPM2 and smoothed with a 12-mm FWHM Gaussian filter. Files were then re-

converted to VoxBo format and a random effects analysis was performed.

RESULTS

Behavioral Data

Mean accuracies and reaction times are given in Table 1. Accuracy data were not available from one subject due to a computer problem. Reaction times are means of medians. Repeated-measures ANOVAs with Bonferroni-corrected post hoc comparisons were conducted to test for differences in accuracy and reaction time between conditions. Reaction times were significantly shorter in the semantic-global than semantic-specific [$t(13) = -7.18$, $p < .001$], phonological word [$t(13) = -10.27$, $p < .001$], and phonological nonword [$t(13) = -8.29$, $p < .001$] conditions. Accuracy was significantly higher in the global semantic condition than the specific semantic [$t(12) = 6.73$, $p < .001$], phonological word [$t(12) = 5.72$, $p < .001$], and phonological nonword [$t(12) = 8.15$, $p < .01$] conditions. When regular and irregular words were considered separately for the phonological word condition, reaction times were marginally longer for the irregular than regular word condition [$t(13) = 3.06$, $p = .09$]. All other comparisons were nonsignificant. It should be noted that three subjects had lower than 60% accuracy on the phonological irregular word items. However, excluding them from the analysis did not change the overall pattern of results. Therefore, they were included in all analyses reported here. Because the semantic-specific, phonological word, and phonological nonword conditions were all well matched for reaction time and accuracy, hypotheses will be evaluated primarily based on these three conditions, although the semantic-global condition will also be reported.

ROI Analyses

Four ROIs were defined for each subject. The LIFG was anatomically defined for each subject in both the coronal

Table 1. Behavioral Data

<i>Condition</i>	<i>No. of Trials</i>	<i>% Correct</i>	<i>RT (msec)</i>
Semantic global	28	95 (1.4)	1135 (56)
Semantic specific	28	77 (2.5)	1588 (82)
Phonological Word (Regular + Irregular)	56	79 (2.6)	1721 (92)
Phonological regular	28	86 (1.7)	1633 (97)
Phonological irregular	28	73 (4.7)	1801 (91)
Phonological nonword	56	78 (2.0)	1711 (102)

Standard error of the mean is in parentheses. Accuracy is given in percent correct. Reaction times are the mean of medians for all trials in milliseconds (see Results for statistical tests).

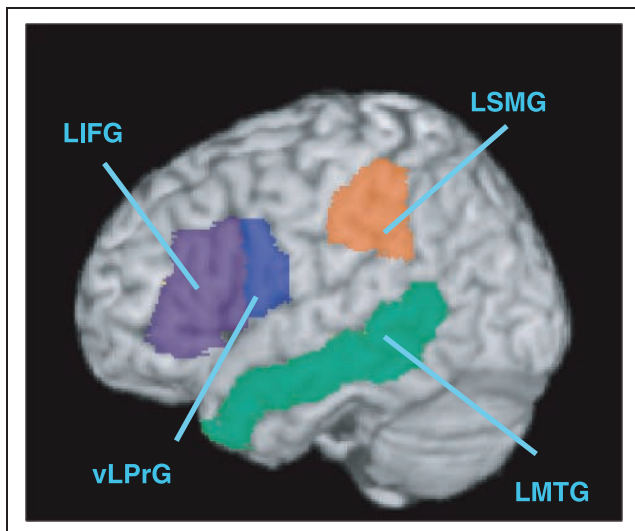


Figure 2. Projection of ROIs onto the lateral surface. For comparison with the whole-brain analysis figures, all ROIs are drawn to the same criteria used to draw individual subject ROIs.

and axial orientations. The ventral bound was defined by the anterior commissure and appearance of the vertical ramus of the lateral sulcus, the dorsal bound by the inferior frontal sulcus and the disappearance of the LIFG, the posterior bound by the precentral sulcus (or inferior frontal sulcus for the most dorsal slices), and the anterior bound by the inferior frontal sulcus. Additionally, coronal ROIs were split into four 9-mm-thick slice regions. This allowed any posterior to anterior functional differences to be examined. Additional ROIs were defined for the left supramarginal gyrus (LSMG) and the left ventral precentral gyrus (premotor cortex, vLPrCG), which have

been implicated in phonological processing (e.g., Omura, Tsukamoto, Kotani, Ohgami, & Yoshikawa, 2004; Booth et al., 2002), and the left middle temporal gyrus (LMTG), which has been linked to semantic tasks (e.g., Copland et al., 2003). For the LSMG, the ventral bound was defined by the lateral fissure, the dorsal bound by the horizontal segment of the intraparietal sulcus, the posterior bound by the sulcus intermedius primus, and the anterior bound by the ascending segment of the intraparietal sulcus. For the vLPrCG, the ventral bound was defined by the end of the lateral fissure, the dorsal bound was defined as extending as far dorsally as the dorsal extend of the LIFG, the anterior bound by the precentral sulcus, and the posterior bound by the central sulcus. For the LMTG, the ventral bound was defined by the inferior temporal sulcus, the dorsal bound by the superior temporal sulcus, the posterior bound by the appearance of the middle occipital gyrus, and the anterior bound by the temporal pole. (For illustration, Figure 2 shows the ROIs mapped onto the lateral surface. However, as noted, ROIs were defined individually for each subject.) Within each ROI, active voxels were defined by a main contrast of all conditions of interest versus the baseline false-font condition. Planned contrasts were then performed averaging across all suprathreshold ($t = 2.0$) voxels in the ROI, and the raw beta values were entered into a random effects analysis across subjects. The results for the three primary ROIs are summarized in Table 2 and are discussed in detail below.

Left Inferior Frontal Gyrus

For the ROI encompassing the entire extent of the LIFG, activation relative to baseline was greater in the

Table 2. Summary of Key Contrasts for Each Region of Interest

<i>Cognitive Process</i>	<i>Response Profile</i>	<i>LIFG</i>	<i>LSMG</i>	<i>LMTG</i>
Phonological retrieval	PW > SS	PW = SS	PW > SS (5.69)	SS = PW ^a
	PN > SS	PN = SS	PN > SS (5.78)	PN < SS (3.05)
	PW = PN	PW > PN (2.29)	PW = PN	PW > PN (2.34)
Semantic retrieval	PW > PN	PW > PN (2.29)	PW = PN	PW > PN (2.34)
	SS > PW	SS = PW	SS < PW (5.69)	SS = PW^a
	SS > PN	SS = PN	SS < PN (5.78)	SS > PN (3.05)
	SS > PW > PN	<i>ns</i>	SS < PW < PN (33.38) ^b	SS > PW > PN (9.32)^b
Cognitive control	PW > PN	PW > PN (2.29)	PW = PN	PW > PN (2.34)
	PW = SS	PW = SS	PW > S (5.69)	SS = PW ^a
	PN = SS	PN = SS	PN > SS (5.78)	PN < SS (3.05)

Effects that are predicted for a given response profile are shown in **bold**. Values in parentheses indicate *t* values (except where noted) that were significant at a threshold of .05. PW = phonological word; PN = phonological nonword; SS = semantic specific.

^aThere was a nonsignificant trend towards SS > PW in the LMTG ($t(13) = 1.47, p = .165$).

^b*F* value associated with the linear contrast across these three conditions.

phonological word condition than in the phonological nonword condition [$t(13) = 2.29, p < .05$], and in the semantic-specific than the semantic-global condition [$t(13) = 6.96, p < .001$]. When irregular and regular phonological word conditions were considered separately, there was marginally higher activity for irregular than for regular words [$t(13) = 1.66, p = .065$]. Importantly, there were no significant differences between the semantic-specific condition and either of the phonological conditions. Figure 3 shows activation levels for each condition versus the false-font baseline for the LIFG as a whole.

For the LIFG slice region analysis, the LIFG was divided into four 3-slice (9 mm) regions, anterior to posterior. Separate beta values for each contrast were calculated for suprathreshold voxels in each of these four regions for each subject. This analysis permitted us to explore regional variation in the pattern described above, without depending on an anatomical delineation of Brodmann's areas that have recently been shown to be highly variable, even within a single subject, with regard to sulcal landmarks (Roland et al., 1997; Zilles et al., 1997). For reference, the most anterior two-slice regions (1 and 2) roughly correspond to Brodmann's areas 45 and 47, and the most posterior two-slice regions (3 and 4) to Brodmann's area 44. For comparison to the literature, Table 3 provides the approximate correspondence of regions found in previous studies to the slice regions used in this study. Comparisons are based on peak voxel coordinates from whole-brain analyses or on ROI locations when peak voxels were not available, and should be taken as rough estimates only. A Slice region \times Condition ANOVA revealed a significant effect of condition [$F(3, 36) = 24.78, p < .001$], a marginal effect of slice region [$F(3, 36) = 2.98, p = .072$, Greenhouse–Geisser corrected], and a marginal interaction [$F(9, 108) = 2.17, p = .097$,

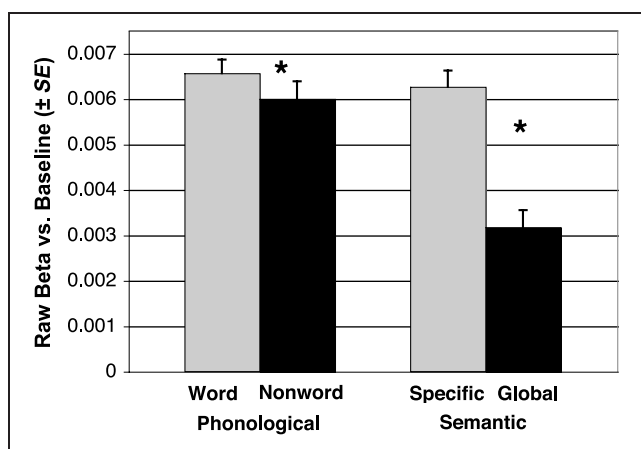


Figure 3. Activation versus baseline for the LIFG as a whole. Activation for the LIFG as a whole is plotted for each condition versus the false-font baseline task. Asterisks denote significant differences between tasks for planned contrasts. Error bars are standard error of the mean (see also Results section).

Table 3. Approximate Locations of Significant Contrasts in the Literature in Terms of the Anterior-to-Posterior 9-mm Slice Regions through the LIFG Defined in This Study (see Methods section)

Study	<i>Semantic > Phonological > Semantic</i>	
	<i>Phonological</i>	<i>Semantic</i>
Burten et al. (2003)	1, 2, 3	–
Devlin et al. (2003)	–	4
Gold and Buckner (2002), Gold et al. (2005), based on ROIs	~2, 3	–
McDermott et al. (2003)	1, 2, 3	4
Poldrack et al. (1999)	1, 2, 3	–
Roskies et al. (2001)	1, 2, 4	–
Turiziani et al. (2001) (based on ROIs)	–	~4, 3

	<i>High > Low Cognitive Control</i>	
	<i>Cognitive Control</i>	<i>Low > High Cognitive Control</i>
Barde and Thompson-Schill (2002) (based on ROIs)	~2, 3, 4	–
Thompson-Schill et al. (1997)	1, 3, 4	–

Estimates are based on peak voxel coordinates, unless otherwise noted.

Greenhouse–Geisser corrected]. When the semantic-global condition was excluded from the analysis, there was no significant effect of condition [$F(2, 26) = 1.56, p = .230$], a marginal effect of slice [$F(3, 39) = 2.58, p = .096$, Greenhouse–Geisser corrected], and a significant Slice \times Condition interaction [$F(6, 78) = 4.87, p < .001$]. Planned contrasts were then conducted for each slice region. The results are given in Table 4 and graphed in Figure 4. In no case was the phonological nonword condition higher than the semantic-specific condition (although there was a marginal difference in the most posterior slice region), which was a key prediction of a region associated with phonological retrieval.

Left Supramarginal Gyrus

In the LSMG, there was significantly higher activation in both the phonological word and nonword conditions than in the semantic-specific condition [$t(13) = 5.69, p < .001$; $t(13) = 5.78, p < .001$]. Importantly, there was no significant difference between phonological word and nonword conditions [$t(13) = -1.53, p = .150$], with a trend in the opposite direction of that observed in the LIFG. Indeed, an ANOVA testing for differences between word and nonword conditions in the LIFG and LSMG revealed a significant interaction between condition and region [$F(1, 13) = 14.35, p < .01$]. As we outlined

Table 4. Slice-Region Analysis for the LIFG

Contrast	Slice Region (Anterior to Posterior)			
	1	2	3	4
Specific–global	$t(13) = 6.16, p < .001^*$	$t(13) = 6.34, p < .001^*$	$t(13) = 5.76, p < .0001^*$	$t(13) = 6.04, p < .001^*$
Word–nonword	$t(13) = 1.67, p = .119$	$t(13) = 2.44, p < .05^*$	$t(13) = 2.22, p < .05^*$	$t(13) = 1.72, p = .109$
Word-specific	$t(13) = 0.38, p = .712$	$t(13) = -0.97, p = .349$	$t(13) = 0.76, p = .461$	$t(13) = 3.14, p < .01^*$
Nonword-specific	$t(13) = -0.56, p = .593$	$t(13) = -2.92, p < .05^*$	$t(13) = -0.62, p = .547$	$t(13) = 2.02, p = .065$
Irregular–regular word	$t(13) = 1.81, p = .093$	$t(13) = 1.64, p = .124$	$t(13) = 1.97, p = .071$	$t(13) = 1.98, p = .069$

Four 9-mm slice regions anterior to posterior through the LIFG were defined for each subject. Planned contrasts were then carried out by slice region. Significant t values are flagged with an asterisk.

earlier, higher activation for both phonological conditions compared to the semantic-specific condition would fit a phonological profile, whereas a region not showing this pattern would not seem to play a domain-specific role in phonological processing.

An ANOVA comparing activation for phonological (word and nonword) versus semantic-specific tasks in the LSMG and LIFG revealed a significant Condition \times Region interaction [$F(1, 13) = 40.65, p < .001$], indicating a highly significant phonological advantage in the LSMG [$t(13) = 5.82, p < .001$] but no significant difference between conditions for the LIFG [$t(13) = 0.045, p = .965$]. When phonological irregular and regular conditions were considered separately, there was significantly higher activation for irregular than regular words [$t(13) = 2.68, p < .05$]. As in the LIFG, the semantic-global condition was associated with significantly less activation than the semantic-specific [$t(13) = 3.08, p < .01$] and both phonological conditions [$t(13) = 8.73, p < .001$; $t(13) = 8.03, p < .001$]. LSMG activations for each condition versus baseline are presented in Figure 5. In sum, the activation pattern observed in the LSMG is most consistent with our predictions of a region associated with phonological retrieval, and differs reliably from the pattern observed in the LIFG.

Left Ventral Precentral Gyrus

Results from the vLPrCG closely mirror those from the LSMG. There was significantly higher activation in both the phonological word [$t(13) = 7.372, p < .0001$] and nonword [$t(13) = 6.757, p < .0001$] conditions than the semantic-specific condition. Importantly, there was no significant difference between the word and nonword conditions, with a slight trend in the opposite direction of that observed in the LIFG [$t(13) = -0.877, p = .396$]. As with the LSMG, this pattern is consistent with a region associated with phonological processing. vLPrCG activations for each condition versus baseline are presented in Figure 6.

Left Middle Temporal Gyrus

In the LMTG, there was significantly higher activation in the semantic-specific condition than in the semantic-global [$t(13) = 3.37, p < .01$] and phonological nonword [$t(13) = 3.05, p < .01$] conditions. The phonological word condition was associated with significantly higher activation than the phonological nonword condition [$t(13) = 2.34, p < .05$]. Although the phonological word condition was marginally higher than the semantic-global condition [$t(13) = 1.94, p = .075$], there was no significant difference between semantic-specific and phonological word conditions [$t(13) = -1.47, p = .165$], with a trend toward higher activation in the semantic-specific condition. As we noted earlier, an area exhibiting a domain-specific semantic effect would be expected to have the highest activation for the semantic-specific condition, followed by the phonological word condition, and finally, the phonological nonword condition. Indeed, when this linear contrast was tested, the LMTG exhibited just such a pattern [$F(1, 13) = 9.32, p < .01$], whereas the LIFG showed no linear relationship [$F(1, 13) = 0.51, p = .487$], and the LSMG exhibited the opposite relationship [$F(1, 13) = 33.38, p < .001$]. All pairwise 2×3 Region by Condition interactions were significant at the .05 level or better, demonstrating that the LIFG, LMTG, and LSMG exhibited reliably different patterns of activation. LMTG activations versus the false-front baseline are given in Figure 7.

Exploratory Whole-brain Random Effects Analysis

Exploratory whole-brain random effects analyses were carried out on normalized data for key contrasts with a $p < .001$ uncorrected probability rate. Areas of activation are depicted in Figure 8, and peak voxel coordinates are given in Table 5. The contrast of the semantic-specific to semantic-global condition revealed a pattern of frontal activation involving the IFG bilaterally, extending into middle and superior frontal gyri. The left middle

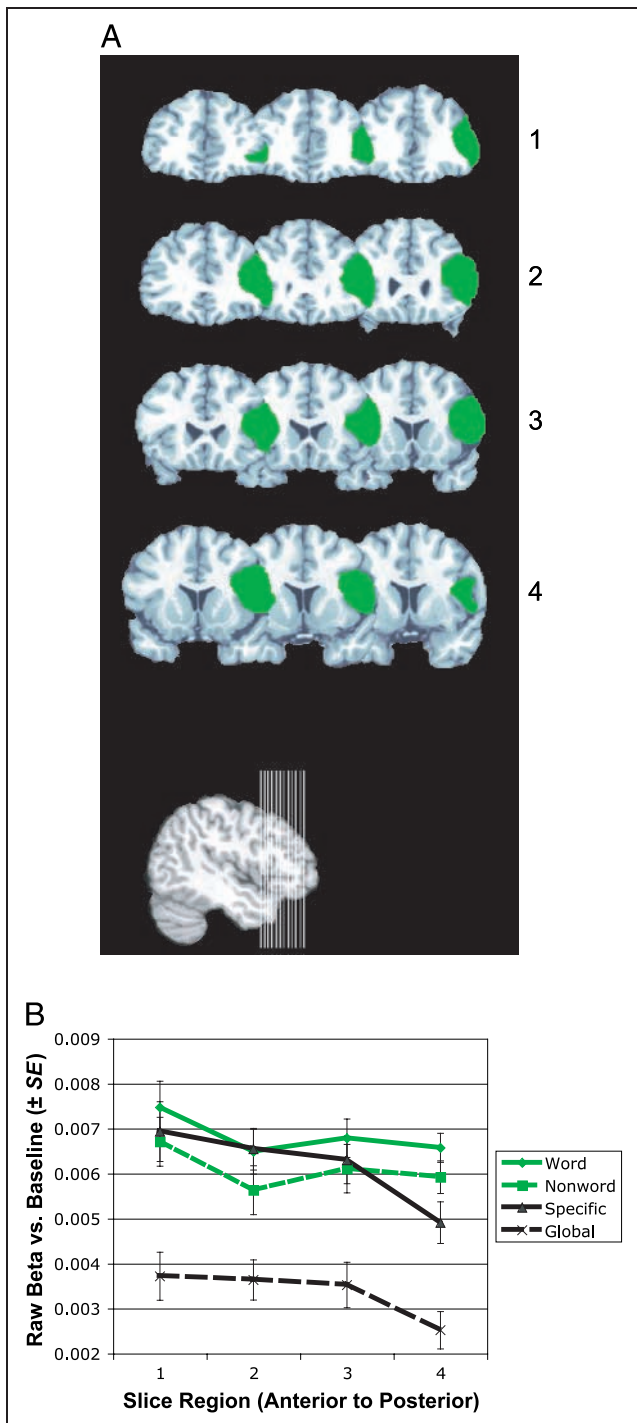


Figure 4. Tasks versus baseline by LIFG slice region. (A) Four 9-mm thick slice regions were defined anterior to posterior for each subject based on sulcal landmarks (see Methods section). Mean approximate MNI y -coordinates are as follows: 1: 2–10; 2: 11–19; 3: 20–28; 4: 29–37. (B) Tasks versus false-font baseline by slice region. Error bars are standard error of the mean. Results are given in Table 3.

temporal, angular, supramarginal, and lingual gyri also showed more activation in the semantic-specific than in the semantic-global condition. Comparing the phonological word and nonword to the semantic-specific con-

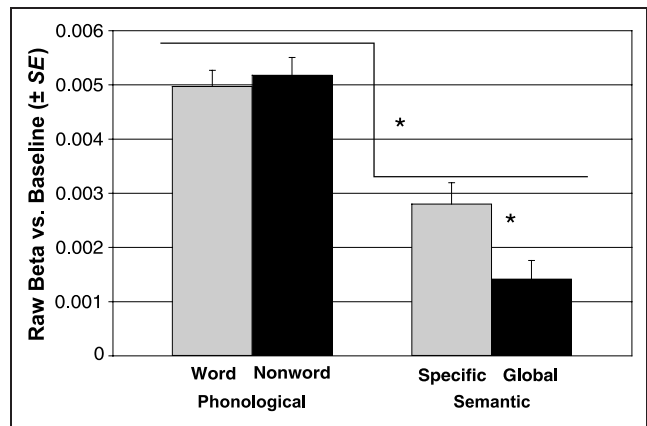


Figure 5. Left supramarginal gyrus (LSMG) activations versus baseline. Activation for the LSMG is plotted for each condition versus the false-font baseline task. Asterisks denote significant differences between tasks for planned contrasts. Error bars are standard error of the mean (see also Results section).

ditions, the semantic-specific condition produced more activation in the MTG bilaterally, and areas of the middle and superior frontal gyri, angular gyrus, and lingual gyrus bilaterally. The phonological conditions produced higher activation in premotor and motor areas bilaterally, the LSMG, the anterior cingulate, small areas of the left middle frontal and right inferior frontal gyri, and the precuneus, middle occipital gyrus, caudate, putamen, and posterior lobe of the cerebellum bilaterally. The contrast between the phonological word and nonword conditions showed greater activation for words in the LIFG, left middle/superior temporal gyrus, left cuneus, and right caudate and thalamus, whereas nonwords

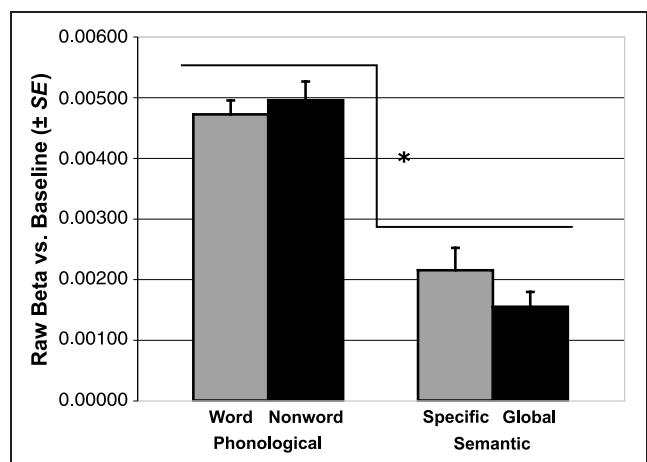


Figure 6. Left ventral precentral gyrus (vLPrCG) activations versus baseline. Activation for the vLPrCG is plotted for each condition versus the false-font baseline task. Asterisks denote significant differences between tasks for planned contrasts. Error bars are standard error of the mean (see also Results section).

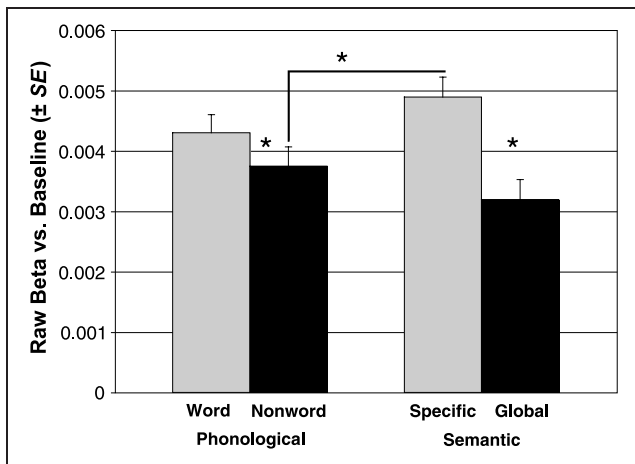


Figure 7. Left middle temporal activation versus baseline. Activation for the LMTG is plotted for each condition versus the false-font baseline task. Asterisks denote significant differences between tasks for planned contrasts. Error bars are standard error of the mean (see also Results section).

produced higher activation in the supramarginal gyrus and precuneus bilaterally.

DISCUSSION

In this study, we investigated the effects of semantic conflict on pLIFG activation during semantic and phonological processing, as a means of addressing domain-specific and cognitive control hypotheses regarding the function of this region. By contrasting phonological judgments of words and nonwords with each other and with a semantic judgment condition, we were able to distinguish domain-specific phonological and semantic effects from a more domain-general cognitive control effect. All three patterns of effects were observed, each localizable to a distinct region of interest.

Phonological Processing: Left Supramarginal and Left Ventral Precentral Gyri

The predicted response profile of a putative phonology-specific area was greater activity in both the phonological conditions than the semantic-specific condition, and no difference between the two phonological conditions. This is precisely the pattern we observed in the LSMG and vPrCG. These findings are consistent with previous evidence of the LSMG and left premotor involvement in phonological processing (Omura et al., 2004; Gelfand & Bookheimer, 2003; McDermott et al., 2003; Booth et al., 2002; Gold & Buckner, 2002; Xu et al., 2002; Price et al., 1997). The LSMG may be involved in phonological processing in general, or specifically in grapheme-to-phoneme mapping (Booth et al., 2002). Although this experiment was not designed to distinguish between

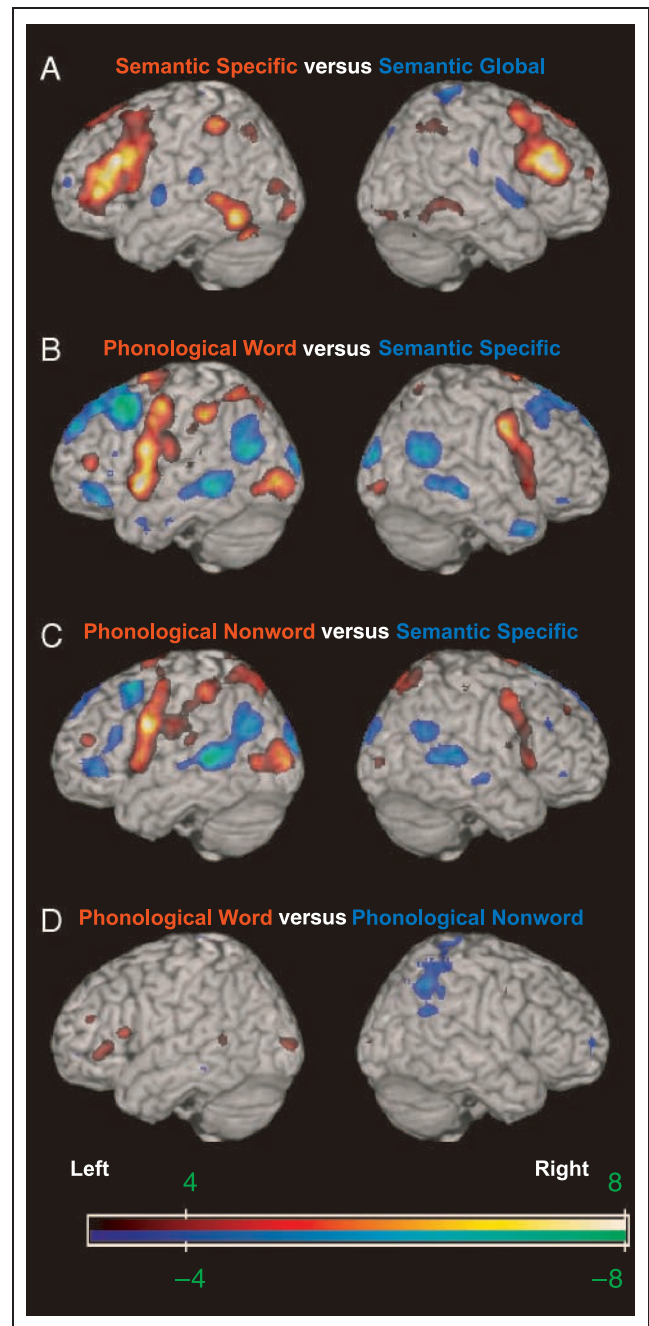


Figure 8. Exploratory whole-brain analysis. Functional contrast overlays are projected onto a high-resolution MNI normalized brain (Colin-27) using MRIcro (Nottingham, UK). Images are for general reference only and should not be taken as exact loci. All areas of activation are significant at $p < .001$, uncorrected. (A) Semantic specific versus Semantic global. Areas in red are more active for semantic specific, in blue for semantic global. (B) Phonological word versus Semantic specific. Areas in red are more active for phonological word, in blue for semantic specific. (C) Phonological nonword versus Semantic specific. Areas in red are more active for phonological nonword, in blue for semantic specific. (D) Phonological word versus Phonological nonword. Areas in red are more active for phonological word, in blue for phonological nonword (see also Results section).

Table 5. Peak Voxel Coordinates, Anatomical Locations, and Approximate Brodmann's Areas from Exploratory Whole-Brain Random Effects Analysis

	<i>Anatomical Area</i>	<i>MNI Coordinates</i>			<i>Max. t</i>
		<i>x</i>	<i>y</i>	<i>z</i>	
Semantic specific > Semantic global	Lingual gyrus (BA 18)	-24	-102	-12	4.95
	L Inferior temporal gyrus (BA 20)	-51	-57	-18	7.82
	L Middle temporal gyrus (BA 21/37)	-57	-48	-3	6.10
	L Superior parietal lobule (BA 7)	-27	-69	48	5.02
	L Supramarginal (BA 40)	-39	-45	51	6.45
	R Precuneus (BA 7)	33	-48	51	4.90
	L Inf./Mid. frontal gyrus (BA 45/46)	-54	27	24	8.45
	L Inferior frontal gyrus (BA 10)	-36	42	0	7.72
	L Inferior frontal gyrus (BA 44)	-57	15	6	7.52
	R Middle frontal gyrus (BA 46)	54	27	24	4.39
	L Middle frontal gyrus (BA 9)	-60	9	39	5.19
	R Middle frontal gyrus (BA 8)	42	18	48	4.99
	Medial superior frontal gyrus (BA 8)	0	45	57	5.08
	Semantic specific > Phonological word	L Parahippocampal gyrus (BA 20)	-39	-27	-21
L Middle temporal gyrus (BA 21)		-57	-27	-12	4.42
L Middle temporal gyrus (BA 39)		-42	-69	15	7.14
R Middle temporal gyrus (BA 21)		63	-36	-9	5.55
R Superior temporal gyrus (BA 22)		60	-60	18	6.20
L Angular gyrus (BA 39)		-42	-66	33	5.13
R Lingual gyrus (BA 18)		6	-87	-6	4.07
L Middle frontal gyrus (BA 8)		39	18	51	9.38
R Inferior frontal gyrus (BA 47)		39	33	-18	3.72
L Middle frontal gyrus (BA 11)		-42	36	-18	5.74
R Middle frontal gyrus (BA 8)		-36	12	51	4.36
L Superior frontal gyrus (BA 9)		-9	57	36	6.82
R Superior frontal gyrus (BA 8)		24	30	54	4.34
Phonological word > Semantic specific		L Cerebellum (posterior lobe)	-21	-60	-21
	R Cerebellum (posterior lobe)	27	-63	-21	7.45
	L Putamen	-24	3	0	5.65
	L Caudate/Putamen	-18	18	0	7.21
	R Caudate/Globus Pallidus	12	3	3	8.04
	L Middle occipital gyrus (BA 18)	-36	-90	-3	6.69
	R Inferior occipital gyrus (BA 18)	30	-93	-6	5.00
	L Middle frontal gyrus (BA 46)	-39	42	9	5.47
	L Precentral gyrus (BA 6)	-63	3	18	8.26
	R Inferior frontal gyrus (BA 44)	57	6	24	5.36
	L Postcentral gyrus (BA 43)	-63	-9	21	5.00

Table 5. (continued)

	<i>Anatomical Area</i>	<i>MNI Coordinates</i>			<i>Max. t</i>
		<i>x</i>	<i>y</i>	<i>z</i>	
	R Postcentral gyrus (BA 3)	60	-15	30	3.04
	Anterior cingulate (BA 32)	3	36	21	4.40
	L Supramarginal gyrus (BA 40/7)	-24	-57	54	6.10
	L Precuneus (BA 7)	-15	-75	39	5.79
	R Precuneus (BA 7)	24	-69	33	4.79
	R Superior frontal gyrus (BA 6)	-3	3	66	7.32
Phonological word > Phonological nonword	L Inferior frontal gyrus (BA 44/45)	-48	18	9	4.94
	L Cuneus (BA 18)	0	-99	-3	7.39
	L Superior temporal gyrus (BA 22)	-54	-51	6	3.79
	R Caudate (body)	15	-9	21	4.23
	Thalamus	-3	-12	9	3.33
Phonological nonword > Phonological word	L Precuneus (BA 31)	-9	-66	37	4.31
	R Precuneus (BA 7)	15	-66	33	4.46
	R Supramarginal (BA 40)	51	-60	45	5.02
	L Supramarginal (BA 40)	-48	-63	39	3.09

All areas are significant at $p > .001$, uncorrected. Brodmann's areas should be considered estimates only. BA= Brodmann's area; L = left; R = right.

these possibilities, the following two results might be relevant: (i) activation in the phonological word and nonword conditions was not reliably different (although a trend toward increased activation in the LSMG to nonwords was evident in both ROI and whole-brain analyses); and, (ii) in the phonological word condition, the response was greater to words with irregular grapheme-to-phoneme mappings than to words with regular mappings. Although these two results seem inconsistent with the notion that the LSMG is specialized for a grapheme-to-phoneme conversion process (which, at least under some accounts of word reading, should be invoked more with nonwords and regular words than with irregular words), caution is needed in drawing inferences such as this when the conditions in question are not matched for difficulty. The left premotor cortex has also been posited to play a role in grapheme-to-phoneme mapping (Omura et al., 2004). Although (i) above also applies to this region, the lack of an advantage for irregular versus regular words leaves this hypothesis open. However, an alternative explanation would be a role in articulation or subvocalization, which subjects may have used in making the phonological vowel sound judgments.

Semantic Processing: Left Middle Temporal Gyrus

Our definition of the response profile for a putative semantic-specific area hinged on the assumption that

semantic information is automatically retrieved during word reading. A variety of sources of evidence (e.g., Stroop interference, semantic priming) support this assumption. In fact, there is even evidence that some semantic information is retrieved during nonword reading (e.g., "gat" primes "dog"; Milberg, Blumstein, & Dworetzky, 1988), although the small magnitude of these effects supports our assertion that less semantic information is retrieved during reading of nonwords than words. Therefore, we defined a semantic-specific area as one that showed a linear increase in activation across the phonological nonword, phonological word, and semantic-specific conditions. Only the LMTG exhibited this response profile. Activation in this region, observed across a wide range of semantic tasks (Gold et al., 2005; Thuy et al., 2004; Copland et al., 2003; McDermott et al., 2003; Gold & Buckner, 2002; Castillo et al., 2001; Price et al., 1997), may be related to the depth or degree of semantic processing required. Furthermore, the high level of activation for our phonological word condition is consistent with Copland et al. (2003) in suggesting a role for the LMTG in automatic semantic processing.

Cognitive Control: Left Inferior Frontal Gyrus

A putative cognitive control region was predicted to exhibit a greater response to the phonological word condition than to the phonological nonword condition,

as a consequence of demands to inhibit semantic information that is automatically retrieved during reading (more so for words than nonwords, as discussed above) but that is irrelevant for the vowel judgment.

Although several other studies have reported greater nonword than word activation in the LIFG (Clark & Wagner, 2003; Gold & Buckner, 2002; Poldrack et al., 1999), there are several key differences between the stimuli and methods of these studies and our own, which lead us to make a different prediction. First, previous studies have used nonwords created by changing one or two letters of the word stimuli used in the study (Clark & Wagner, 2003; Gold & Buckner, 2002), or other medium-frequency English words (Poldrack et al., 1999). Thus, these stimuli are likely to elicit some semantic retrieval (e.g., “gat” primes “dog”; Milberg et al., 1988). In contrast, the present study used nonwords (Seidenberg et al., 1994), which followed legal English orthography but were not closely related to the words we used in the study (e.g., “tolve,” “bense”). Secondly, in the previous studies, subjects were given no prior exposure to the nonwords. Aside from producing a reaction time difference in one study (Clark & Wagner, 2003), this could potentially lead to phonological indeterminacy (i.e., because there is more than one potential way to pronounce the nonword, the subject must select from competing “right” answers), which could increase cognitive control demands as well. In contrast, in the present study, subjects read each nonword four times (see Methods section), allowing them to settle on a preferred pronunciation before the study, thus minimizing conflict in the task and matching the nonword and word phonological tasks on reaction time. Therefore, in the present study, we predicted a phonological word greater than nonword effect in a cognitive control region, rather than the reverse. Indeed, this contrast was significant in the LIFG.

The word–nonword effect was significant in the LIFG, consistent with its hypothesized role in cognitive control. However, this effect was also significant in the LMTG. On what basis then can one ascribe the effect to cognitive control on the one hand but semantic retrieval on the other? Clearly, this effect alone cannot distinguish a semantic response from a cognitive control response because our manipulation of conflict on the phonological task was based on a correlated increase in semantic retrieval. Instead, we rely on several other observations for this conclusion.

First, the LIFG exhibited the word–nonword effect in the absence of any other domain-specific effects: Unlike the LSMG, there was no difference in activation between either phonological condition and the semantic-specific condition. And, unlike the LMTG, there was no linear increase across conditions reflecting a putative increase in semantic processing demands. Therefore, the overall pattern in the LIFG is more consistent with cognitive control than with either a phonological or semantic domain-specific effect.

Second, the LIFG and LMTG responded differently to the regularity manipulation in the phonological word condition: Only the LIFG responded more to phonological judgments about irregular than regular words. Several theories of reading posit that irregular word reading requires more complete semantic access than reading regular words (e.g., Plaut et al., 1996); therefore, performing a phonological task with irregular words might result in higher demands to inhibit a greater degree of retrieved semantic information. Yet, the absence of an LMTG effect suggests a different interpretation: Vowel-sound judgments of irregular words are likely to produce conflict *within* the domain of phonology, in addition to any conflict from irrelevant semantic content. For example, determining that “pint” has the same vowel sound as “kite” but not “win” might require inhibiting a strong grapheme-to-phoneme correspondence. This post hoc interpretation is complicated by the regularity effect we observed on both latency and accuracy; nonetheless, it suggests a potentially interesting difference in the response profiles of the LIFG and LMTG.

The most parsimonious interpretation of the pattern of activation observed in the LIFG—as contrasted with those observed in the LSMG, vLPrCG, and LMTG—is that of a domain-general mechanism that responds to conflict from irrelevant semantic or phonological information. However, this is the pattern evinced when suprathreshold voxels from the entire ROI are considered as a single functional unit. In order to address the possibility of regional specializations *within* the LIFG, we examined how this pattern changed along the anterior–posterior axis. Indeed, there was a significant Condition \times Region interaction in the LIFG: The critical word–nonword effect only reached significance in the middle two subregions of the LIFG. Only in the most posterior subregion of the LIFG was there more activation in the phonological word than in the semantic-specific condition (cf. McDermott et al., 2003). However, in the absence of any clear a priori way of comparing the degree of conflict between the phonological word and semantic-specific condition, this effect does not necessarily indicate a specific role for this region in phonological processing. Although the most posterior slice region did show a marginal nonword versus specific advantages, this also does not necessarily indicate a phonological profile for the pLIFG. First, the second most posterior slice region, which is also within BA 44, does not show a similar pattern. Second, the whole-brain analysis did not indicate any nonword greater than specific activation within the pLIFG, but rather a robust band of activation encompassing the precentral and central gyri. This activation, seen only in the phonological tasks, is likely to be related to articulation or subvocalization. Third, this whole-brain analysis finding is reinforced by the vLPrCG ROI analysis, which also found greater activation for phonological than semantic tasks. Given the lack of direct mapping between Brodmann’s

areas and sulcal boundaries (Roland et al., 1997; Zilles et al., 1997), the pattern of results seen for the most posterior slice region may indicate that it included areas of the premotor cortex. Indeed, the pLIFG does not exhibit other aspects of the profile of a phonology-specific region, nor does the most anterior region exhibit the profile of a semantic-specific region.

One potential concern is that the phonological task used in this study (vowel-sound matching) was not ideally suited to engaging phonology-specific processes. Although we follow much previous research in using word sound judgments as a phonological task (Martin et al., 2003; McDermott et al., 2003; Pillai et al., 2003; Gold & Buckner, 2002; Turriziani et al., 2001; Crosson et al., 1999), some have suggested that the LIFG may be particularly engaged in phonological segmentation tasks (Burton, Small, & Blumstein, 2000). However, two points argue against this concern. First, because the LSMG, a region known to be involved in phonological processing, responded robustly to the phonological tasks used in this study, the lack of a phonology-specific profile in the pLIFG cannot be attributed to the failure of the task to produce phonological processing.

Second, a review of the literature shows no clear relationship between the phonological task used and the pattern of results. Of the studies which found greater activation in the pLIFG for phonological than semantic tasks, two used a syllable count task (Devlin et al., 2003; Price et al., 1997, trend), one used a rhyming task (Burton et al., 2003), and one asked subjects to think about how the words sounded similar (McDermott et al., 2003). Of those failing to find a phonological advantage in the pLIFG, two used a syllable count task (Poldrack et al., 1999; Mummery et al., 1998), which according to Burton et al. (2000), should be the most likely to produce such an effect. Thus, there is no clear evidence that using a syllable count task would have produced a different pattern of results in the LIFG.

Another potential concern arises in respect to the behavioral results. Some may question why the phonological conflict manipulation would produce differences in LIFG activation, while not producing differences in reaction time. This might be expected if the stimuli had been constructed such that conflict from semantic information would lead to an incorrect answer in the phonological word condition. Indeed, this was the case in the semantic-specific condition, which did show longer reaction times than the semantic-global condition. However, because semantic information would not lead to an incorrect answer in the phonological word condition, if the LIFG is *successfully* controlling conflict, no reaction time effect would be expected. In this way, BOLD activation is a purer measure of conflict than reaction time because reaction time effects are not sensitive to conflict that is successfully resolved and are easily contaminated by other sources of variance in the tasks. Indeed, reaction time differences between tasks

are a potential confound when considering BOLD data, as increased time-on-task can increase signal without necessarily being attributable to of the manipulation of interest.

If the organization of the LIFG is not based on material, as we would argue based on these data, what is the basis for regional variation reported here and elsewhere? A complete consideration of process variation within this region is beyond the scope of the article and the reach of these data. Instead, here we suggest a couple of avenues for future investigation. First, in other arenas, both proactive and reactive cognitive control mechanisms have been described and associated with sustained or transient responses in the prefrontal cortex, respectively (Bauer, Rebert, Korunka, & Leodolter, 1992). It is possible that the pLIFG controls reactive demands to regulate conflict on a transient basis, but that the aLIFG permits proactive control of task set, for example. This account is reminiscent of characterizations of the role of the aLIFG in top-down controlled retrieval put forth by Wagner, Maril, Bjork, and Schacter (2001). Second (although by no means mutually exclusive), regions of the LIFG may be recruited in response to qualitatively distinct types of conflict (which necessitate different control mechanisms). Botvinick, Braver, Barch, Carter, and Cohen (2001) have distinguished conflict arising from underdetermined responses from that created by a need to override prepotent responses. It is likely that the mechanisms to reduce conflict and select a response are quite different in these two cases, and the functional organization of the LIFG might reflect this distinction.

Conclusions

Phonological judgments of words require not only retrieval of phonological representations but also regulation of automatically active but task-irrelevant semantic information. When activation under these conditions is compared to tasks that place minimal demands on cognitive control mechanisms, material-specific effects become confounded with general regulatory mechanisms. The design of the present study allowed us to distinguish domain-specific phonology and semantic effects from at least one source of cognitive control demands (i.e., task-irrelevant semantic information). When profiles of activation across three cortical regions were compared, the LIFG evinced a unique pattern that is best explained by a role for this region in cognitive control.

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