

# Common and Segregated Neuronal Networks for Different Languages Revealed Using Functional Magnetic Resonance Adaptation

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## Abstract

■ The effect of word repetition within and across languages was studied in English–Chinese bilinguals who read rapidly presented word pairs in a block design and an event-related fMRI study. Relatively less increase in MR signal was observed when the second word in a pair was identical in meaning to the first. This occurred in the English-only and mixed-languages conditions. Repetition-induced reductions in BOLD signal change were found in the left lateral prefrontal and lateral temporal regions in both types of conditions in the block experiment, suggesting that processing in these regions

is sensitive to semantic features present in words and characters, and that part of the semantic neuronal networks serving English and Chinese is shared. In addition, these regions showed greater absolute signal change in the mixed-languages trials relative to the English-only trials. These findings were mostly replicated in an event-related experiment. Together, the experiments suggest that while the networks for Chinese and English word processing have shared components, there are also components that may be language specific. ■

## INTRODUCTION

At a resolution afforded by fMRI, overlapping brain areas are activated when fluent bilinguals process words or sentences in different languages (Hernandez, Martinez, & Kohnert, 2000; Chee, Caplan, et al., 1999; Chee, Tan, & Thiel, 1999; Illes et al., 1999; Klein, Milner, Zatorre, Zhao, & Nikelski, 1999; Perani et al., 1998). This suggests that common, specialized areas for language exist at a macroscopic level. Intuitively, it seems probable that at a finer-grained level, distinct neuronal networks are involved in processing different languages. However, it is presently unclear if conventional functional neuroimaging techniques have the capability of demonstrating these finer-grained distinctions in functional specialization.

Neurons within a functionally specialized brain region that show response selectivity to different stimuli can be revealed, using experiments that repeatedly present stimuli that are identical or differ on specific dimensions. Electrophysiological (Desimone, 1996) and functional imaging studies (Grill-Spector & Malach, 2001) of the brain suggest that neurons in higher visual areas may discriminate many different properties of visually presented objects. For example, repeated visual presentation of an object over time intervals of seconds or less results in reduced neuronal firing during the second and subsequent presentations of that object. However, when

subsequent presentations differ along some critical dimension with respect to the initial stimulus, this reduction in neuronal firing is not observed. Invasive electrophysiological methods have shown this “repetition suppression” effect in the inferior temporal cortex of primates (Li, Miller, & Desimone, 1993; Miller, Li, & Desimone, 1991). The effect occurs in neurons that are dispersed within the region of study such that one macroscopic region appears to be sensitive to a variety of object classes. Such a model contrasts with a view of brain organization where neuronal networks sensitive to particular categories are coarsely clustered in macroscopically differentiable regions (Damasio, Grabowski, Tranel, Hichwa, & Damasio, 1996).

A distributed and overlapping arrangement of representations, coupled with the ability to code for abstract rules (Wallis, Anderson, & Miller, 2001) and to reconfigure response according to task demands (Freedman, Riesenhuber, Poggio, & Miller, 2001), may provide a better explanation for our apparently limitless capacity to categorize words along different dimensions without “running out of space” (a concern if we were to have one set of neurons coding for “cats,” another set coding for “dogs” and so on; see Tyler and Moss, 2001, for a review). Thus, work on how semantic knowledge is organized in the brain is relevant in guiding the formulation of a realistic model (Kirsner, Smith, Lockhart, King, & Jain, 1984) of how different languages may be organized in the brain.

Two complementary functional imaging techniques have recently been used to uncover the coding specificities of neurons within a particular brain region, and promise to reveal finer-grained functional-anatomical correlations than previously possible. One method is to examine the pattern of within and across category correlations of BOLD signal in individual voxels activated by viewing objects belonging to different categories. The first study of this type has revealed a mosaic of highly correlated activated voxels corresponding to distributed and overlapping representations for faces and objects (Haxby et al., 2001). The other technique, which we use in the present work, and whose conceptual basis we explained earlier, is to compare the magnitude of activation of repeated stimuli that are similar along the dimension of interest but differ along other dimensions, in order to determine the dimension along which neurons of interest are sensitive (Grill-Spector & Malach, 2001; Naccache & Dehaene, 2001; Henson, Shallice, & Dolan, 2000; Grill-Spector et al., 1999).

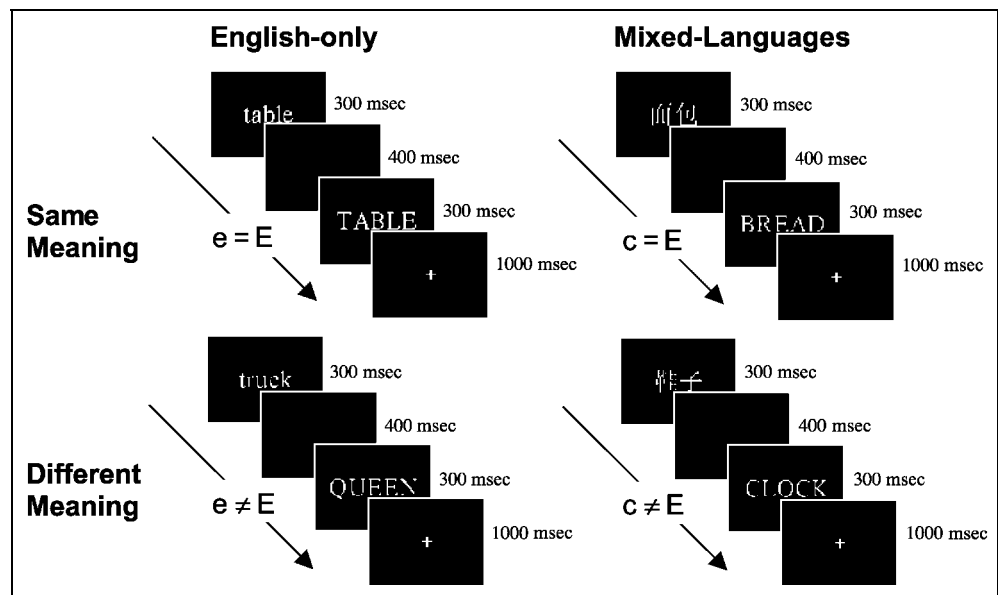
Whereas the “repetition suppression” effects alluded to earlier have been confined to work in primates, the effects of manipulating the transformation of a word between first and second presentations have been extensively studied using event-related potentials (ERPs) in human volunteers. Complete replication of the initial stimulus in subsequent presentations results in a modulation of the evoked response (Rugg, 1990). If the transformation of an attribute causes a smaller repetition effect relative to that observed with direct repetition, it can be inferred that the transformed attribute is salient to the cognitive system. ERP provides temporally detailed information but lacks the spatially detailed information invasive electrophysiological methods can provide. In contrast to ERP, fMRI provides higher-resolution spatial information about the regions

where processes discriminating between different word attributes may occur. Superior spatial resolving power relative to ERP is a key benefit of using imaging methodology to study repetition effects. For instance, it has been shown that the repeated presentation of object pictures results in a reduction in hemodynamic response in left frontal, lateral temporal, and medial temporal regions but not in the early visual or motor regions following second and subsequent exposures of a target stimulus (Buckner et al., 1998).

Grill-Spector et al. (1999) and Grill-Spector & Malach (2001) demonstrated the feasibility of using rapid serial presentation of visually presented object drawings or photographs to uncover the sensitivity or invariance of neurons in the lateral occipital cortex (LOC) to different visual features. They demonstrated greater invariance of neurons in the LOC to changes in size and position of objects, compared to illumination and viewpoint. They inferred neuronal sensitivity to particular visual characteristics from the difference in magnitude between trials where modified and identical stimuli were shown. The authors named this technique “fMR-A” or “functional magnetic resonance adaptation,” a term that does not presume the underlying physiological basis for the effect. In addition to showing sensitivity to a particular stimulus parameter (e.g., size), it may also be possible to use this adaptation technique to determine the extent to which features along a particular dimension are related by observing the magnitude of the difference in adaptation between test conditions (Grill-Spector & Malach, 2001).

In the present set of experiments, we evaluated adaptation effects for serially presented English word pairs by comparing two identical concrete nouns, presented in different case (lower and UPPER), with another pair of nonidentical, unrelated, concrete nouns (Figure 1). We

**Figure 1.** Exemplars of the four conditions employed as well as the stimulus timing used in the block design experiment.



also compared signal differences between word pairs consisting of an English concrete noun and its Chinese translation equivalent against Chinese–English word pairs where each word did not share the same meaning as the other in that pairing. The goals of these experiments were, firstly, to demonstrate repetition effects involving words using a paradigm that engages repetition without the need for overt behavioral response, and secondly, to determine how the magnitude of repetition effect differs in English-only and mixed-languages conditions. We predicted that if English and Chinese word processing involved nonidentical neuronal networks, a larger BOLD signal would be associated with translation-equivalent Chinese–English word pairs compared to repeated English word pairs. We further expected that the mixed-languages condition would result in greater activation compared to the English-only condition when translation-equivalent word pairs were compared and that this effect would be regionally specific. That is, we expected the effect to occur in regions whose functions relate to semantic processing, but not in regions primarily related to early visual processing.

## RESULTS

### Experiment 1: Block Design

Consistent with most single-word reading experiments, inferior temporal, lateral temporal, and lateral prefrontal cortices showed a pattern of left-hemisphere-dominant activation, whereas visual areas showed bilateral activation. Only results from the left hemisphere are presented here. Unless otherwise stated, all 12 participants showed activation in the regions of interest (ROIs) discussed (see Methods section). Areas activated in the “English-only” and “mixed-languages” conditions were spatially congruent. For each ROI, a repeated-measures ANOVA was performed on the percent signal change from each participant.

No significant adaptation was found across individuals in the lateral occipital (Figure 2) and medial occipital (results not shown) regions, although some individuals showed effects in opposite directions (Figure 3). This result is important in denoting the lack of sensitivity of the early visual areas to word meaning.

Most participants showed two separate clusters of activation in the left lateral prefrontal cortex, a ventral (−40, 25, 20) region, and a dorsal (−42, 7, 30) region. The ventral cluster of activation corresponded to the previously described “anterior left inferior prefrontal cortex” that has been associated with word semantic processing (Poldrack et al., 1999).

Ten participants showed activation of the ventrolateral prefrontal region. The effect of meaning [ $F(1,9) = 9.10, p < .05$ ] was significant, while the effect of language [ $F(1,9) = 3.64, p = .09$ ] did not reach significance. There was no interaction [ $F(1,9) < 1$ ]. All partic-

ipants activated the dorsolateral prefrontal region. Significant effects were found for both meaning [ $F(1,11) = 12.48, p < .01$ ] and language [ $F(1,11) = 10.65, p < .01$ ], without interaction [ $F(1,11) < 1$ ].

Eleven participants showed activation in the lateral temporal region, including the posterior part of the superior temporal gyrus and the supramarginal gyrus (Figure 2). Significant effects were found for both meaning [ $F(1,10) = 13.44, p < .005$ ], and language [ $F(1,10) = 6.59, p < .05$ ], but there was no interaction [ $F(1,10) < 1$ ]. In the inferior temporal region (BA 37), there was a marginally significant effect of meaning [ $F(1,11) = 4.81, p = .051$ ] but neither a significant effect of language [ $F(1,11) = 2.69, p = .13$ ] nor interaction [ $F(1,11) < 1$ ].

Within the left parietal lobe, the ANOVA showed a significant effect for meaning [ $F(1,11) = 5.89, p < .05$ ], but not for language [ $F(1,11) = 1.99, p = .19$ ]. There was no significant interaction [ $F(1,11) = 3.69, p = .08$ ].

### Experiment 2: Event-Related Design

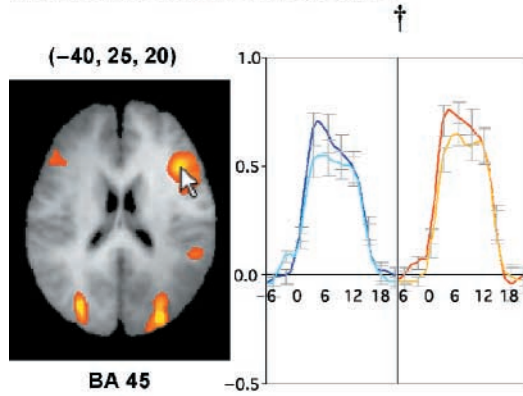
At the group level, strikingly similar regions of activation were revealed in the event-related design experiment as compared to the block design experiment when all predictors were “on” (Figure 3). Compared to the block design, fewer persons showed activation in all possible ROIs (particularly true for the left lateral temporal region).

Eight out of 10 participants showed activation in the ventrolateral prefrontal region. Both the effects of meaning [ $F(1,7) = 52.85, p < .001$ ] and language [ $F(1,7) = 20.86, p < .005$ ] were significant. There was no interaction [ $F(1,6) < 1$ ]. The dorsolateral prefrontal region, activated by nine participants, also showed significant effects for both meaning [ $F(1,8) = 26.39, p < .001$ ] and language [ $F(1,8) = 26.39, p < .001$ ], but no interaction [ $F(1,8) < 1$ ]. The present experiment does not allow us to discriminate the different reasons as to why both these functionally differentiated areas showed sensitivity to meaning and language. However, present knowledge would suggest that the adaptation in the ventral region relates to semantic processes whereas the dorsal changes may relate to language switching. These points are elaborated on in the ensuing discussion.

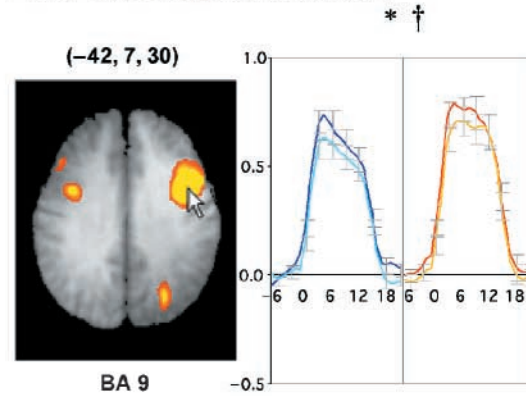
Only 7 participants showed activation in the left lateral temporal region, with both meaning [ $F(1,6) = 5.56, p = .056$ ] and language [ $F(1,6) = 5.95, p = .051$ ] at borderline significance (Figure 3). There was no interaction [ $F(1,6) = 3.29, p = .12$ ]. The borderline significance for this region in this experiment contrasts with the more positive finding in the block design, and could be a result of lack of power due to relatively fewer participants who activated this region (7 in the event-related vs. 11 in the block design), as well as the relatively lower statistical power inherent in event-related designs (Friston, Zarahn, Josephs, Henson, & Dale, 1999). No significant effect of meaning

## Block Design

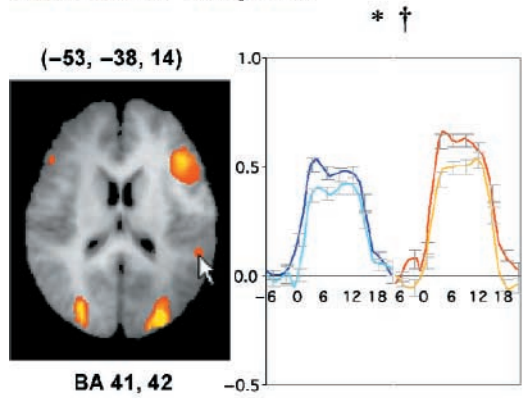
### Left Ventrolateral Prefrontal



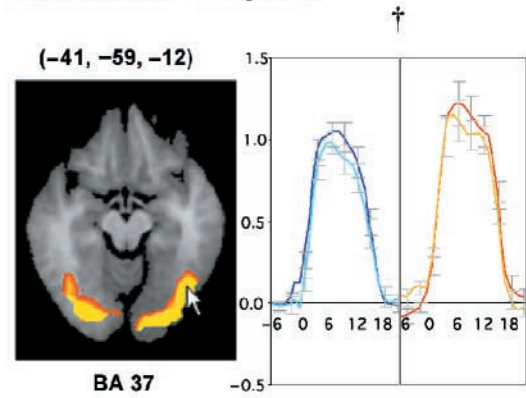
### Left Dorsolateral Prefrontal



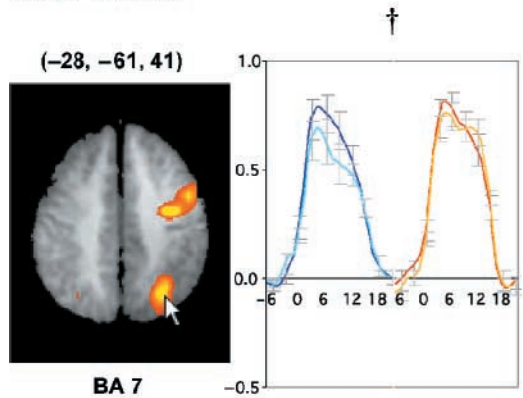
### Left Lateral Temporal



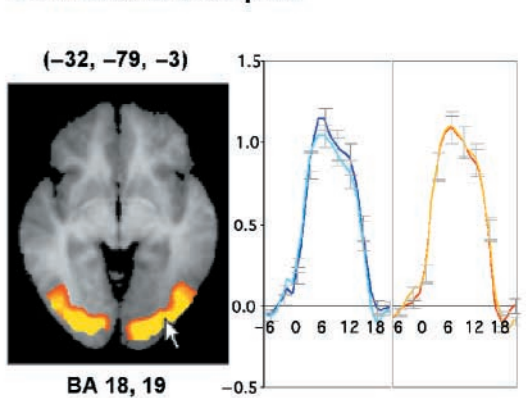
### Left Inferior Temporal



### Left Parietal



### Left Lateral Occipital

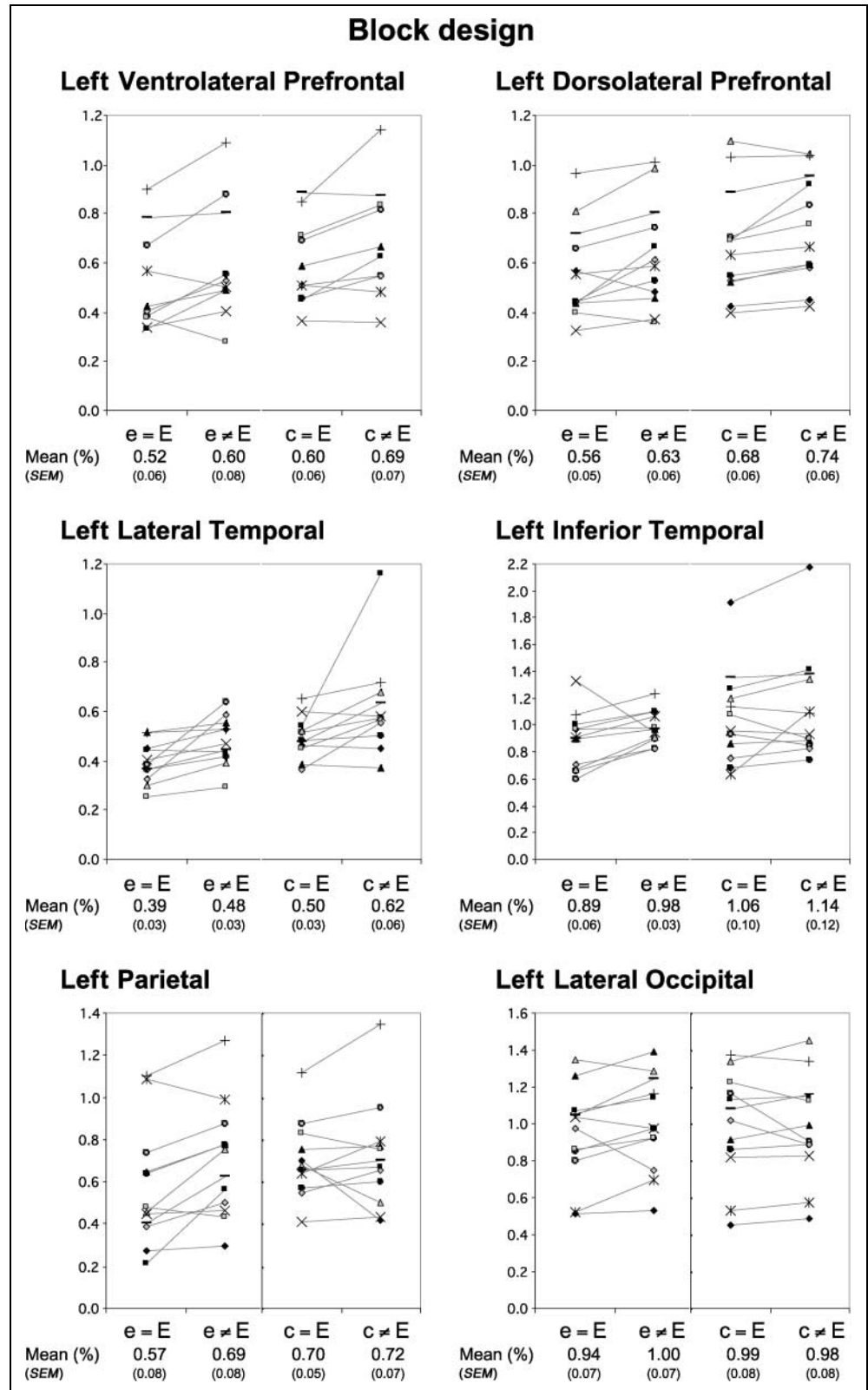


e ≠ E —■— c ≠ E  
e = E —■— c = E

\* Significant effect of Language ( $p < .05$ )  
 † Significant effect of Meaning ( $p < .05$ )  
 § Significant Interaction ( $p < .05$ )

**Figure 2.** Group level activation maps relating to the block design experiment showing particular regions of interest (ROI) and their corresponding average responses to blocked stimuli. The Talairach coordinates for the activation peak in the ROI are shown above each axial section. In the adjacent panels, blue traces represent the English-only conditions with the darker blue denoting the  $e \neq E$  condition and lighter blue denoting the  $e = E$  condition. The mixed-languages conditions appear in the adjacent box, where red denotes the  $c \neq E$  condition and yellow denotes the  $c = E$  condition. The error bars represent  $\pm 1 SE$ . The horizontal axis shows image number and the vertical axis is percent change in BOLD signal. ROI showing significant effect(s) in repeated-measures ANOVA are marked.

**Figure 3.** Percent signal change data obtained from individual participants in the block design experiment segregated by task and region. The vertical axis shows percent change in BOLD signal. The numbers below each graph indicate the group mean percent change in BOLD signal for that condition.



[ $F(1,6) = 1.49, p = .27$ ] was found in the inferior temporal region. However, significant effects of language [ $F(1,6) = 6.36, p < .05$ ] and interaction [ $F(1,6) = 9.57, p < .05$ ] were found.

The left parietal lobe, activated in 8 participants, showed significant effects of meaning [ $F(1,8) = 28.32, p < .001$ ] and language [ $F(1,8) = 55.02, p < .001$ ]. There was no significant interaction [ $F(1,8) < 1$ ].

In the lateral occipital region, activation was detected in 8 participants. Meaning had no significant effect [ $F(1,7) = 3.54, p = .10$ ], but language was significant [ $F(1,7) = 10.29, p < .05$ ]. However, there was a significant interaction [ $F(1,7) = 7.75, p < .05$ ]. Individual  $t$  tests showed that the  $e = E$  condition was associated with significantly lower activation than the  $e \neq E$  [ $t(7) = 2.91, p < .05$ ],  $c = E$  [ $t(7) = 6.09, p < .001$ ] and  $e \neq E$  [ $t(7) = 3.30, p < .05$ ] conditions, while there was no significant difference among the other three conditions [ $t(7) < 1$ ]. This suggests that using case as a means of generating perceptual dissimilarity in the English-only stimuli was not as effective as originally envisaged.

In sum, considering the results from block and event-related designs, adaptation for meaning was most consistently observed in the left ventrolateral and dorsolateral prefrontal regions. There was also a consistent effect for language in the dorsolateral prefrontal region. The left lateral temporal region showed effects for both meaning and language in the block design and borderline effects in the event-related design. The left inferior temporal region showed mixed effects depending on the acquisition method. The parietal region showed a reproducible effect for meaning. The lateral occipital region showed no consistent effect of meaning in either experiment. The interaction effect seen in the event-related design may be a result of inadequate control provided by the change in case in the  $e = E$  condition.

## DISCUSSION

### Semantic Properties Account for Much of the Adaptation Effect

Adaptation was observed when concrete words of the same meaning were silently read in rapid succession. It was observed irrespective of whether the first item was an English or a Chinese word and this supports the notion that at some level, the semantic system is language independent. Adaptation in the context of the English-only conditions is likely a result of the identical phonological and semantic properties of the repeated word. The observation that adaptation of the same magnitude occurred in the mixed-languages conditions (where the two words differ orthographically and phonologically even in the translation-equivalent condition) indicates that the adaptation observed in these experiments may be attributed to the shared semantic properties of the test items. The significant observations noted here are that within the left prefrontal and temporal areas, neuronal networks differ in their sensitivity to different concrete words, and that these neuronal networks are distributed over a relatively extensive brain region in contrast to being clustered into language-sensitive groups differentiable at a macroscopic level.

### Neuronal Networks Sensitive to Semantic Information Are Shared between Languages

Of the various models of the bilingual brain proposed, the present findings correspond closely to the concept-mediation model of lexical organization in bilinguals. In this model, words referring to the same concept in different languages carry distinctive language-specific tags, but access a language agnostic conceptual store (Kirsner et al., 1984). The existence of adaptation in the mixed-languages, translation-equivalent ( $c = E$ ) condition implies that the concept associated with a Chinese word is simultaneously accessible to the equivalent English word. The accessibility of conceptual information embedded in written words or digits may be available prior to conscious awareness of viewing the stimuli, such that access to meaning is automatic and independent of voluntary control (Naccache & Dehaene, 2001).

The sharing of semantic information across languages can also be assessed using lexical decision speed. Interestingly, this sharing of semantic information only occurs when words in different languages denoting the same referent are repeated over a short interval (Smith, 1997; Chen & Ng, 1989; Schwanenflugel & Rey, 1986). If lexico-semantic systems are spatially separated at a macroscopic level, we might expect to observe a different spatial pattern of activation in the mixed-languages condition compared to the English-only condition. Further, we would expect either no adaptation or minimal adaptation when comparing the mixed-languages conditions. Neither of these was true in the present experiments.

### Language-Dependent Differences in Neuronal Networks

The higher mean signal in the left prefrontal, lateral, and inferior temporal regions in the mixed-languages conditions compared to the English-only conditions suggests that processing words in both English and Chinese engages greater cognitive resources than processing words in English only.

One interpretation of the higher mean signal is that switching between languages requires cognitive control to activate the task-appropriate language, and to inhibit other languages (Green, 1986). "Switching cost" appears in some language tasks but not others. For example, there is no response time delay when participants perform within-language switching from action naming to object naming (Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001). Further, the specific brain regions whose activation is modulated by between-language switching may vary according to task demands. Both supramarginal gyri and the left posterior inferior frontal gyrus were found to be relatively more active in one switching experiment where participants alternated languages while naming printed words (Price, Green, & von Studnitz, 1999), whereas the left dorsolateral prefrontal cortex was found

to be more active in another experiment (Hernandez et al., 2001). In the present experiment, even if part or all of the higher mean signal in the left prefrontal region were attributed to switching cost (although this is unlikely given the results obtained in Price et al., 1999), language switching alone would not explain the higher mean signal in the left lateral temporal region, an area not known to be involved in executive tasks.

An alternative explanation for the higher mean signal in the mixed-languages conditions is that at some level, different neuronal arrays are involved in the processing of Chinese and English. Whether or not one attributes this higher mean signal to switching, increased demands on the attention system or implicit translation, these various explanations converge on the point that the written scripts of the two test languages were recognized as dissimilar by left prefrontal and lateral temporal neurons.

Our experiments reveal two partially dissociated levels of organization within the language system. At the semantic level, the lower BOLD signal in the translation-equivalent compared to the different meaning conditions, irrespective of whether one or two languages was involved, supports the notion that the semantic system is shared across languages. On the other hand, higher BOLD signal in both mixed-languages conditions suggests that there is differentiation of neuronal networks at the lexical level. Taken together, these findings support a model of brain organization where neuronal networks with differential sensitivity to semantics and language coexist in the same broad location, but are differentiable at a finer level.

### **Adaptation in the Prefrontal Region**

The finding that prefrontal regions show adaptation, while not surprising from the perspective of human ERP and functional neuroimaging studies on pure repetition and repetition priming, merits elaboration as it is in striking contrast to results obtained from direct electrophysiological recordings from the prefrontal region in primates using a delayed match-to-sample task (Miller, Erickson, & Desimone, 1996). Of specific interest is the observation that prefrontal neurons, in contrast to those in the inferior temporal region, demonstrate stimulus-selective responses when presented with line drawings. On the other hand, repeated stimuli that matched the sample stimulus elicited a stronger enhancement of firing in the prefrontal region in contrast to repetition suppression observed in the inferior temporal region. The electrophysiological responses described in primates performing delayed match-to-sample tasks have been replicated in humans who performed similar tasks while undergoing fMRI (Jiang, Haxby, Martin, Ungerleider, & Parasraman, 2000). In the light of this delayed match-to-sample data, the present findings suggest that prefrontal neurons may modulate

their firing rather dramatically according to different task demands. In the delayed match-to-sample task, the identification of a target stimulus has to be matched with an appropriate response (either a saccade or a bar release). The requirement to deliberately hold a target item in working memory was not present in our task. The increased firing in a match condition likely relates to processing required to appropriately respond to a match (“remember for action,” see Fuster, 2001) as distinct from passively acknowledging the existence of a match. In primates, more spatially restricted firing of neurons in response to familiar stimuli has been reported in the prefrontal cortex, but in the context of exposure to these stimuli in a training/learning environment that takes place over a time frame of at least several days (Rainer & Miller, 2000).

An increase rather than a decrease in neuronal firing in response to the second reading of visually presented words was also recently reported in recordings made within the lateral temporal cortex of epileptic patients (Ojemann, Schoebfield-McNeill, & Corina, 2002). The adaptation effect in the prefrontal cortex could still be explained if a smaller population of neurons fires (albeit more rapidly) in response to the repeated stimulus (Henson et al., 2000). Direct electrophysiological recording in primates has recently shown that the BOLD response to visual stimuli is best correlated with local field potentials that relate to neural input and local processing and less well correlated with local neuronal spiking (Logothetis, Pauls, Augath, Trinath, & Oeltermann, 2001). In view of the uncertainty of the specific neurophysiological mechanism underlying MRI adaptation effects in the prefrontal and lateral temporal cortices, we have chosen to use the term “adaptation” in the present work.

### **Potential Effects of Fluency and Age of Acquisition (AOA)**

As present experiments evaluated only fluent, early-onset bilinguals, it is prudent to restrict inferences regarding language representation derived from this study to such a population. Proficiency and AOA interact with task demands to influence what is revealed about the functional anatomy of language processing in two or more languages.

In an experiment where participants listened to spoken sentences, greater activation in the dominant temporal lobe within the temporal pole, middle temporal gyrus, and superior temporal sulcus was observed when participants who were less proficient in L2 than in L1 listened to L1 sentences (Perani et al., 1996). Another effect observed when listeners were less proficient in L2 was a spatial disparity in activation between L2 and L1 (Dehaene et al., 1997). When proficiency in L2 was higher and more closely matched to L1, activation in the left temporal region in response to L2 sentences closely resembled

that of L1. Proficiency had greater influence than AOA in modulating this activation (Perani et al., 1998).

On the other hand, associative semantic judgments recruit the prefrontal regions such that greater language proficiency is associated with less, not more, activation (Chee, Hon, Lee, & Soon, 2001). This may be because a more refined representation of conceptual knowledge facilitates or renders more automatic the retrieval of semantic information in one's more proficient language. Greater activation for the less fluent language has also been demonstrated in a sentence-comprehension task involving bilingual volunteers (Hasegawa, Carpenter, & Just, 2002).

Some but not all investigators have demonstrated AOA effects, and that these effects may be task dependent. ERP responses obtained during the detection of syntactic and semantic violations are differentially influenced by AOA. While the detection of syntactic violations is sensitive to AOA effects, detection of semantic violations is relatively insensitive to AOA (Weber-Fox & Neville, 1997). The use of a sentence-generation task revealed differences in frontal peak activation for L1 and L2 in early- and late-onset bilinguals of at least moderate fluency in L2 (Kim, Relkin, Lee, & Hirsch, 1997), whereas several word-level experiments did not replicate these differences (Chee, Caplan, et al., 1999; Illes et al., 1999; Klein et al., 1999).

## Conclusions

In sum, the present findings suggest that adaptation effects for concrete words reveal sensitivity to semantic differences between words irrespective of language. Neural networks in the left prefrontal and lateral temporal regions that are sensitive to semantic features are shared between languages, but networks that discriminate between languages may also exist within the same brain regions. These statements do not preclude the possibility that any given neuron within these regions may code for different linguistic properties (that is, the ability to code for both semantic as well as lexical properties). While we have provided evidence to support one model of how language processing circuitry is organized, further studies need to be conducted to reconcile the present data with electrical stimulation (Ojemann & Whitaker, 1978) and optical imaging data (Pouratian et al., 2000) that support a coarser (i.e., macroscopic) segregation of multilingual language processing centers.

## METHODS

### Experiment 1: Block Design

#### Participants

Twelve healthy right-handed participants (5 women) between the ages of 20 and 24 years gave informed

consent for this experiment. They were right-handed, neurologically normal, ethnic Chinese undergraduates proficient in both English and Chinese.

There are four official languages in Singapore: English, Chinese (Mandarin), Malay, and Tamil. English serves as the major language of government, jurisdiction, education, commerce, and other important spheres of life. The participants come from an educational system in which English is the dominant language. All our subjects were exposed to both English and Chinese by 4 years of age. Formal instruction in both languages started at the age of 6 years. A pass in both English and Chinese is a compulsory criterion for university admission. All the participants were selected on the basis of their excellent grades for both languages in standardized high school examinations, and they continue to use both languages in daily life in a mixture of contexts.

### Experimental Stimuli and Tasks

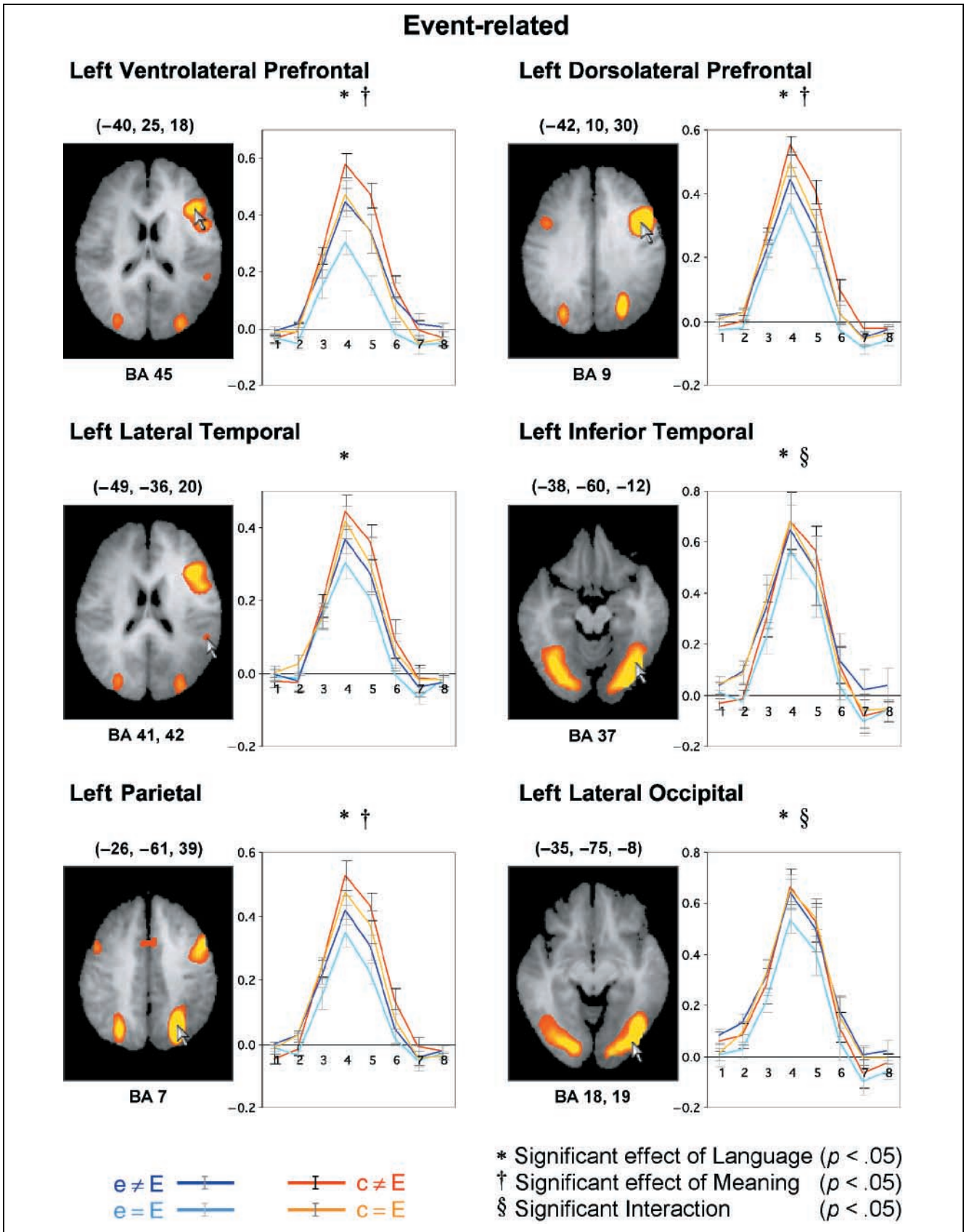
A set of high-frequency concrete English nouns (word length 3–8 letters) was selected from the MRC Psycholinguistic Database and translated into Chinese. Concrete nouns instead of abstract words were chosen in order to achieve greater equivalency in meaning following translation, and by inference, greater potential for shared representation within the semantic network. The words were grouped into pairs to create four conditions:

- (1a) English-only, identical word, different case ( $e = E$  condition), for example, “table” and “TABLE”;
- (1b) English-only, nonsynonymous, different case ( $e \neq E$  condition), for example, “truck” and “QUEEN”;
- (2a) Mixed-languages, translation-equivalent word pairs ( $c = E$  condition), for example, “mian-bao” and “BREAD”;
- (2b) Mixed-languages, nonsynonymous word pairs ( $c \neq E$  condition), for example, “xie-zi” and “CLOCK.”

The change in case between the first and second word in the English-only conditions was intended to reduce the visual similarity between the two presentations of a word without affecting its lexico-semantic properties (Scarborough, Cortese, & Scarborough, 1977). However, this objective was incompletely fulfilled in the event-related design experiment as the  $e = E$  condition still showed adaptation in the lateral occipital region when compared against the other three conditions (Figures 4 and 5).

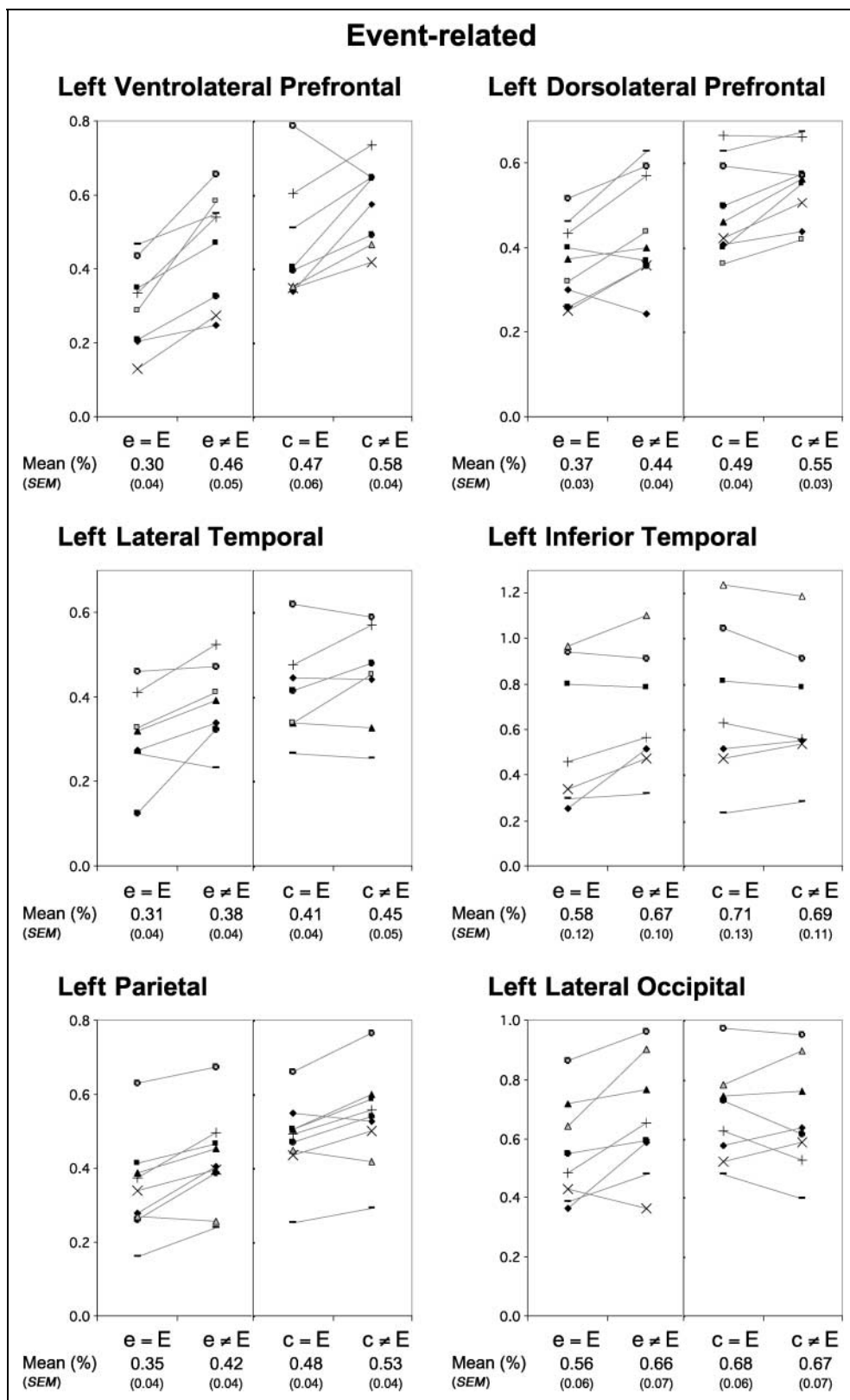
Words were counterbalanced across conditions for familiarity and word length. A new word pair was presented every 2 sec. During each trial, the first word was presented for 300 msec, followed by a blank screen for 400 msec. The second word then appeared





**Figure 4.** Group level activation maps relating to the event-related experiment showing particular regions of interest (ROI) and their corresponding average responses to individual conditions. The Talairach coordinates for the activation peak in the ROI are shown above each axial section. The error bars represent  $\pm 1 SE$ . The horizontal axis shows image number and the vertical axis is percent change in BOLD signal. ROI showing significant effect(s) in repeated-measures ANOVA are marked.

**Figure 5.** Percent signal change data obtained from individual participants in the event-related experiment segregated by task and region. The vertical axis shows percent change in BOLD signal. The numbers below each graph indicate the group mean percent change in BOLD signal for that condition.



for 300 msec. This was followed by a 1-sec fixation cross. Task blocks consisting of 14 word pairs; each was separated by 28 sec of fixation. Each participant viewed a total of six blocks of each condition involving

three runs of English-only word pairs and three runs of mixed-languages word pairs. Participants were instructed to read each word silently and to think of its meaning.

### *Imaging and Image Analysis*

Imaging was performed on a 2.0 T Bruker Tomikon S200 system (Bruker, Karlsruhe, Germany). A blipped gradient-echo EPI sequence with the following parameters was used: effective TE 40 msec, TR 2000 msec, FOV  $23 \times 23$  cm,  $128 \times 64$  pixel matrix. Fifteen oblique axial slices approximately parallel to the AC-PC line, 4 mm thick (2 mm gap) were acquired. High-resolution anatomical reference images were obtained using a three-dimensional spoiled-gradient-recalled-echo sequence. Functional images underwent phase correction prior to further processing with Brain Voyager 2000 Version 4.4 (Brain Innovation, Maastricht, Holland). Intensity normalization was performed, followed by motion correction. Gaussian filtering was applied, using a three-time-point FWHM filter in the temporal domain, and a smoothing kernel of 4 mm FWHM in the spatial domain. A set of T2 images acquired in an identical orientation to the functional MR data set was used to align the functional images to the high-resolution three-dimensional anatomical image. The resulting realigned data set was then transformed into Talairach space (Talairach & Tournoux, 1988).

The expected BOLD signal change was modeled using a gamma function (tau of 2.5 sec and a delta of 1.5) convolved with the blocks of cognitive tasks. The English-only conditions ( $e = E$  and  $e \neq E$ ) and the mixed-languages conditions ( $c = E$  and  $c \neq E$ ) were analyzed separately. A general linear model (GLM) with  $e = E$  and  $e \neq E$  as predictors in the English-only experiments was used. The mixed-languages conditions utilized  $c = E$  and  $c \neq E$  as predictors. This separation of predictor variables was necessary because of a slight change in baseline across time and was intended to afford more reliable comparisons between the mixed-languages and English-only sections of the experiment. Statistical maps for individual participants were created showing only regions where the two predictors (either  $e = E$  and  $e \neq E$ , or  $c = E$  and  $c \neq E$ ) together accounted for variance greater than 0.36. Similar thresholds have been used in our previous studies (Chee, Hon, Caplan, Lee, & Goh, 2002; Chee et al., 2001).

### *ROI Time Course Analysis*

Individual analyses were performed for the ROIs, as demarcated in Figures 2 and 4: lateral occipital, inferior temporal, lateral temporal, parietal, dorsolateral prefrontal, and ventrolateral prefrontal cortices. ROIs were defined by a combination of functional activation and anatomical landmarks. This approach considered activated voxels within the anatomically defined ROI without including areas that lay in the ROI but were not activated above threshold. The dorsolateral prefrontal ROI included the middle frontal gyrus and the dorsal part of the inferior frontal gyrus corresponding to BA 9,

while the ventrolateral prefrontal ROI included the ventral part of the inferior frontal gyrus corresponding to BA 44, 45. The lateral temporal ROI included regions in the posterior middle and superior temporal gyrus as well as the supramarginal gyrus incorporating regions in BA 41 and 42. The inferior temporal ROI incorporated regions in the posterior fusiform (occipito-temporal gyrus) and parahippocampal areas corresponding to BA 37. The parietal ROI incorporated the superior and inferior parietal lobules that included BA 7 and 40. The lateral occipital regions included the "higher visual areas" within the temporo-occipital gyrus, corresponding to BA 18 and 19.

Time courses were collected from activated voxels bounded by a cube measuring  $30 \times 30 \times 30$  mm, and were averaged across blocks of the same condition for each participant. The mean percentage signal change was obtained between 8 to 28 sec following the onset of each task block. This was compared to the mean signal during 12 sec of fixation immediately prior to the beginning of each task block (time points during transition between baseline and active task, and vice versa, were excluded). These values were then subjected to repeated-measures ANOVA (SPSS v10.0, SPSS, Chicago, IL), with language (English-only or mixed-languages) and meaning (Same or Different) as independent variables.

### **Experiment 2: Event-Related Design**

An event-related experiment was performed to control for the possible confound of stimulus predictability in the block design experiment and to take into account the possibility that baseline drift could affect comparisons across conditions in the block design experiment. The trade off with an event-related design is that it may be less sensitive to differences in activation between conditions compared to a block design.

### *Participants, Experimental Tasks*

Ten healthy right-handed participants (8 women) between 19 and 26 years of age, who came from the same language background as described previously but who did not participate in the previous experiment, gave informed consent for this experiment.

This experiment used the same corpus of word pairs as in the block design experiment. Eight word pairs from each of the four conditions were randomly presented within each of four runs. During each trial, the first word was presented for 300 msec, followed by a blank screen for 400 msec. The second word then appeared for 300 msec. This was followed by a fixation cross for either 4, 6, 8, or 10 sec. The intertrial intervals were varied to facilitate the deconvolution of the hemodynamic responses. The randomization of stimulus order took into account the need to allow signal to

drop to a “baseline” value in order to improve detection efficiency.

### *Imaging and Image Analysis*

The same imaging parameters were used as in the block design experiment, except that no temporal smoothing was applied to the functional data. Percent signal change data was obtained through a two-step process.

In the first stage, functional images were analyzed using a GLM with four predictors:  $e = E$ ,  $e \neq E$ ,  $c = E$  and  $c \neq E$ . The expected BOLD signal change in the event-related design was convolved with a gamma function (tau of 2.5 sec and a delta of 1.5) for each event. Statistical maps were created for individual participants, using an  $F$  threshold of 20 ( $p < 10^{-15}$ , uncorrected for multiple comparisons).

In the second stage of analysis, signal time courses were collected from the respective ROI for the event-related experiment using deconvolution (Beauchamp, Lee, Haxby, & Martin, 2002). No prior assumptions were made concerning response onset latency, peak or waveform. A set of 8 predictors was used to model the hemodynamic response for each condition, one predictor for each scan since stimulus onset, covering a total of 16 sec. A GLM with a total of 32 predictors of interest was computed on the time-series data obtained from each ROI. This process yielded four sets of estimates for each type of stimulus ( $e = E$ ,  $e \neq E$ ,  $c = E$  and  $c \neq E$ ), and these were presented as percentage signal change curves for each ROI (Figures 3 and 5). For each ROI, repeated-measures ANOVA was performed on the peak percent signal change values obtained from these curves, using the same independent variables as for the block design experiment.

### *Group-Level Activation Maps*

For each experiment, voxel-by-voxel GLM was also performed at the group level. Activation maps where all four predictors contributed to the explanation of the variance were generated (Figures 2 and 4). Voxels exceeding a threshold of  $p < .001$  were highlighted.

### **Acknowledgments**

This work was supported by NMRC Grant 2000/0477, BMRC Grant 014, and The Shaw Foundation. Nicholas Hon and Vinod Venkatraman provided helpful comments.

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The data reported in this experiment have been deposited in the fMRI Data Center (<http://www.fmridc.org>). The accession number is 2-2002-1132M.

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