

Task-specific Repetition Priming in Left Inferior Prefrontal Cortex

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Previous neuroimaging studies have shown that activation in left inferior prefrontal cortices (LIPC) is reduced during repeated (primed) relative to initial (unprimed) stimulus processing. These reductions in anterior (~BA 45/47) and posterior (~BA 44/6) LIPC activation have been interpreted as reflecting implicit memory for initial semantic or phonological processing. However, prior studies do not unambiguously indicate that LIPC priming effects are specific to the recapitulation of higher-level (semantic and/or phonological), rather than lower-level (perceptual), processes. Moreover, no prior study has shown that the patterns of priming in anterior and posterior LIPC regions are dissociable. To address these issues, the present fMRI study examined the nature of priming in LIPC by examining the task-specificity of these effects. Participants initially processed words in either a semantic or a nonsemantic manner. Subsequently, participants were scanned while they made semantic decisions about words that had been previously processed in a semantic manner (within-task repetition), words that had been previously processed in a nonsemantic manner (across-task repetition), and words that had not been previously processed (novel words). Behaviorally, task-specific priming was observed: reaction times to make the semantic decision declined following prior semantic processing but not following prior nonsemantic processing of a word. Priming in anterior LIPC paralleled these results with signal reductions being observed following within-task, but not following across-task, repetition. Importantly, neural priming in posterior LIPC demonstrated a different pattern: priming was observed following both within-task and across-task repetition, with the magnitude of priming tending to be greater in the within-task condition. Direct comparison between anterior and posterior LIPC regions revealed a significant interaction. These findings indicate that anterior and posterior LIPC demonstrate distinct patterns of priming, with priming in the anterior region being task-specific, suggesting that this facilitation derives from repeated semantic processing of a stimulus.

Introduction

Prior processing of a stimulus often facilitates subsequent processing of that stimulus. At the behavioral level, earlier experience with a word or object may result in faster reaction times and increased performance accuracy during repeated stimulus processing. At the neural level, decreased activation is often observed during repeated stimulus processing in the specific brain regions that are recruited during initial stimulus processing (Schacter and Buckner, 1998; Wiggs and Martin, 1998; Wagner and Koutstaal, 2000). Neuropsychological and behavioral research indicates that such facilitated processing can reflect the benefits of implicit or nondeclarative memory for a past event. In particular, research has focused on priming phenomena that reflect a nonconscious facilitative influence of past experience on current performance or behavior (Tulving and Schacter, 1990; Roediger and McDermott, 1993; Schacter *et al.*, 1993).

Neuroimaging investigations of priming, using positron

emission tomography and functional magnetic resonance imaging (fMRI), have revealed activation reductions in left inferior prefrontal cortices (LIPC) during repeated relative to initial semantic processing of a stimulus in a given task. Studies revealing LIPC priming effects have relied on semantic processing tasks, such as judging whether a presented word refers to an abstract or concrete entity (Demb *et al.*, 1995; Gabrieli *et al.*, 1996) or generating a semantic associate of a presented noun (Raichle *et al.*, 1994; Buckner *et al.*, 2000). Performance on semantic processing tasks typically requires access to and evaluation of both semantic and phonological stimulus attributes (Price *et al.*, 1997), and often further requires the selection of task-relevant attributes from among competing attributes (Thompson-Schill *et al.*, 1997). LIPC priming effects have been observed in the same posterior and anterior LIPC regions that demonstrate greater activation during unprimed (initial) semantic processing compared to unprimed non-semantic processing (Petersen *et al.*, 1988) [reviewed by a number of authors (Buckner and Koutstaal, 1998; Poldrack *et al.*, 1999; Wagner *et al.*, 1999)]. These posterior LIPC responses correspond to the posterior and dorsal extent of the inferior frontal gyrus (pars opercularis) and the bordering precentral gyrus (at or near Brodmann's areas [BA] 44/6). The anterior LIPC responses correspond to the anterior and ventral extent of the inferior frontal gyrus (pars triangularis and pars orbitalis; at or near BA 45/47).

Although some evidence suggests that posterior LIPC activation may reflect processing of phonological or lexical codes, whereas anterior LIPC activation may reflect processing of semantic attributes (Buckner, 1996; Fiez, 1997; Poldrack *et al.*, 1999; Wagner, 1999), all published studies to date have revealed a qualitatively similar pattern of priming in posterior and anterior LIPC (Raichle *et al.*, 1994; Buckner *et al.*, 1998a, 2000). Repetition-induced reductions in LIPC activation have been interpreted as neural correlates of conceptual priming, perhaps reflecting the facilitative consequences of implicit memory for conceptual and phonological attributes (Demb *et al.*, 1995; Gabrieli *et al.*, 1996; Wagner *et al.*, 1997; Buckner *et al.*, 2000). However, because in all prior studies both perceptual and conceptual processing were reinstated during the repeated experience, it is not possible to conclude unambiguously that LIPC reductions reflect conceptual priming. This ambiguity raises at least two central questions about the nature of LIPC priming effects. First, do LIPC priming effects reflect implicit memory for higher-level knowledge (conceptual and/or phonological) or for lower-level knowledge (perceptual)? Second, are there functional differences between posterior LIPC and anterior LIPC priming effects? To address these questions, the present study examined whether item-specific repetition priming in LIPC is observed during within- and across-task repetition.

A number of investigators have attempted to examine whether LIPC priming effects are specific to higher-level processing. For example, Blaxton and co-workers observed anterior LIPC priming reductions in a conceptual reprocessing paradigm (semantic generation), but not in a perceptual reprocessing paradigm (visual word-fragment completion) (Blaxton *et al.*, 1996). This single dissociation is consistent with a higher-level priming interpretation of LIPC reductions. However, it is worth noting that an interaction analysis was not conducted to support this single dissociation. Moreover, because a task manipulation was used to vary the processes that were critical at test, the nature of the test task and perceptual stimuli differed across the conceptual and perceptual priming conditions. Thus, it is possible that these test differences might account for the differences in observed LIPC priming across conditions.

Using semantic and nonsemantic word processing tasks that held the perceptual inputs constant across all conditions, Demb and colleagues demonstrated a single dissociation in LIPC priming across conceptual and perceptual reprocessing conditions (Demb *et al.*, 1995). Specifically, anterior LIPC activation was reduced during repeated semantic classification compared with initial semantic classification (deciding whether words were abstract or concrete), but not during repeated nonsemantic classification compared with initial nonsemantic classification (deciding whether words were printed in uppercase or lowercase letters). However, similar to Blaxton *et al.*, an interaction analysis was not conducted to support this single dissociation. In addition, Demb *et al.* only sampled from anterior LIPC and thus did not address whether priming in posterior LIPC is selective to higher-level processing. Finally, the influences of initial non-semantic processing on LIPC activation during later semantic processing were not examined.

Subsequent behavioral studies using the abstract/concrete classification task also raise questions about the precise nature of the priming effects manifested in this task. Vaidya and co-workers reported that behavioral priming on the abstract/concrete task does not appear to be affected by modality match between study and test stimuli, which is consistent with the hypothesis that priming on this task reflects conceptual implicit memory (Vaidya *et al.*, 1997). However, perhaps surprisingly, they also observed that behavioral priming on this task was unaffected by manipulations of conceptual processing at study. Participants demonstrated similar magnitudes of priming in the abstract/concrete judgment task when items were preceded by an initial abstract/concrete decision or by an initial uppercase/lowercase decision. This apparent insensitivity to conceptual elaboration raises the possibility that priming on the abstract/concrete task may not be specific to the recapitulation of conceptual processing. If so, then LIPC priming effects may not be specific to implicit memory for higher-level representations.

Recently, Buckner and colleagues examined item repetition separately for visual and auditory cues during word-stem completion (Buckner *et al.*, 2000). In a series of experiments, they observed that similar regions of LIPC showed repetition-induced activation reductions in both visual-to-visual and auditory-to-auditory priming conditions, suggesting that LIPC priming modulations are not specific to either the visual or auditory modality. While suggestive that LIPC priming is due to an amodal conceptual process or processes, these results do not preclude the possibility that LIPC priming simply derives from a perceptual match between study and test stimuli. Moreover, in those experiments, no attempt was made to directly manipulate

conceptual processes to elucidate the nature of the processes that give rise to LIPC priming effects.

The aim of the present fMRI study was to address these ambiguities regarding the nature of anterior and posterior LIPC priming. A blocked-design fMRI paradigm was used to contrast two repetition conditions: *within-task* and *across-task* repetition. In both conditions, participants were scanned while they made semantic decisions (abstract/concrete judgments) for novel (i.e. not previously processed) and for repeated (i.e. previously processed) words. The nature of the stimuli, the perceptual processing demands, and the tasks were held constant across the two conditions. The critical difference was the task, and therefore presumably the type of processing, *initially* performed on an item. In within-task repetition, participants processed words by making semantic judgments during both their initial and repeated presentations. In across-task repetition, words were initially processed in a nonsemantic manner (uppercase/lowercase judgments) and then reprocessed in a semantic manner.

Several priming patterns were possible in this experiment, with each outcome potentially providing novel evidence regarding the functional characteristics of anterior and posterior LIPC priming. First, it was assumed that although participants would perform minimal semantic analysis during performance of the uppercase/lowercase task, this task would require perceptual processing that was similar to that of the abstract/concrete task. Thus, to the extent that LIPC priming derives from perceptual operations, then the magnitude of LIPC priming should be similar in the within-task and the across-task conditions. Alternatively, if LIPC priming reflects higher-level processing, then priming should be greater in the within-task condition.

Second, given prior neuroimaging evidence suggesting that, during the processing of novel stimuli, anterior and posterior LIPC may be functionally dissociable (Buckner, 1996; Fiez, 1997; Poldrack *et al.*, 1999; Wagner, 1999), this raises the question as to whether the present within-task/across-task priming manipulation will reveal similar or different patterns of priming in these two LIPC regions. Should different patterns of task-specific priming be observed in posterior and anterior LIPC, then this would provide important further evidence that these prefrontal regions are functionally distinct, extending the dissociation to the domain of implicit memory phenomena.

Materials and Methods

Subjects

Twelve right-handed subjects between the ages of 18 and 35 years volunteered and received \$50 as payment for participation. Because two subjects produced data with sufficient artifacts during the repetition scans to preclude further analysis, data from 10 subjects (four females) are reported. Informed consent was obtained prior to scanning in a manner approved by the Human Studies Committee of the Massachusetts General Hospital.

Behavioral Procedures

The stimuli were taken from a set of 240 abstract and 240 concrete words (Gabrieli *et al.*, 1996). Blocks of 20 words were constructed with the constraint that each block contained five abstract words in uppercase letters (e.g. LOVE), five abstract words in lowercase (e.g. trust), five concrete words in uppercase (e.g. CHAIR), and five concrete words in lowercase (e.g. book). Words were 3–8 letters in length and were counterbalanced across conditions across subjects.

The experimental design consisted of four levels-of-processing (LoP) scans (Craik and Lockhart, 1972), each followed by a *repetition scan*. During each LoP scan, subjects processed novel words in either a

semantic or nonsemantic manner, depending on the task block, or visually fixated on a '+' sign. During word blocks, 20 words were presented centrally over a 40 s period (one word every 2 s; 1 s on, followed by 1 s of fixation). For nonsemantic processing blocks, subjects made uppercase/lowercase decisions; for semantic processing blocks, subjects made abstract/concrete decisions. Responses were indicated by a left-handed key press. The semantic and nonsemantic blocks were separated by 24 s periods (22 s of visual fixation followed by a 2 s cue indicating the task that was to be performed for the immediately following block).

The critical scans for the present purposes were the repetition scans that followed each LoP scan. For all four repetition scans, the stimulus list consisted of alternating blocks of novel words (i.e. items not previously encountered in the experiment) and repeated words (i.e. items previously encountered in the immediately preceding LoP scan). The perceptual form (i.e. the letter case) was held constant across the initial and repeated presentations of the repeated words. The order of conditions within each scan was held constant, alternating as follows: novel, fixation, repeated, fixation, novel, fixation, repeated. In all word blocks, participants made abstract/concrete semantic decisions. For two *within-task* repetition scans, the repeated words had been previously processed in an identical semantic manner. For two *across-task* repetition scans, the repeated words had been previously processed in a nonsemantic manner. Again, 24 s periods separated each word block. Across subjects, the order of the within-task/across-task scans was counterbalanced (for half the subjects the order was within, across, within, across and for the other half the order was reversed). Coinciding with the collection of dummy images acquired to allow T_1 stabilization (see MR procedures), 8 s of fixation were presented prior to the first task block.

Magnetic Resonance (MR) Procedures

Imaging was performed on a 1.5 T General Electric scanner with an echo planar imaging upgrade (Advanced NMR Systems). Stimuli were presented to participants using a PowerMacintosh computer connected to a LCD projector. Images were projected onto a screen attached to the standard General Electric quadrature head-coil through a collimating lens. Performance and reaction times were measured through a custom-designed, magnet-compatible key-press. Head motion was minimized through the use of pillows, pads and a restraining strap. Multiple experiments were performed within a single 2 h session, including a study of the LoP effect during episodic encoding (Wagner *et al.*, 1998b), a study of episodic retrieval (Buckner *et al.*, 1998b), and a study of within- and across-task word repetition. This paper reports the results from this latter study.

Scanning procedures have been described elsewhere (Buckner *et al.*, 1998b). Briefly, high-resolution anatomical images [conventional RF-spoiled GRASS sequence (SPGR), 60 slice sagittal, 2.8 mm thickness] and T_2^* -weighted functional images [asymmetric spin echo sequence sensitive to blood oxygenation-level-dependent contrast ($T_E = 50$ ms, offset = 25 ms)] were acquired. Functional images were acquired within runs of 118 time points (16 slice, 3.125 mm in-plane, 7 mm thickness, skip 1 mm between slices, acquisition aligned to the plane intersecting the anterior and posterior commissures, $T_R = 2$ s). Four discarded dummy time points were acquired prior to each run to allow T_1 stabilization. Data for each individual subject were transformed into Talairach-Tournoux stereotaxic space (Talairach and Tournoux, 1988) as described previously (Buckner *et al.*, 1998b) and averaged across subjects.

fMRI Data Analysis

Voxel-based activation maps were constructed using the nonparametric Kolmogorov-Smirnov (K-S) statistic to compare: (i) semantic to non-semantic processing during the LoP scans (Wagner *et al.*, 1998b); (ii) novel to repeated item processing collapsed across the within- and across-task repetition scans; (iii) novel to repeated item processing in the within-task repetition scans; and (iv) novel to repeated item processing in the across-task repetition scans. Time points were shifted 4 s to account for hemodynamic delay. A spatial smooth with a one-voxel-wide Hanning filter was applied prior to activation map generation. Peak activations were identified using the Talairach and Tournoux coordinate system (Talairach and Tournoux, 1988) by selecting local statistical activation

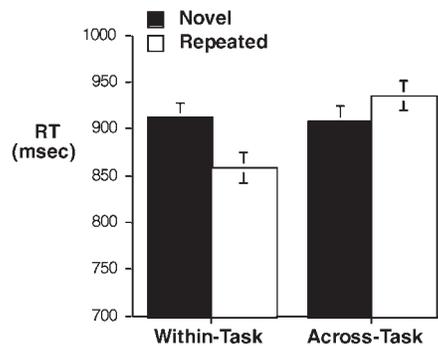


Figure 1. Mean median reaction times to make the abstract/concrete decision for the novel and repeated conditions in the within- and across-task repetition scans. Error bars reflect one standard error.

maxima that were $P < 0.001$ and within clusters of five contiguous significant voxels. Application of these criteria to a control data set, using the logic of control activation runs (Zarahn *et al.*, 1997), revealed that they minimize false positives.

To further examine the effect of within- and across-task repetition, three-dimensional regions of interest (ROIs) were defined around peak activations of theoretical interest (i.e. anterior and posterior LIPC). ROIs were defined in two ways. First, anterior and posterior LIPC regions demonstrating a greater response during semantic relative to non-semantic processing in the LoP scans were defined and applied to the data from the repetition scans. Second, regions demonstrating a greater response during novel relative to repeated word processing were defined *collapsed across* the within- and across-task repetition data, without reference to any differences between these conditions, and were then applied to the data from these conditions separately. ROIs were defined using an automated algorithm that identified all contiguous voxels within 8 mm of the peak, where each voxel must have reached a significance level of $P < 0.001$. For each subject, the mean signal change for each condition with respect to baseline was derived across these significant voxels. These ROIs provided a small number of *a priori* regional hypotheses to test for differences between the within- and across-task conditions. First, we examined whether there was a repetition effect (i.e. novel > repeated), and whether this effect interacted with scan type (i.e. within-task, across-task). Second, because the mean within-scan position of the novel blocks was earlier than that of the repeated blocks, thus raising the possibility that observed novel > repeated effects might reflect early > late scan effects, we further examined whether regions demonstrating a significant novel > repeat effect (collapsing across the first and second blocks of each condition) also demonstrated less activation during the first repeated block relative to the second novel block.

Results

Behavioral Results

Figure 1 displays the mean median reaction times (RTs) associated with making the abstract/concrete classification for novel and repeated blocks in the repetition scans (RT data from one subject were lost due to an equipment malfunction). RTs were derived across all experimental trials for each condition. In contrast to the findings of Vaidya *et al.* (Vaidya *et al.*, 1997), comparison of RTs during the novel and repeated blocks in the within- and across-task repetition scans revealed that behavioral priming was task-specific [Item Type (novel/repeated) \times Specificity (within/across) interaction, $F(1,8) = 8.31$, $P < 0.05$]. Whereas RTs were longer in the novel compared to the repeated blocks in the within-task condition [$F(1,8) = 7.22$, $P < 0.05$], RTs did not significantly differ across the novel and repeated blocks in the across-task condition [$F(1,8) = 1.94$, $P < 0.20$].

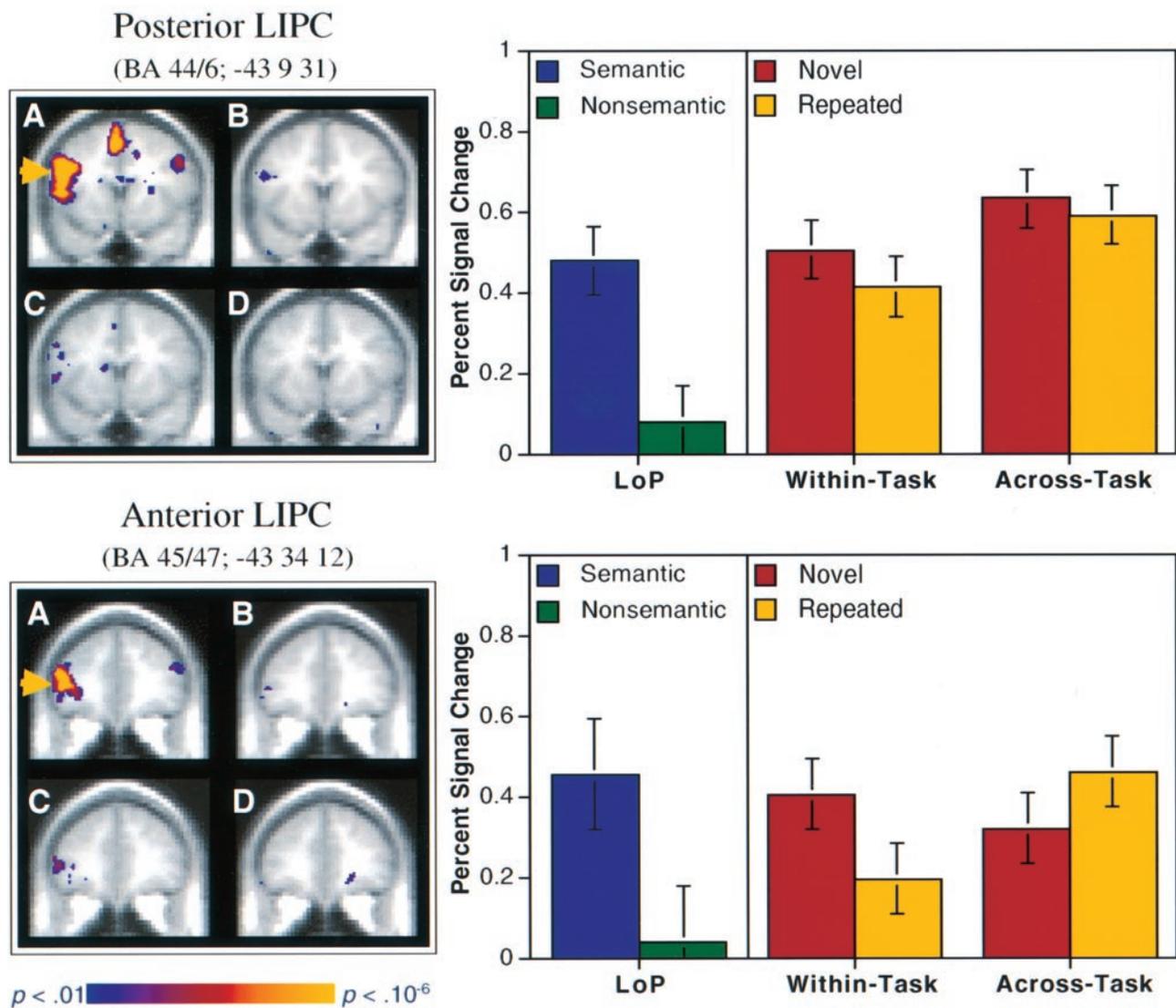


Figure 2. Functional priming data are displayed for posterior and anterior LIPC. At the left are voxel-based statistical activation maps from a coronal section through the peak activation of the posterior LIPC and the anterior LIPC regions of interest identified in the semantic > nonsemantic comparison from the LoP Scans (highlighted by yellow arrows). Displayed are the LoP effect (A), the priming effect collapsed across the within-/across-task repetition scans (B), the priming effect in the within-task scans (C), and the priming effect in the across-task scans (D). At the right are measures of percent signal change (relative to the fixation baseline blocks) for each experimental condition from the LoP, Within-task, and Across-task scans. Error bars reflect one standard error.

fMRI Results

Left inferior prefrontal cortex (LIPC) ROIs were identified in the LoP scans. The outcome of the voxel-based analysis of the LoP scans has been reported elsewhere (Wagner *et al.*, 1998b). Here, we briefly note that LIPC regions demonstrated a greater response during the semantic relative to the nonsemantic processing conditions, including posterior LIPC (-43, 9, 31; ~BA 44/6) and anterior LIPC (-43, 34, 12; ~BA 45/47). [Note that these coordinates differ slightly from those reported previously (Wagner *et al.*, 1998b) because the present report describes a subset (10 of 12) of the subjects included in that earlier report.]

The effects of within- and across-task repetition on activation in these anterior and posterior LIPC regions were explored. The upper panel of Figure 2 presents data from the posterior LIPC region that demonstrated a LoP effect. In the LoP scans, percent signal change in posterior LIPC during the nonsemantic

condition was quantitatively above the fixation baseline, although this difference was not reliable [$t(9) = 1.09$, $P > 0.25$]. Turning to the repetition scans, priming was examined using a 2 (Task-specificity: within/across) \times 2 (Item Type: novel/repeated) \times 2 (Block: first/second) repeated-measures ANOVA, with subjects treated as a random factor. This analysis revealed that, although both the within- and across-task conditions demonstrated greater activation during novel relative to repeated blocks, the main effect of Item Type (novel versus repeated) failed to reach significance [$F(1,9) = 1.71$, $P > 0.20$], and the Task-specificity \times Item Type interaction was not reliable ($F < 1.0$). Thus, priming was not observed in this posterior LIPC region. However, it is important to emphasize that while ROI identification based on the LoP comparison has the advantage of permitting priming analyses that are orthogonal to the LoP effect, there is the disadvantage that such ROIs do not

Posterior LIPC

(BA 44/6; -43 3 31)

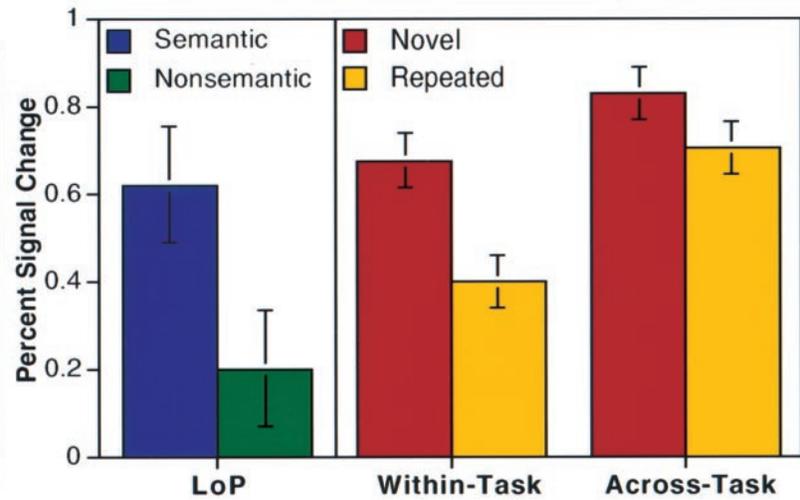
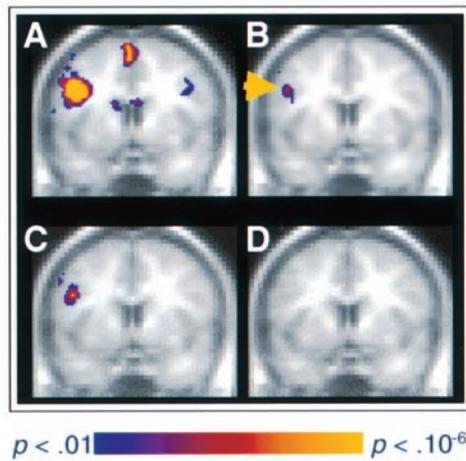


Figure 3. Functional priming data are displayed for posterior LIPC. At the left are voxel-based statistical activation maps from a coronal section through the peak activation of the posterior LIPC region of interest identified in the novel > repeated comparison when collapsing across all repetition scans (highlighted by yellow arrow; the left side of each image corresponds to the left hemisphere). Displayed are the LoP effect (A), combined priming effect (B), within-task priming effect (C) and across-task priming effect (D). At the right are measures of percent signal change (relative to the fixation baseline blocks) for each experimental condition. Error bars reflect one standard error.

Table 1

Regions Demonstrating Neural Priming Effects

Region	Talairach coordinates			Significance -log(p)	BA
	x	y	z		
Novel > repeated: collapsed across within- and across-task					
L post. inferiorfrontal/precentral	-43	3	31	10.33	44, 6
Novel > repeated: within-task					
L post. inferior frontal/precentral	-43	3	28	12.53	44, 6
L ant. inferior frontal	-40	25	3	11.41	45, 47
L middle/inferior frontal	-53	16	37	10.33	9, 44
L superior frontal	-9	41	50	10.33	8
L ant. inferior frontal	-43	38	12	10.33	45, 47
L ant. inferior frontal	-50	25	21	9.31	45
L superior/middle temporal	-56	-21	0	8.33	22, 21
L middle frontal	-46	25	28	8.33	9
L ant. inferior frontal	-40	22	18	8.33	45
Novel > repeated: across-task					
None					

Coordinates are listed in Talairach and Tournoux atlas space (Talairach and Tournoux, 1988); L, left; ant., anterior; post., posterior; BA, approximate Brodmann's area(s) based on atlas coordinates.

specifically target voxels that demonstrate priming. This non-specificity of the LoP comparison with respect to priming may account for the present failure to observe reliable priming in posterior LIPC. The status of priming in posterior LIPC was further examined in subsequent voxel-based and ROI analyses (see below).

The lower panel of Figure 2 presents data from the anterior LIPC region that demonstrated a LoP effect. In the LoP scans, percent signal change in anterior LIPC during the nonsemantic blocks did not differ from the fixation baseline ($t < 1.0$), indicating that this region was selectively engaged during the semantic task. Turning to the repetition scans, there was a significant Task-specificity \times Item Type interaction [$F(1,9) = 10.21$, $P < 0.05$]. Planned contrasts revealed that there was a significant priming effect in the within-task [$F(1,9) = 7.30$, $P <$

0.05], but not in the across-task [$F(1,9) = 3.31$, $P > 0.10$], condition. Additional planned contrasts revealed that this priming effect in the within-task condition was also observed when comparing the first repeated block to the second novel block [$F(1,9) = 11.58$, $P < 0.01$]. Thus, anterior LIPC demonstrated a task-specific priming reduction with no significant effect of repetition for the across-task comparison. This pattern is consistent with the hypothesis that priming in this region derives from the recapitulation of higher-level semantic processes.

A subsequent voxel-based analysis was conducted to identify regions that demonstrated a priming effect (i.e. novel > repeated) when collapsing across the within- and across-task repetition scans. A single region, situated in posterior LIPC, extending into precentral gyrus (-BA 44/6), demonstrated a priming effect when collapsing across all repetition scans (upper panel of Table 1; Fig. 3). The peak of this activation fell 6 mm posterior to that of the posterior LIPC region identified in the LoP comparison. Thus, this region overlaps with, but is not identical to, that identified in the LoP scans.

ROI analyses were conducted to further explore the effects of LoP and within- and across-task repetition on this posterior LIPC region. Figure 3 presents voxel-based statistical maps from a coronal section through the peak activation observed for the region, as well as measures of percent signal change in the ROI for the experimental conditions. The effect of LoP – examined using a 2 (LoP: semantic/nonsemantic) \times 2 (Block: first/second) repeated-measures ANOVA – revealed a main effect of LoP in this ROI: the percent signal change was greater in the semantic than in the nonsemantic condition [$F(1,9) = 12.62$, $P < 0.01$], indicating that the processes mediated by this region are more likely to be engaged during the semantic task than during the nonsemantic task. An additional t -test revealed that activation in the nonsemantic condition was greater than that in the fixation baseline [$t(9) = 2.30$, $P < 0.05$], revealing that while the processes mediated by this region were engaged to a greatest extent during the semantic task, these processes nevertheless were engaged to

a greater extent during the nonsemantic task relative to baseline. Thus, posterior LIPC showed differential activation between the two LoP conditions as well as activation during the two conditions independently.

Turning to the repetition scans, we do not report the main effect of priming in this ROI because such an effect must be observed since the ROI was defined as those voxels demonstrating a priming effect when collapsed across the within- and across-task conditions. The critical question of interest is whether the magnitude of priming interacted with the within/across manipulation. It should be emphasized that by defining this ROI collapsing across the within- and across-task repetition scans, this renders the ROI unbiased with respect to the two conditions but may bias region identification towards voxels that demonstrate a priming effect in both the within- and across-task repetition scans. That latter bias would work against our ability to detect the critical interaction of interest.

Considering the pattern of priming in this posterior LIPC region, a Task-specificity (within/across) \times Item Type (novel/repeated) \times Block (first/second) ANOVA revealed a trend toward a Task-specificity \times Item Type interaction [$F(1,9) = 3.94, P < 0.08$]. Planned contrasts revealed a significant priming effect in *both* the within-task [$F(1,9) = 26.70, P < 0.001$] and across-task [$F(1,9) = 5.57, P < 0.05$] conditions, with the interaction suggesting a trend for greater priming in the within-task condition. Additional planned contrasts revealed a within-scan reversal of activation across the first repeated and second novel blocks in the within-task condition [$F(1,9) = 15.14, P < 0.005$]. In the across-task condition, there was a numerical reversal in the pattern of activation such that it declined from the first novel block (0.91) to the first repeated block (0.73), and then increased very modestly for the second novel block (0.75) and declined again for the second repeated block (0.68). Statistically, this reversal was not reliable ($P < 1.0$), raising the possibility that posterior LIPC demonstrates a task-related priming effect in the across-task condition in addition to an item-related priming effect. (Note, however, that this task-effect is confounded with time and thus awaits further investigation.) Aside from this issue, these data clearly demonstrate posterior LIPC priming during semantic processing of words previously processed in a semantic manner (within-task) and of words previously processed in a nonsemantic manner (across-task), with the trend toward an interaction suggesting that priming was greater when the processing task was held constant. This latter observation is consistent with the hypothesis that priming in posterior LIPC reflects higher-level processing (either semantic or phonological) rather than perceptual processing.

Collectively, these analyses suggest that posterior and anterior LIPC demonstrated a different pattern of priming. To further examine whether posterior and anterior LIPC demonstrated different patterns of priming, additional ANOVAs were conducted including Region as a factor. When comparing the posterior and anterior LIPC regions defined from the LoP data, a significant Region (posterior/anterior) \times Task-specificity \times Item Type interaction was observed [$F(1,9) = 10.34, P < 0.05$]. Similarly, when comparing the posterior LIPC region defined from the collapsed priming data to that of the anterior LIPC region defined from the LoP data, a significant Region \times Task-specificity \times Item Type interaction was observed [$F(1,9) = 7.11, P < 0.05$]. Although *both* the within- and across-task conditions demonstrated modest to significant reductions in posterior LIPC activation when comparing repeated to novel blocks, only the within-task condition demonstrated a significant

reduction in anterior LIPC activation with the across-task condition resulting in a modest (but non-significant) increase in anterior LIPC activation.

Finally, regions that demonstrated a priming effect in separate voxel-based comparisons for the within-task repetition scans and the across-task repetition scans are presented in the lower portions of Table 1 for completeness.

Discussion

The goals of the present study were to determine whether LIPC priming effects specifically reflect the consequences of implicit memory for higher-level (semantic and/or phonological) or lower-level (perceptual) representations, and in the process to explore whether posterior and anterior LIPC regions demonstrate distinct patterns of priming. There were three main results. First, behavioral measures of priming revealed that performance on the abstract/concrete task (as indexed by reaction times) was facilitated when participants had previously made an abstract/concrete decision for a word but not when participants had previously made an uppercase/lowercase decision for a word. Thus, behavioral priming was task-specific, suggesting a dependence on the recapitulation of specific processes. Second, anterior LIPC also demonstrated a task-specific pattern of neural priming. Specifically, anterior LIPC demonstrated a significant reduction in neural activity during the semantic processing of words previously semantically processed, but not of words previously nonsemantically processed. Third, the pattern of neural priming observed in posterior LIPC differed from that in anterior LIPC. In contrast to anterior LIPC, posterior LIPC demonstrated significant priming during the semantic processing of words previously processed in a semantic manner and of words previously processed in a nonsemantic manner; there was a trend for greater priming following prior semantic processing. The functional significance of these findings will be discussed in turn.

Task-specific Behavioral Priming

In the present experiment, participants were significantly faster in deciding whether a word was abstract or concrete when they had previously made this decision for the word, but not when they had previously decided whether the word was printed in upper- or lowercase letters. This observation contrasts with a previous report of significant priming on the abstract/concrete task when preceded by either abstract/concrete or uppercase/lowercase decisions [the magnitude of priming in that study was numerically, but non-significantly, greater in the within-task condition (Vaidya *et al.*, 1997)]. There were a few procedural differences between the present experiment and that of Vaidya *et al.*, including differences in (i) the number of relevant study stimuli (40 versus 20 respectively); (ii) test format (whether novel and repeated items were blocked or unblocked in the test phase); and (iii) stimulus presentation rates (1 s in the present study versus subject-terminated in Vaidya *et al.*). Unfortunately, it is unclear how these procedural differences might account for the differences in the pattern of priming observed in the two studies. Additional behavioral investigation is necessary to resolve this discrepancy. Nevertheless, it is important to emphasize that within the present experiment, behavioral priming on the abstract/concrete task was task-specific, and thus presumably process-specific. Priming was observed in the semantic-to-semantic condition, where the same processes were repeated or recapitulated for the two exposures, but not in the

nonsemantic-to-semantic condition, where the letter case judgment preceded the abstract/concrete judgment. This observation, in conjunction with the report that priming on this task is unaffected by changes in presentation modality (Vaidya *et al.*, 1997), suggests that the priming indexed by this task reflects implicit memory for semantic and/or phonological representations, rather than implicit memory for perceptual representations.

Task-specific Neural Priming: Anterior LIPC

Congruent with these task-modulations of priming at the behavioral level, the fMRI results revealed a pattern of task-specific neural priming in anterior LIPC. In the non-priming LoP scans, anterior LIPC demonstrated greater activation during semantic relative to nonsemantic processing, but no difference in activation between nonsemantic processing and visual fixation. This pattern indicates that the processes mediated by anterior LIPC were engaged during performance of the semantic task, but were minimally or not at all engaged during performance of the nonsemantic task. Importantly, in the repetition scans, significant priming was observed in anterior LIPC – both in the voxel-based and ROI analyses – following prior semantic processing but not following prior nonsemantic processing. This observation complements an earlier report that failed to demonstrate anterior LIPC priming during repeated relative to initial nonsemantic processing (Demb *et al.*, 1995) [see also Blaxton *et al.* (Blaxton *et al.*, 1996)], suggesting that mere perceptual recapitulation does not yield anterior LIPC priming. Critically, the interaction between Task-specificity (within-versus across-task) and Item Type (novel versus repeated) in the present study unambiguously indicates that priming in anterior LIPC was observed only under conditions where participants had previously accessed semantic and/or phonological representations of an item. Thus, anterior LIPC priming derives from prior higher-level, rather than perceptual, processing.

Prior research suggests that anterior LIPC may mediate processes supporting access to, maintenance of, and/or evaluation of long-term semantic knowledge associated with a stimulus (Petersen *et al.*, 1988; Buckner *et al.*, 1995; Demb *et al.*, 1995; Buckner, 1996; Wagner *et al.*, 1997). To successfully perform the abstract/concrete decision task, participants need to access and select specific semantic attributes that allow for determination of whether a word represents an abstract or concrete concept. Moreover, once accessed, these attributes may need to be held online and evaluated in order to arrive at the decision. Anterior LIPC may be the neural substrate of these executive control processes that allow for such ‘working with’ semantic knowledge in the service of satisfying a goal state (Kapur *et al.*, 1994; Fiez, 1997; Gabrieli *et al.*, 1998; Wagner *et al.*, 1998a; Poldrack *et al.*, 1999; Wagner, 1999). Consistent with this ‘semantic working memory’ hypothesis, recent fMRI and PET studies suggest that anterior and posterior LIPC are functionally dissociable. Whereas anterior LIPC tends to demonstrate greater activation during semantic relative to phonological processing conditions, posterior LIPC tends to show similar levels of activation across semantic and phonological conditions or greater activity under phonological processing conditions (Buckner *et al.*, 1995; Price *et al.*, 1997; Poldrack *et al.*, 1999). The present priming observations suggest that prior processing of semantic attributes, but not of nonsemantic attributes, serves to decrease the computational demands placed on anterior LIPC during subsequent attempts to process these attributes. These neural priming effects may reflect enhanced efficiency in

accessing, selecting and/or evaluating the target semantic knowledge necessary to achieve the goal of semantically categorizing a word, with this efficiency perhaps deriving from an increased availability of the target attributes as a result of earlier processing.

It has been proposed that LIPC regions may specifically subserve the selection of, rather than the retrieval of or access to, target representations from among competing representations (Thompson-Schill *et al.*, 1997, 1998, 1999). The evidence supporting this selection interpretation of LIPC function includes fMRI observations of increased LIPC activation under conditions of increased selection demands, and the null observation of no change in LIPC activation under conditions where retrieval demands may increase but selection is apparently not necessary (Thompson-Schill *et al.*, 1997) – though see Vandenberghe *et al.* for observations of LIPC activation using a similar ‘non-selection’ semantic retrieval paradigm (Vandenberghe *et al.*, 1996). Moreover, Thompson-Schill and colleagues have reported that patients with LIPC lesions demonstrate impaired performance under conditions associated with high, but not low, selection demands (Thompson-Schill *et al.*, 1998). Within the context of the selection hypothesis, the present priming results would suggest that the computational demands on anterior LIPC decrease as a result of prior access to target semantic attributes because this prior access makes these target attributes more readily available than competing attributes, thus reducing the selection demands of the task during repeated performance (Thompson-Schill *et al.*, 1999). Importantly, no such reduction in selection demands would be afforded by prior attention to nonsemantic stimulus attributes, consistent with our failure to observe priming in anterior LIPC during semantic processing preceded by nonsemantic processing.

Although the selection hypothesis and the present results can be easily integrated, it is important to emphasize that the LIPC region implicated in mediating selection in the studies of Thompson-Schill and colleagues (at or near BA 44) (Thompson-Schill *et al.*, 1997, 1998, 1999) falls well posterior and dorsal to the anterior LIPC region observed in this, and other, semantic processing studies (falling at or near BA 45/47) (Poldrack *et al.*, 1999). Thus, it is possible that the anterior LIPC region that demonstrated task-specific, and thus presumably process-specific, priming in the present experiments may be distinct from that implicated in selection. Although additional studies – using both neuroimaging and neuropsychological methods – are clearly necessary to resolve this important question, the present results indicate that anterior LIPC benefits from prior semantic, but not prior nonsemantic, processing consistent with the hypothesis that this region subserves ‘semantic working memory’ functions.

Dissociable Patterns of Neural Priming: Across-task Priming in Posterior LIPC

In contrast to the pattern of task-specific priming observed behaviorally on the abstract/concrete task and neurally in anterior LIPC, the ROI analyses revealed that priming in posterior LIPC (~BA 44/6) was observed during the semantic processing of words previously processed in either a semantic or nonsemantic manner. Moreover, consideration of the relative magnitudes of priming across these conditions revealed a trend for greater priming in the semantic-to-semantic condition suggesting that posterior LIPC priming does not derive from perceptual processing. Interestingly, whereas anterior LIPC did

not demonstrate activation during novel nonsemantic processing, significant activation was observed in posterior LIPC during performance of the nonsemantic task relative to baseline. Thus, the modest engagement of posterior LIPC during the nonsemantic blocks in the LoP scans may have been sufficient to yield priming during subsequent performance of the semantic processing task in the repetition scans. Consistent with this interpretation, the pattern of posterior LIPC activation during the LoP scans paralleled the pattern of posterior LIPC priming. First, there was greater posterior LIPC activation during the semantic relative to the nonsemantic processing of novel stimuli. Second, the magnitude of priming in posterior LIPC during subsequent semantic processing was greater following semantic than following nonsemantic processing.

Importantly, the present experiment revealed that the pattern of priming in posterior LIPC differed from that observed in anterior LIPC, with this functional dissociation between these LIPC regions being supported by a Region \times Task-specificity \times Item Type interaction. This observation provides the first evidence – to our knowledge – of distinct patterns of priming within multiple LIPC regions, providing important additional evidence that posterior and anterior LIPC regions are functionally separable.

How might we understand the dissociation between within- and across-task priming in posterior and anterior LIPC and the observation of reliable posterior, but not anterior, LIPC activation during novel nonsemantic task performance? Although not explicitly manipulated in this experiment, one possibility is that these distinct task-specificity effects reveal a differential role of anterior and posterior LIPC in semantic and phonological control processes respectively. A number of investigators have hypothesized that anterior LIPC mediates semantic working memory operations, whereas the posterior and dorsal extent of LIPC mediates phonological working memory mechanisms (Awh *et al.*, 1996; Fiez *et al.*, 1996; Kirchoff *et al.*, 2000) [this region is probably dorsal to a LIPC region that recently has been implicated in syntactic processing (Vigliocco, 2000)]. Prior neuroimaging studies have revealed activation in posterior LIPC – but not in anterior LIPC – during other ‘nonsemantic’ processing tasks in which participants are required, or have the opportunity, to access phonological codes, such as when simply viewing words, reading words aloud or making lexical decisions about word and pseudo-word letter strings [reviewed by Poldrack (Poldrack *et al.*, 1999)]. Moreover, neuropsychological evidence indicates that posterior LIPC lesions, in addition to leading to difficulties on ‘high selection’ semantic retrieval tasks, also impair performance on lexical or phonological processing tasks (Fiez and Petersen, 1998; Swick, 1998). Finally, behavioral evidence suggests that phonological recoding of a printed word may be performed by default even when the explicit task demands do not require access to the word’s phonology (Ziegler and Jacobs, 1995) [reviewed by Frost (Frost, 1998)]. Based on such findings it has been specifically hypothesized that posterior LIPC may contribute to lexical-to-phonological transformation and the subsequent maintenance of the resulting phonological representations. From this perspective, the within-task priming advantage in posterior LIPC would be interpreted as reflecting a greater reliance on phonological operations during the abstract/concrete task than during the uppercase/lowercase task. Moreover, the modest but reliable across-task priming in posterior LIPC would be thought to derive from modest engagement of phonological operations during the uppercase/lowercase task (as revealed by above baseline activation in

posterior LIPC during novel uppercase/lowercase classification). However, it should be emphasized that this interpretation is speculative. Because we did not directly manipulate phonological operations in this study, subsequent studies that directly manipulate the extent to which participants recruit phonological working memory operations during initial processing are necessary to appropriately test this interpretation.

The present study provides strong evidence that posterior and anterior LIPC regions are functionally distinct and that priming in these regions does not derive from mere perceptual recapitulation. Whereas anterior LIPC revealed a pattern of task-specific semantic priming that paralleled that observed behaviorally, posterior LIPC activation showed priming during semantic processing preceded by either semantic or non-semantic processing. This latter observation does not necessarily indicate that priming in posterior LIPC is insensitive to the recapitulation of higher-level processes. Rather, priming in posterior LIPC also appears to be process-specific, with the critical difference between anterior and posterior LIPC being that the processes mediated by posterior LIPC also appear to be engaged during performance of the nonsemantic processing task. Thus, consistent with the transfer appropriate processing framework (Morris *et al.*, 1977), priming appears to be observed in these distinct LIPC regions depending on the extent to which the processes mediated by these regions are required during subsequent task performance with an item and have been engaged during initial task performance with that item.

Notes

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