

Convergent Cortical Representation of Semantic Processing in Bilinguals

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This study examined whether semantic processes in two languages (English and Spanish) are mediated by a common neural system in fluent bilinguals who acquired their second language years after acquiring their first language. Functional magnetic resonance imaging was performed while bilingual participants made semantic and nonsemantic decisions about words in Spanish and English. There was greater activation for semantic relative to nonsemantic decisions in left and right frontal regions, with greater left frontal activation. The locations of activations were similar for both languages, and no differences were found when semantic decisions for English and Spanish words were compared directly. These results demonstrate a shared frontal lobe system for semantic analysis of the languages and are consistent with cognitive research on bilingualism indicating that the two languages of a bilingual person access a common semantic system. © 1999 Academic Press

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A prominent issue in cognitive research on bilingualism has been the degree of functional integration or separation of the two languages in a bilingual brain. At one end of the spectrum, the mental representations of two languages are viewed as being shared; at the other, each language has its own separate representation. Similarly, in neuropsychological and neuroscientific

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research on bilingualism, the degree of integration or separation of two languages in the brain has been a primary issue. In studying bilingualism, cognitive research has focused mainly on semantic representations. In contrast, neuropsychological and neuroscientific research has focused mainly on whole language performance, including not only semantic processes but also phonological, syntactic, and other processes. This difference in approach has made it difficult to map the cognitive behavioral and neuroscientific results in order to build a unified cognitive neuroscientific theory of bilingual language processing. In the present study, we take steps toward this goal by focusing on the cortical substrates of semantic processing in bilinguals using functional magnetic resonance imaging (fMRI).

Cognitive experiments with bilinguals strongly support the position that the two languages of a bilingual access a common semantic network (Francis, 1999b). Three main sources of experimental evidence support this view. First, semantic comparisons between words from different languages have been shown to take no longer than comparisons between words in the same language, suggesting the integration of semantic information between languages (Caramazza & Brones, 1980; Dufour & Kroll, 1995; Potter, So, Von Eckhardt, & Feldman, 1984; Popiel, 1987). Second, primed lexical decision tasks have revealed that processing of a word is facilitated about 75% as much when immediately preceded by a semantic associate in the other language as when preceded by a semantic associate in the same language (e.g., Chen & Ng, 1989; de Groot & Nas, 1991; Grainger & Beauvillain, 1988; Keatley et al., 1994; Keatley & de Gelder, 1992; Kirsner et al., 1984; Schwanenflugel & Rey, 1986; Tzelgov & Eben-Ezra, 1992). Third, studies of interference effects, such as the Stroop and Stroop-like interferences (e.g., Preston & Lambert, 1969; Ehri & Ryan, 1980), or of part-set cueing during category exemplar generation (Peynircioglu & Goksen-Erelcin, 1988) have shown that processing in one language can automatically interfere with processing of another, and these interference effects also tend to be about 75% of the magnitude of the corresponding within-language effects (Francis, 1999b; MacLeod, 1991). Additionally, several studies of bilingual memory have shown a high degree of transfer across languages for tasks that involve primarily semantic processing (e.g., Francis, 1999a; Francis & Bjork, 1992; MacKay & Bowman, 1969; MacLeod, 1976; Seger et al., in press; Smith, 1991). The attenuation of some of the between-language relative to within-language effects have been cause for debate, but are mostly attributed to nonsemantic contributions to the within-language priming and interference effects.

Neuropsychological studies of bilingualism have attempted to clarify whether the two languages of a bilingual have shared or separate representations in the brain. Behavioral hemispheric lateralization studies have given mixed results (for reviews and critiques of this literature, see Paradis, 1990,

1992; Mendelsohn, 1988; Vaid, 1983). Compelling clinical case studies of differential language recovery after stroke-induced aphasia in multilinguals (e.g., Lecours et al., 1983; Solin, 1989; Vaid & Genesee, 1980; Paradis, 1977) have been used as evidence for separate cortical representations for each language. However, this interpretation depends critically on reports of language use prior to the stroke and these studies are not able to discriminate among the particular aspects of language that might underlie these impairments. From the neurosurgical literature, first and second language naming can be selectively or simultaneously disrupted in cortical stimulation studies of presurgical patients (Ojemann, 1983; Ojemann & Whitaker, 1978), which suggests some shared and some separate regions for processing of the two languages. However, the specific components of language that are shared or separate are not clear.

One factor that likely influences the mental and neural organization of bilingual language is the degree of proficiency in a second language acquired after the first language has been mastered. Several cognitive studies indicate that the organization of the second language changes during the acquisition process. For example, in early stages of learning, second language (L2) vocabulary items are processed primarily through association with their translation equivalents in the first language (L1), whereas in later stages of learning they are more directly concept-mediated, i.e., associated with their meanings (Chen & Leung, 1989; Chen, 1990; Dufour & Kroll, 1995; Kroll & Stewart, 1994; Potter, So, von Eckhardt, & Feldman, 1984). In these studies, L1 and L2 vocabulary are thought to access a common semantic system as a person becomes proficient in L2.

The age at which a second language is acquired has been shown to influence the rate of learning and degree of proficiency attained (e.g., Johnson & Newport, 1989; Krashen, Long, & Scarcella, 1982). In general, the younger the learner, the more similar second language learning is to first language learning. The causes of these age effects on proficiency are highly controversial, with explanations ranging from biologically based critical periods to differences between child and adult learning contexts. Because studies that address age of the learner generally do not address cognitive processes, it is unknown at present whether mental representations of the second language or cognitive processes in the second language differ qualitatively for early and late learners. Although research in this area has provided no evidence that semantic processing differs for languages learned early or late, it suggests that any cognitive or neural differences between L1 and L2 should be greater for late than for early learners.

Most directly relevant to the present study are neuroimaging studies of bilingualism using positron emission tomography (PET) and fMRI. A summary of these studies is given in Table 1. Two PET studies with highly fluent English–French bilinguals showed similar cortical localization of activation

TABLE 1
Summary of Previous Neuroimaging Studies of Bilingual Language Processing

Study	Imaging modality	Languages	Fluency in L2	Age of first L2 exposure (years)	Task	Analyses	Results
Chee et al. (1999)	fMRI	L1 = Mandarin, L2 = English	High	Early group: before age 6; late group: after age 12	Stem completion	Subtraction, <i>t</i> test, peak locations, voxel counts	No differences between L1 and L2 or between early and late bilinguals and late bilinguals. Activation in the left and right frontal regions more widespread in L2.
Dehaene et al. (1997)	fMRI	L1 = French, L2 = English	Moderate	After age 7	Listen passively to story	Activation cluster, voxel counts, subtraction	Activation for L1 and L2 in left IFG (BA 44) further separated for early than late bilinguals. Greater left putamen activation for L2 words than for L1 words.
Kim et al. (1997)	fMRI	Mixed	High	Early group: infancy; late group: mean = 11.2	Covertly recount previous day's events	Centroids, pixel counts within Broca's and Wernicke's areas	Activation for L1 and L2 in left IFG (BA 44) further separated for early than late bilinguals. Greater left putamen activation for L2 words than for L1 words.
Klein et al. (1994)	PET	L1 = English, L2 = French	High	After 5, mean = 7.3	Repeat aloud words presented auditorially	Group average, subtraction	Greater left putamen activation for L2 words than for L1 words.
Klein et al. (1995)	PET	L1 = English, L2 = French	High	After 5, mean = 7.3	Generate aloud synonyms of words presented auditorially	Group average, subtraction	Greater left putamen activation for L2 words than for L1 words.
Perani et al. (1996)	PET	L1 = French, L2 = English	Moderate	After age 7	Listen passively to story	Group average, subtraction	No difference between L2 and unknown language.
Perani et al. (1998)	PET	Group 1: L1 = Italian, L2 = English; Group 2: L1 = Spanish, L2 = Catalan	High	After age 10	Listen passively to story	Group average, subtraction	Group 1: No difference between L1 and L2; group 2: greater right middle temporal gyrus for L1 and greater right hippocampal and superior parietal lobule for L2.

for L1 and L2 in word repetition and synonym-generation tasks (Klein et al., 1994, 1995). A PET study of whole-language comprehension in highly fluent Italian–English and Spanish–Catalan bilinguals also showed nearly identical activation patterns for L1 and L2 (Perani et al., 1998). These studies indicate that there is a shared cortical system for semantic knowledge in two languages. These PET studies, however, analyzed group averages. It remains possible, therefore, that adjacent cortical representations of semantic knowledge would not be resolved, especially if the topographical relation between the adjacent representations varied across individuals. In such a case, across-subject averaging could blend two distinct semantic activations.

fMRI may be better suited to resolve such adjacent activations because it has superior spatial resolution and because it is more common to visualize individual participant's activations. Indeed, two fMRI studies have revealed not only common activations for L1 and L2, but also separate activations for L1 and L2. Both fMRI studies, however, used whole-language comprehension or covert production tasks (Dehaene et al., 1997; Kim et al., 1997). Therefore, it is unclear whether the differences between L1 and L2 activations were based on semantic processes per se or, alternatively, based on other linguistic processes, such as phonological or syntactic processes. In the one previously published fMRI study of single-word processing in 24 Mandarin–English bilinguals, no differences were found between L1 and L2 activation patterns for word stem completion in either early or late learners of English (Chee et al., 1999).

The goal of the present study was to exploit the spatial resolution of fMRI to ask whether L1 and L2 have a unitary cortical system for specifically semantic performance. In previous fMRI studies of semantic judgments with native English speakers performing tasks in English, individual words consistently elicited greater left inferior prefrontal cortex (LIPC) activation than did nonsemantic judgments (Demb et al., 1995; Desmond et al., 1995; Gabrieli et al., 1996; Wagner et al., 1997). The reproducibility of these results led us to use a similar manipulation for studying bilingual semantic processing. In order to maximize the possibility that L1 and L2 would have partially nonoverlapping cortical semantic representations, we recruited fluent bilingual participants who had learned their two languages sequentially rather than simultaneously. For each participant, we examined the difference in activation between semantic and nonsemantic judgments in English, the difference in activation between semantic and nonsemantic judgments in Spanish, and the difference in activation between semantic judgments for English versus Spanish words. The main question was whether there would be any reliable difference between cortical activations for L1 versus L2 during semantic performance. The presence of such a difference would indicate partially nonoverlapping neural systems for semantic performance, whereas the absence of any difference would indicate a common semantic system for sequentially learned languages.

METHOD

Participants

Eight participants were recruited primarily from the Department of Spanish and Portuguese, Stanford University. They were healthy, bilingual volunteers, fluent in both English and Spanish. They acquired their second languages sequentially to their first languages, with a mean age of second language acquisition of 12.25 years. One subject acquired his second language earlier than the others, but he was retained for analysis because his results appeared similar to those of the others. A summary of the language backgrounds of these participants is shown in Table 2.

Procedure

Participants performed two kinds of tasks, each requiring a different type of judgment about words presented visually: (1) semantic decisions about whether words were concrete or abstract in meaning and (2) nonsemantic decisions about whether words were printed in uppercase or lowercase type. To accommodate both tasks, every word series consisted of half concrete nouns and half abstract nouns, with half of each noun type printed in uppercase and half printed in lowercase type (e.g., ADVICE, potato, soul, FROG, . . .). Thus, the only difference across tasks was the kind of decision (semantic versus nonsemantic) that participants made for each set of words. The word series appeared in either English or Spanish, and instructions for each series were always given in the corresponding language. Each item appeared on the screen for 1 s, with a 1-s interval between items.

Responses were made with a pneumatic squeeze ball, requiring participants to respond using a 'go/no-go' system. For the concrete-abstract task, half the participants were told to respond only to the concrete words ('Task-Concrete' or 'Tarea-Concreta'), and half were told to respond only to the abstract words ('Task-Abstract' or 'Tarea-Abstracta'). For the case judgment task, half were told to respond to uppercase words ('Task-UPPER' or 'Tarea-MAYUSCULA'), and half were told to respond to lowercase words ('Task-lower' or 'Tarea-minuscula'). The timing of the instruction trials was the same as for test trials.

TABLE 2
Language Background Characteristics of Participants

ID No.	Sex	Age	L1	Age L2 exposure	Age L2 fluent	L1 fluency	L2 fluency	Number of other languages
S1	F	28	English	12	20	10	8.8	0
S2	M	28	Spanish	24	27	10	8	0
S3	F	24	English	13	18	10	9.3	0
S4	F	22	Spanish	11	12.5	10	10	1
S5	F	29	Spanish	12	14	10	10	1
S6	F	36	English	10	17	10	9	2
S7	F	28	Spanish	11	15	10	9.8	3
S8	M	32	Spanish	5	13	10	10	0

Note. L1, first language acquired; L2, second language acquired. Fluency ratings reflect the average of self-reported ratings of proficiency in reading, writing, speaking and comprehending each language (1 = not at all proficient, 10 = totally proficient). Age L2 exposure is the age at which the participant first began to learn L2. Other languages are languages in addition to English and Spanish in which the participant reported high fluency.

Data were collected in a series of three experimental scans. In Scan 1, all words were presented in English, and the task alternated between blocks of concrete/abstract judgments and uppercase/lowercase judgments. In Scan 2, all words were presented in Spanish, and the task again alternated between *concreta/abstracta* judgments and *mayuscula/minuscula* judgments. In Scan 3, words were presented in blocks alternating between English and Spanish. The task was to make concrete/abstract judgments. The order of the three scans and the order of the conditions within each scan were counterbalanced across participants. In all scans, stimuli were presented in four cycles, with each cycle consisting of two blocks each consisting of an instruction cue and 20 test trials.

Stimuli

All experimental stimuli were drawn from a set of 480 English nouns and their Spanish translations. Half of the words were concrete nouns and half were abstract nouns, according to normative ratings (Paivio, Yuille, & Madigan, 1968). For each scan, two sets of 80 items were constructed, each divided into four blocks of 20 items containing half concrete and half abstract words, and half of each word type were printed in uppercase and half in lowercase letters. Items were randomized to scan, set, and block, as well as to position within a block. In Spanish language scans and blocks, Spanish translations were substituted for the English words. Specific-item effects were controlled by counterbalancing the assignment of word sets to scans, languages, and conditions across subjects.

Data Acquisition

For each of the three scans, functional images were collected continuously for 336 s from 6 axial slices (two participants) or 10 axial slices (six participants) ranging from $Z = -10$ to $Z = +48$, based on the stereotaxic atlas of Talairach and Tournoux (1988). A T2*-weighted gradient echo spiral sequence was used (1.5T, 5-mm-thick slices, 1.5-mm interslice spacing, in-plane resolution 2.8×2.8 mm, 8 or 4 spiral interleaves, TR = 400 or 900 ms, TE = 40 ms, flip angle = 30° or 70° ; Glover and Lai, 1998). A 5-in. surface coil was used for subjects 1–4 and a whole head coil for subjects 5–8.

RESULTS

Behavioral Data

Participants performed a total of 80 trials per task per scan. Every participant had at least 90% accuracy in each language for the semantic task ($M = 93.8$, $SD = 1.9$ in L1; $M = 94.6$, $SD = 2.9$ in L2). As expected, accuracy in the case judgment task was at ceiling in both languages ($M = 98.9$, $SD = .5$).

fMRI Data Analysis

Time series of each pixel were correlated with a reference waveform and transformed into a Z-score map, SPM{Z} (Friston et al., 1994). The reference waveform was calculated by convolving a square wave (.012 Hz) representing the time course of the alternating conditions with a data-derived estimate of the hemodynamic response function.

Comparisons between semantic and nonsemantic conditions in the English and Spanish scans and comparisons between English and Spanish conditions

in the semantic scan are illustrated in Fig. 1. Inferential tests were made at $\alpha = .05$. Consistent with the results of previous levels of processing studies, all eight participants exhibited clusters of significantly greater activation for semantic than nonsemantic processing in the left IFG (Brodmann's areas (BA) 44, 45, 47) for both languages. Six participants also showed activation increases in the right IFG (BA 44, 45, 47) for both languages. Four participants showed significant activation in the left temporal lobe (BA 22) for each language, and four showed significant activation in the right middle frontal gyrus (BA 9,46) for both languages. When comparing English and Spanish or L1 and L2 directly, no consistent patterns were found; that is, there were no areas of significant differential activation that were seen across more than two subjects.

ROI Analysis

We conducted an ROI analysis to further confirm our fMRI observations and verify results in a threshold-free analysis. This analysis further allowed us to make direct comparisons between performance-related activation patterns in purely English and purely Spanish word sequences. We defined the left and right inferior frontal gyri as the regions of interest. For every slice, these regions were demarcated on the structural images to include the entire gyrus. From the *Z*-score maps derived for the semantic versus nonsemantic comparisons in the preceding analysis, we obtained the average *Z*-score for each region of interest for each language for each participant, combining across slices and weighting each pixel equally.

The language variable was analyzed in two ways. First, the language variable was defined in terms of the languages learned first (L1) and second (L2). In an alternate analysis, the language variable was defined in terms of the languages English and Spanish to examine possible language-specific effects. Semantic judgments led to significantly greater activation than did nonsemantic judgments in the left IFG for both L1 and L2 words ($t(7) = 8.08, p < .0001$; $t(7) = 3.76, p < .01$). In the right IFG, the pattern of greater activity for semantic than for nonsemantic judgments was statistically significant for L2 ($t(7) = 3.54, p < .01$) and approached significance for L1 ($t(7) = 2.31, p < .06$). The pattern of greater activation for semantic than for nonsemantic processing was significantly stronger in the left IFG than in the right IFG for L1 ($t(7) = 3.89, p < .01$) and marginally significant for L2 ($t(7) = 2.03, p < .10$). There was no indication that the laterality of semantic processing differed for L1 and L2, as indicated by a nonsignificant interaction ($F < 1$). There was also no indication that L1 and L2 led to different increases in activation for semantic over nonsemantic processing in either left or right IFG ($F_s < 1$).

For both English and Spanish words, semantic judgments led to significantly greater activation than did nonsemantic judgments in the left IFG

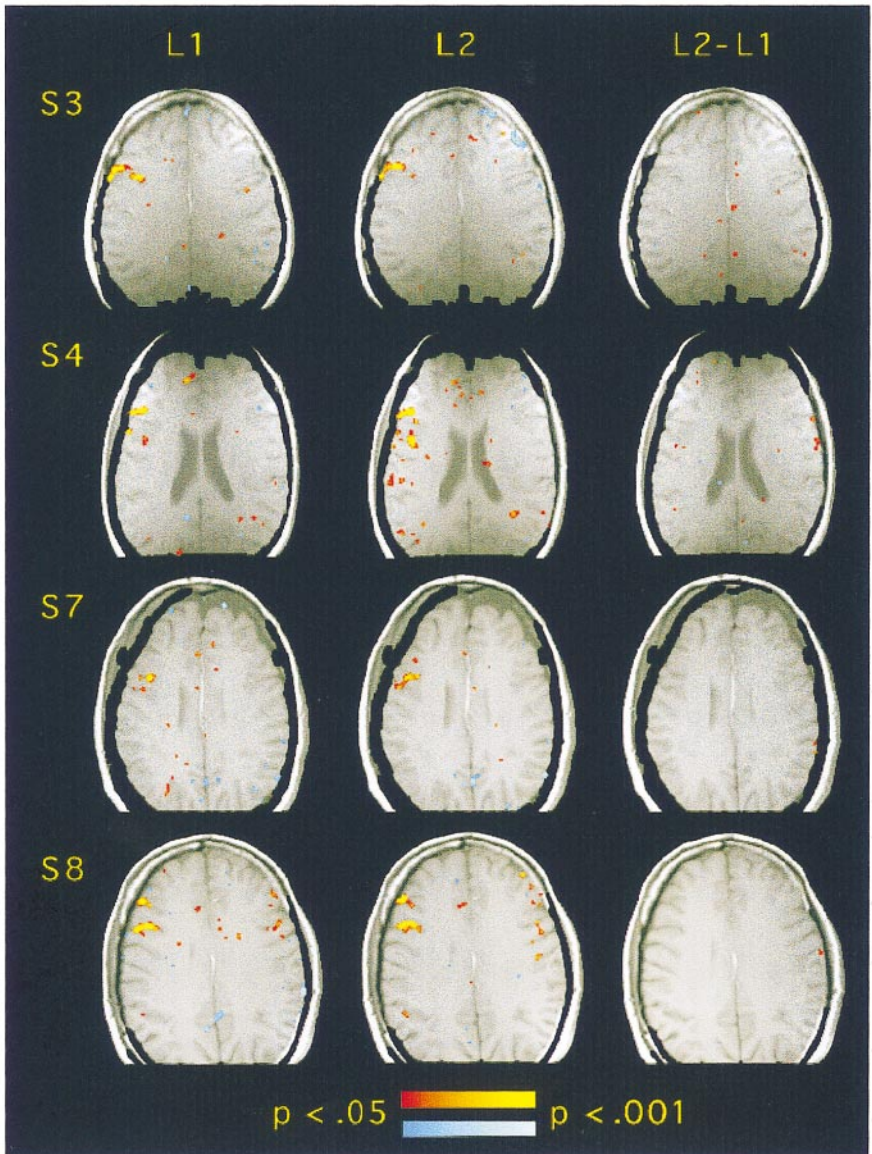


FIG. 1. Representative images from four bilingual participants showing consistent activation in the left prefrontal gyrus for semantic processing in both languages (English or Spanish). The first two columns show the result of the semantic minus nonsemantic subtraction within L1 and within L2. The third column shows the result of a direct comparison between L2 and L1 semantic processing. Pixels in color represent activation differences significant at $p < .05$, with warm colors representing areas more active either for semantic processing than for nonsemantic processing in the first two columns or more active for L2 than for L1 in the final column and cool colors representing areas less active either for semantic or for L2 processing.

($t(7) = 4.63, p < .005$; $t(7) = 5.73, p < .001$). In the right IFG, the pattern of greater activity for semantic than for nonsemantic judgments was statistically significant for English ($t(7) = 3.50, p < .01$) and approached significance for Spanish ($t(7) = 2.36, p < .06$). The pattern of greater activation for semantic than for nonsemantic processing was significantly stronger in the left IFG than in the right IFG for English and Spanish ($t(7) = 3.36, p < .05$; $t(7) = 2.39, p < .05$). There was no indication that the laterality of semantic processing differed for English and Spanish ($F < 1$) or that English and Spanish led to different increases in activation for semantic over nonsemantic processing in either left or right IFG ($F_s < 1$).

DISCUSSION

The present study examined semantic activations in bilingual participants who sequentially learned English and Spanish (or vice versa). The participants became fluent in their second language a decade after initial language acquisition, but were proficient in both languages, as evidenced by near-perfect performance for both English and Spanish. Consistent with prior studies (Demb et al., 1995; Gabrieli et al., 1996; Kapur et al., 1994; Wagner et al., 1997), the present study revealed robust activations for semantic relative to nonsemantic processing of English words in the left inferior frontal gyrus. A weaker activation was observed in corresponding regions of the right inferior frontal gyrus (seen also in Chee et al., 1999; Demb et al., 1995; Desmond et al., 1995). The same patterns of activation were also observed for semantic relative to nonsemantic processing of Spanish words. Critically, the semantic activation for both languages occurred in the same cortical locations. Further, no activation difference was observed in a direct comparison of semantic judgments in English and Spanish. These findings suggest that, at least to the resolution provided by fMRI, a common neural system mediates semantic processes for the two languages in the bilingual brain.

The conclusions of the present study are based on two complementary sources of evidence: the two unilingual scans, comparing semantic and nonsemantic processing in either English or Spanish, and the bilingual scan, which directly contrasted semantic processing in English and Spanish. In each unilingual scan, increased activation was observed when participants attended to the meaning rather than to the appearance of words, even though the stimuli and responses were otherwise identical for both sorts of judgment. These activation increases were evident in the left and right IFG for both languages (whether considered as English and Spanish or L1 and L2), with stronger and more consistent activation increases on the left. The patterns observed for the two languages within each participant were remarkably similar. The ROI analysis comparing the mean levels of activation across scans within the inferior frontal gyrus showed that the activity related to semantic processing did not differ for the two languages in either the left or right IFG

(nor did the relative left-dominant laterality of the two languages differ). A limitation of the unilingual scans, however, was the absence of a direct statistical comparison across languages.

The bilingual scan, however, permitted a direct statistical comparison of semantic processing across the two languages. No difference was found except for a few pixels for each participant, and these were sparsely scattered throughout the brain with no apparent systematicity within or across participants. Successively lowering the significance threshold to $\alpha = .10$ and $\alpha = .20$ did not reveal any systematic subthreshold activation patterns, so the absence of differences does not appear to be an artifact of threshold setting. The bilingual scan has two potential drawbacks. First, it yielded a null result, or the absence of an effect. Second, the alternation between two languages could have led participants to use different strategies than they would use in a single-language scan, possibly encouraging them to use language-general strategies that eliminated differences that might otherwise occur. Neither of these issues, however, apply to the unilingual scans. The convergent results from the unilingual and bilingual scans, each with different strengths and weakness as sources of evidence, indicate that that semantic processing yielded similar activations for both languages.

Our results replicate and extend previous neuroimaging studies that demonstrate LIPC involvement in semantic processing of English words (Demb et al., 1995; Gabrieli et al., 1996; Kapur et al., 1994; Wagner et al., 1997), of French words (Klein et al., 1995), and of pictures (Wagner et al., 1997). The present results, like those of many other imaging studies, differ from the results of lesion studies and cortical mapping studies in two important ways. First, although language-related activation is primarily left lateralized, right hemisphere activation is also indicated, here in six of eight participants. Second, activation in the posterior language areas is not consistently observed (seen in the present study in only four of eight participants). It remains to be determined why imaging studies converge only partially with lesion and stimulation findings.

The psychological processes underlying the activation patterns observed must be interpreted within the constraints of fMRI. That is, we must be able to assume that the primary cognitive processing difference between the two tasks is semantic in nature. The extent to which this activation can be attributed to semantic processing cannot be established without considering two alternative explanations. First, the LIPC activation attributed to semantic processing could reflect the relative difficulty of the two tasks, because the semantic concrete/abstract task is more difficult than the nonsemantic case judgment task with difficulty gauged as response latency (Demb et al., 1995; Gabrieli et al., 1996). However, greater LIPC activation for semantic over nonsemantic processing is observed even when the nonsemantic task is made more difficult than the semantic task, as operationalized by longer response times (Demb et al., 1995). Thus, the LIPC activation cannot be attributed

merely to task difficulty. The language-specific nature of this activation is further supported by evidence that LIPC activation for these tasks is lateralized in accordance with Wada-validated hemispheric dominance for language (Desmond et al., 1995).

A second alternative explanation is that some aspect of language other than semantic processing drives the LIPC activation associated with the semantic task. Semantic processing is likely not to be the only difference between the concrete–abstract and the case judgment tasks. As pointed out by Price et al. (1997), the concrete–abstract judgment likely involves more phonological processing than does the case judgment task, and this difference in phonological processing may underlie the increased LIPC activation for the semantic over nonsemantic task. The sensitivity of the LIPC to phonological processing is supported, for example, by a study in which a rhyme generation task elicited greater LIPC activation than a word repetition task (Klein et al., 1995). Further, LIPC activation has been observed to be greater for a phonological task than for a case judgment task; however, when the semantic and phonological tasks were compared directly, the semantic task led to greater activation in the anterior portion of the LIFG than did the phonological task (Poldrack et al., in press). This combination of results led to the proposal that the anterior portion of the IFG is sensitive to semantic processing, whereas the posterior portion is sensitive to phonological processing (Buckner, 1996; Fiez, 1997; Gabrieli et al., 1998; Wagner, 1999). From Fig. 1, it can be seen that both the anterior and posterior portions of the LIFG are significantly more active for the semantic than for the nonsemantic task. Thus, the LIPC activation observed in the present study is likely due to a combination of semantic and phonological processing that occur to a greater degree in the semantic than in the nonsemantic task.

If the common activation patterns found for English and Spanish, or alternatively for L1 and L2, in the present study are based on both phonological and semantic processing, this does not weaken the argument for a semantic system shared by both languages. What it does is to suggest further that for languages with phonological structures as similar as those of English and Spanish, the phonological systems of the two languages also have a shared cortical representation.

The results of our study were consistent with those of the two PET studies of single word processing in French–English bilinguals, in that no differences between languages were observed in frontal regions (Klein et al., 1994, 1995), even though the mode of presentation was auditory in those studies and visual in ours. Consistent with Klein et al. (1995), both languages showed LIPC activation for semantic relative to nonsemantic tasks in both languages. A PET study of story comprehension in fluent Spanish–Catalan and Italian–English bilinguals is also consistent with our findings (Perani et al., 1998). The Italian–English bilinguals, who were late learners, like our participants, exhibited no differences between languages. The Spanish–Cata-

lan bilinguals, who were early learners (and also had the more similar pair of languages), likewise showed no differences in cortical areas typically associated with language processing. The activation patterns we observed were very similar to those of the fMRI study of single word processing in Mandarin–English bilinguals, which also showed activation increases in the left inferior frontal gyrus that were indistinguishable for L1 and L2, even for the late bilinguals (Chee et al., 1999). In that study, as in ours, several participants also exhibited weaker but significant right inferior frontal gyrus activation increases that were consistent across languages.

The two prior fMRI studies that did show differences between L1 and L2 language processing may appear to be at odds with our findings. Consideration of those studies, however, suggests a number of ways in which the studies differ and, therefore, are not contradictory. One study examined story comprehension in French–English bilinguals only moderately fluent in their second language and found differences between L1 and L2 in frontal and temporal regions (Dehaene et al., 1997). This result constituted a more sensitive replication of a previous PET study showing differences between L1 and L2, but no differences between L2 and an unknown language in a similar population (Perani et al., 1996). Proficiency clearly affects the cortical representation and processing of the second language. As shown by Perani, less proficient bilinguals showed very different activation patterns when listening to L1 and L2 speech with L2 no different than an unknown language (Perani et al., 1996), whereas highly proficient late learners showed no differences between L1 and L2 (Perani et al., 1998). It could well be the case that as a second language learner becomes increasingly proficient in L2, the cortical implementation of language processes in L2 becomes increasingly like that of L1.

The second fMRI study examined covert production in early and late bilinguals with a variety of different language backgrounds and found greater separation of the two languages in Broca's area for late than for early bilinguals (Kim et al., 1997). As pointed out by Perani et al. (1998), proficiency may be an issue in this study as well; late bilinguals, the group showing the difference, are typically less proficient in the second language than early bilinguals (Johnson & Newport, 1989), and there is no indication that proficiency is equated across groups.

Both of these studies showing differences between L1 and L2 activation for late bilinguals used whole-language tasks that require types of processing not necessary for our tasks, including syntactic processing. It is possible that syntactic processing differences drive the differences observed. Although neuroimaging studies have only begun to explore the patterns of cortical activation associated with syntactic processing, one PET study has shown that increases in syntactic processing demands lead to increased activation in the region of Broca's area (Stromswold et al., 1996). In the Kim et al. (1997) study, the frontal region of interest was Broca's area, which typically

includes only the posterior portion of the LIFG, the part thought to be more involved in phonological than in semantic processing (Poldrack et al., in press). Because of the variety of languages and the phonologically distinct nature of some of these language combinations, phonological differences may also explain the separation. However, the particular aspects of language, if any, that are represented differently for early and late learners cannot be determined definitively from those data sets. Our data, in combination with the other study of semantic processing (Klein et al., 1995) and the study of word completion (Chee et al., 1999), indicate shared semantic processing systems for the two languages of highly proficient bilinguals. Age of acquisition does not appear to be a factor in the localization of semantic processing in highly proficient bilinguals, and proficiency effects on the localization of semantic processing have yet to be explored.

In sum, we conclude from our data that learning a new language, even after the age of 10, does not require the addition of a new semantic processing system or the recruitment of new cortical regions for semantic processing. We further suggest, therefore, that neither the differential loss or reacquisition of languages in bilingual aphasic patients nor the apparent dissociations in cortical activation seen in whole-language fMRI studies of bilingualism can be attributed to independent semantic subsystems.

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