

Overlap and Dissociation of Semantic Processing of Chinese Characters, English Words, and Pictures: Evidence from fMRI

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The functional anatomy of Chinese character processing was investigated using fMRI. Right-handed Mandarin-English bilingual participants made either semantic or perceptual size judgements with characters and pictures. Areas jointly activated by character and picture semantic tasks compared to size judgement tasks included the left prefrontal region (BA 9, 44, 45), left posterior temporal, left fusiform, and left parietal regions. Character processing produced greater activation than picture processing in the left mid and posterior temporal as well as left prefrontal regions. The lateral occipital regions were more active during picture semantic processing than character semantic processing. A similar pattern of activation and contrasts was observed when English words and pictures were compared in another set of bilingual participants. However, there was less contrast between word and picture semantic processing than between character and picture processing in the left prefrontal region. When character and word semantic processing were compared directly in a third group, the loci of activation peaks was similar in both languages but Chinese character semantic processing was associated with a larger MR signal change. The semantic processing of Chinese characters, English words, and pictures activates a common semantic system within which there are modality-specific differences. The semantic processing of Chinese characters more closely resembles English words than pictures. © 2000 Academic Press

Key Words: Chinese characters; fMRI; semantic memory; bilinguals; character recognition.

INTRODUCTION

How and where we extract meaning from words and pictures is a subject of considerable interest and debate (Caramazza, 1996a, 1996b). The extent to which meaning or the access to meaning is separate (Warrington and McCarthy, 1994; Warrington and Shallice, 1984) or common for words and pictures (Caramazza *et al.*,

1990; Vandenberghe *et al.*, 1996) has been the subject of many studies and is still controversial. Cases of visual agnosia (Albert *et al.*, 1979; Gomori and Hawryluk, 1984) and the existence of a “picture superiority” effect (Paivio, 1973), whereby pictures of objects are more easily remembered than words, suggest that at some point along the path from the perception of surface features to meaning, picture, and word processing differ. Functional neuroimaging suggests the existence of an amodal semantic system that has modality specific access (Vandenberghe *et al.*, 1996). Specifically, word semantic processing has been shown to activate the left superior temporal sulcus, left anterior middle temporal gyrus and left inferior temporal sulcus whereas picture specific semantic processing activates the left posterior inferior temporal sulcus.

Does type of script determine whether a “picture” or a “word” route is taken to process meaning? It has been proposed that the logographic nature of the Chinese script makes the concept represented by each character (or group of characters) relatively transparent to the reader (Smith, 1985; Wang, 1973). Advocates of this view suggest that there is greater predictability in the mapping of the surface form of a Chinese character to its meaning than is the case for English words. This may be so for characters that are pictographic as they portray the object that they represent. For example, the character for horse, “ma” is a pictograph that resembles an abstract figure galloping across the page (Wang, 1973). In support of such a view, greater Stroop-interference effects were found for bilingual Chinese-English speakers on Chinese word naming tasks compared to English word naming tasks when semantically related pictures were presented simultaneously with written verbal stimuli (Biederman and Tsao, 1979). This result suggests that there may be relatively greater overlap between the cognitive processes that are engaged during Chinese character identification and picture identification than is the case for word identification in English. Reports of differential deficits in kana (syllable based Japanese script) and

kanji (character based Japanese script) reading following stroke (Iwata, 1984; Sasanuma, 1975; Sasanuma and Monoi, 1975) imply that the two scripts differ in their underlying functional neuroanatomy (Benson, 1985; Cremaschi and Dujovny, 1996). Specifically, the ventral or object pathway is believed to be involved in accessing Kanji semantics whereas a dorsal pathway involving the angular gyrus and Wernicke's area is involved in processing Kana, the latter requiring greater phonologic processing.

An alternative viewpoint states that characters are discrete linguistic units and that they are not processed like pictures at all (Tzeng and Hung, 1984). The majority of written characters are composed of arbitrary symbols called radicals that denote the meaning and/or the sound of the word but these are neither pictographic nor alphabetic. According to this view, processing a character is more like word processing than picture processing for Chinese speakers. Evaluation of language deficits in a large series of Japanese aphasics has shown that the processing routes for Kanji and Kana are not clearly separated as previously believed (Sugishita *et al.*, 1992). The authors noted that in earlier reports emphasizing dissociation between kanji and kana, the test items used were few, not adequately documented or inappropriate. A recent MEG study where subjects read Kanji and Kana words (Koyama *et al.*, 1998) also showed that the locations of equivalent current dipoles (ECDs) to Kanji and those to Kana did not differ in the left posterior inferior temporal and left perisylvian regions. Comparing English and Mandarin Chinese, we previously found that cued word completion (Chee *et al.*, 1999b) and sentence comprehension (Chee *et al.*, 1999a) activate an overlapping network of brain areas.

We sought to determine whether processing of characters more closely resembles words or pictures for Chinese speakers. We predicted that character semantic processing would more closely resemble word processing than picture processing and undertook to demonstrate this by first showing differences in activation between characters and pictures while subjects performed semantic judgements. We also predicted that these differences would mirror those seen when words and pictures were compared in English–Mandarin bilinguals. Finally, we compared the processing of Mandarin and English directly in the same individual.

METHODS

Experiment One: Mandarin Characters and Pictures Comparison

Six right-handed, English–Mandarin bilingual participants (undergraduates or graduates) aged between 20 and 23 years gave informed consent for this study. Singaporean students of Chinese ethnicity are exposed

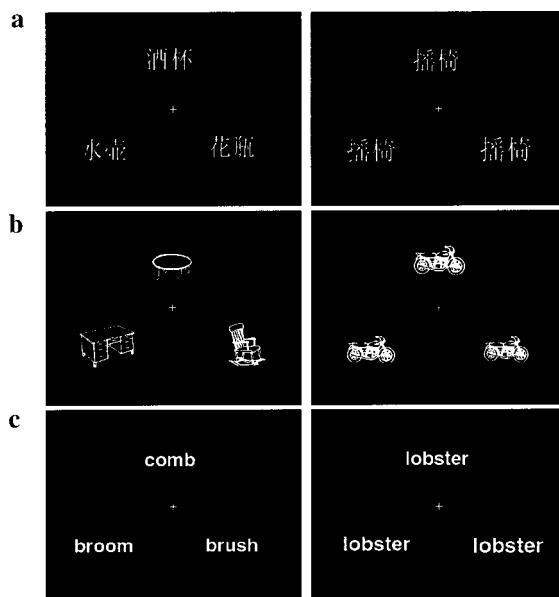


FIG. 1. The left panel of each column shows the semantic association task where the subject is instructed to respond by matching one of the lower items to the sample (uppermost item). Characters (a), pictures (b), and words (c) were presented in separate blocks. In the right panel of each column are exemplars of the size judgement task.

to both English and Mandarin at or before the age of 5 years so it is difficult to state what their “native language” is. To gain entry into local undergraduate education, a passing grade in both languages is a mandatory condition. The mass media operates in both English and Mandarin. Participants were chosen on the basis that they use both languages in conversation in daily life. As the medium of instruction for most courses is English words, there is a bias toward language processing in English.

In this experiment, we compared semantic processing of pictures and Chinese characters. Most of the pictures came from the Snodgrass–Vanderwart (1980) stimulus set. All test items represented objects or animals and all the characters or words used were concrete nouns. Test items were chosen on the basis that they were familiar to Mandarin speakers (Hua *et al.*, 1992). Stimulus triplets (Fig. 1) were presented for 3.0 s and were followed by 0.5 s of fixation. Participants performed two different matching to sample tasks with pictures or Mandarin characters. In the semantic task, they were instructed to choose the item closer in meaning to the sample stimulus (uppermost item in each panel in Fig. 1). This task is known as the Pyramids and Palm Trees (PPT) task (Howard and Patterson, 1992). We used roughly similar numbers of natural and man-made items to ensure that any differential activation of category specific systems did not confound comparisons between characters and pictures (Moore and Price, 1999). In the size judgement task, one of the items was 6% smaller or larger than the sample item

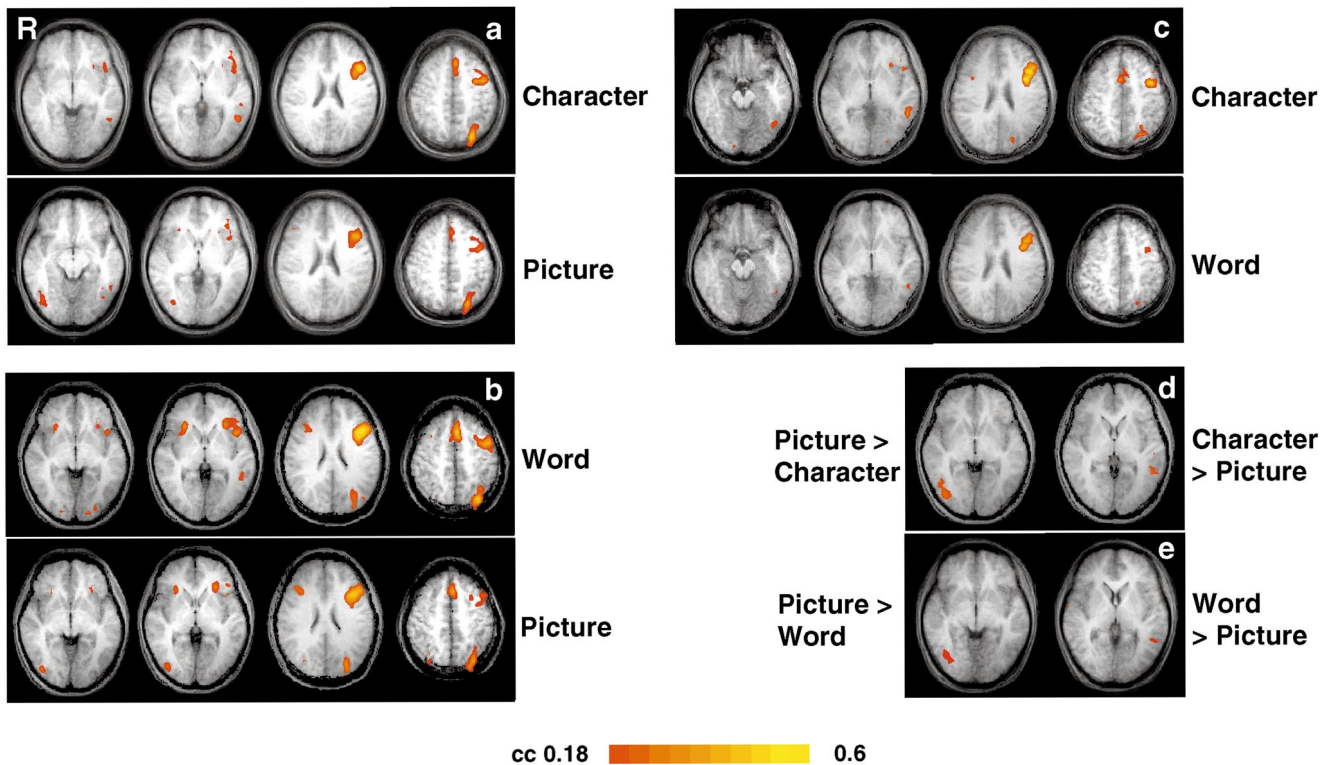


FIG. 2. The data in all the panels is derived from within-experiment, pooled subject data and is oriented in Talairach space. (a) Character and picture comparison. The upper panel shows activation maps comparing character semantic judgement vs size judgement; the lower panel shows the comparison between picture semantics and picture size judgement. (b) Word and picture comparison. (c) Character and word comparison. (d) Areas relatively more active during character and picture tasks in the experiment involving characters and pictures when media and task were set as explanatory variables. (e) Areas relatively more active during word and picture tasks.

and the other was 12% smaller or larger. Participants were instructed to choose the item that was closer in size to the sample. A picture-semantic task block comprised eight stimulus triplets totaling 28 s in duration. A block of stimuli comprising 8 picture-size judgement triplets followed, serving as a control task. Character stimuli (with semantics preceding size judgement) were then presented in an identical manner. A mixture of single and multicharacter test items was used. It has recently been shown that contrary to previous belief the number of characters denoting a specific concept in Chinese does not affect the locus of cortical activation when subjects generate semantically related words (Tan *et al.*, 2000). Each run comprised two such cycles of picture and character tasks (PCPC). Each subject participated in four experimental runs. The order of presentation of picture and character tasks was counterbalanced. Equivalents of picture and character stimuli were used so that if the picture of a comb appeared as a sample, it also appeared as a sample in character form at some point in the experiment. In repeating the stimuli we wished to minimize category and item specific effects between picture and character stimuli (Cappa *et al.*, 1998; Moore and Price, 1999). Stimuli

were presented via a MR compatible fibre-optic light-guide system (Avotec, Jensen Beach) and responses were collected using a two button mouse which the subject held in the right hand. Head motion was minimized by the use of a bite-bar system.

Experiment Two

Participants were 6 young adults aged between 20 and 23 years. Experimental details were identical to those in the previous experiment except that the comparison was between picture stimuli and English words.

Experiment Three

In this experiment, Chinese and English were compared in five participants aged between 19 and 29 years. The English words were different from the Chinese characters used in this comparison. This was to obviate the repeated exposure of words and characters denoting the same objects which could reduce activation in regions of interest through conceptual priming. Care was taken to ensure a similar balance of animate and inanimate items in the two stimulus sets.

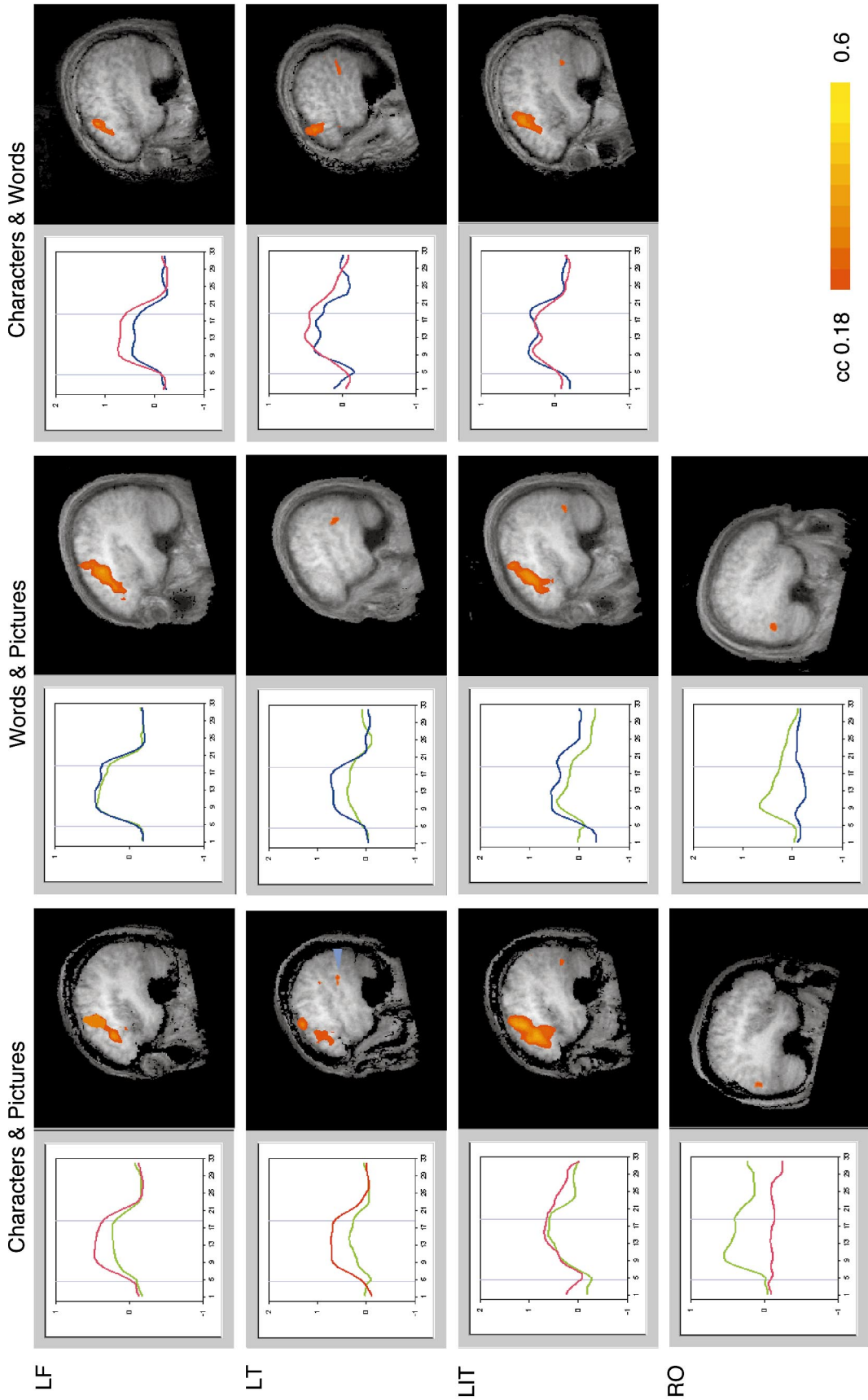


FIG. 3. This montage shows activation derived from within-experiment, pooled subject data, oriented in Talairach space. "PC" denotes regions activated by either the Picture and Character semantic conditions relative to their controls. "PW" shows areas activated in either the Picture or Word semantic conditions relative to their controls; "WC" shows data from the Word and Character experiment. Averaged time courses from each region of interest denoted by the label on the left side of each panel are displayed alongside each sagittal image-map. LF, left inferior temporal; LIT, left inferior temporal; LT, left inferior occipital; RO, right occipital. The averaged time courses show the percent signal change in the region of interest. "Character semantics" is coded red, "Word semantics" blue, and "Picture semantics" green. A light blue arrow denotes a region of interest in the temporal region.

Imaging and Image Analysis

Scanning was performed in a 2.0T Bruker Tomikon S200 system (Bruker, Karlsruhe, Germany) fitted with a 30 mT/m gradient system. A blipped gradient-echo EPI sequence with the following parameters was used: Effective TE 40 ms, TR 2000 ms, FOV 23 × 23 cm, a 128 × 64 pixel matrix (128 pixels in the A-P direction). Fifteen oblique axial slices approximately parallel to the AC-PC line 4-mm thick (with a 2-mm gap) were acquired. High-resolution, T1-weighted anatomical reference images were obtained as a set of 128 contiguous axial slices with a reformatted matrix of 256*256 pixels, using a three-dimensional spoiled-gradient-recalled-echo sequence. Functional images underwent phase correction prior to further processing. Images were 3-D motion corrected using a rigid body algorithm. Intensity normalization was performed in two steps. Global shifts in signal intensity were corrected prior to removal of linear drift. Gaussian filtering was applied in the temporal and spatial domains. In the spatial domain a smoothing kernel of 4 mm FWHM was used. In the temporal domain, a three time-point FWHM filter was used. Registration of the functional MR data-set to the high resolution anatomical image of the brain was performed by manually registering the stack of T2 images acquired in an identical orientation to the functional MR data set to the 3-D image. The resulting realigned data-set was then transformed into Talairach space.

The functional imaging data was analyzed in a step-wise manner. In the first stage of analysis regions of interest (ROI) were defined. This provided a qualitative appreciation of the effect of different media and tasks on activation. Next, percentage signal change graphs were obtained from ROIs showing activation during semantic judgement. Finally, we compared the mean percentage BOLD signal change for each semantic task using different media, in each ROI across subjects. Quantitative comparisons concerning the effects of different media on semantic processing were derived from these latter stages. These stages are explained in greater detail as follows.

A linear cross correlation map of the size judgement tasks in each experiment was first performed. No significant differences emerged from this comparison even when the cross correlation threshold was lowered to below 0.2 (for single subjects). Statistical maps comparing semantic judgement with size judgements using different pairs of media were then computed using a general linear model (GLM) using two explanatory variables: character semantics and picture semantics in Experiment 1, word semantics and picture semantics in Experiment 2; character semantics and word semantics in Experiment 3. In defining each explanatory variable, each semantic task was contrasted to its corresponding size judgement task. The expected

BOLD signal change was modeled using a gamma function (tau of 2.5 s and a delta of 1.5) synchronized to blocks of cognitive tasks. Statistical maps for individual participants for each explanatory variable were created using a correlation coefficient cut off of 0.4 corresponding to an F value of approximately 85 ($P < 0.001$). Clusters of voxels smaller than six voxels were not displayed. This resulted in the detection of activation in the prefrontal, temporal, medial frontal, parietal, and lateral occipital regions.

A multiple subject GLM in which each pair of semantic judgement contrasts were explanatory variables was used to compute pooled activation maps for each of the three experiments (Figs. 2a–2c and 3). The correlation coefficient cut-off was reduced to 0.18 (as a result of the increased df) corresponding to an F value of approximately 85 ($P < 0.001$). From these maps it was determined that the left mid and posterior temporal as well as the lateral occipital regions showed media specific effects on the magnitude of activation during the semantic task. A secondary analysis involved setting media and task as explanatory variables in the GLM and determining the effect of media on activation (Figs. 2d and 2e).

ROI were defined by sampling voxels that were active in either of each pair of semantic judgements relative to their respective size judgements. In doing so, we sought to select the ROI in an unbiased manner (Kelley *et al.*, 1998). In the left mid and posterior temporal region, there were some subjects who had noncontiguous temporal activation (Fig. 3). In such cases, the contribution of each subregion within the temporal lobe was averaged into a single time course representing the “temporal ROI” for that subject. (While it is possible that the specific neural computations taking place in these subregions is different, this experiment does not allow us to predict how they differ. As such the middle and posterior temporal areas were considered a common functional region.)

Within each individual's ROI, averaged time courses comprising 28 time points (14 task related and 14 baseline points) were calculated in order to show the average BOLD signal change due to the semantic tasks with respect to their size judgement baseline tasks. (For better visualization of the time courses four additional time points corresponding to the baseline task were displayed in Figs. 3 and 4 prior to the task block.) BOLD signal change was expressed as percentage signal change relative to the baseline (size judgement) task. For each subject, eight average time courses were generated (four ROI: left prefrontal, left temporal, left and right occipital; and two semantic tasks). The mean percentage signal change between semantic and size judgement task was calculated from points 5 to 14 located on the plateau of the BOLD response corresponding to the semantic task and from the points in

time 20 to 28 corresponding to the size judgement control. In this way, points in the transition phase during the rise and fall of the BOLD signal were omitted. In order to determine if the differences in BOLD signal at particular ROI could be generalized, the mean percentage signal-change data from each subject was pooled yielding 11 data elements for character and word semantic processing and 12 data elements for picture semantic processing (Table 5). The significance of differences between the BOLD signal change elicited by the different semantic tasks was then assessed using a two-tailed *t* test.

RESULTS

Behavioral Data

Subject performance in Experiment 1 is shown in Table 1. For accuracy, there was a main effect of media (characters vs pictures) $F(1,5) = 10.5$, $P = 0.02$ but no effect of task (semantic vs size judgement) $F(1,5) = 4.49$, $P = 0.08$ and no significant interaction between task and media $F(1,5) = 2.28$, $P = 0.19$. For reaction times, there was no effect of task $F(1,5) = 3.94$, $P = 0.1$ or media $F(1,5) = 4.72$, $P = 0.08$ but there was an interaction between task and media $F(1,5) = 30.3$, $P = 0.003$. Semantic judgement in Chinese was slower than size judgement.

In terms of accuracy, the English word and picture comparison again showed a main effect of media (word vs pictures) $F(1,5) = 29.1$, $P = 0.003$ but no effect of task (semantic vs size judgement) $F(1,5) < 1$, *NS* and no significant interaction between task and media $F(1,5) = 1.30$, $P = 0.3$. For reaction times, there was no effect of task $F(1,5) < 1$, *NS* or media $F(1,5) < 1$, *NS* and no interaction between task and media $F(1,5) = 4.1$, $P = 0.09$.

In the English word and Chinese character comparison, the English version of the task was performed more accurately $F(1,5) = 9.56$, $P = 0.04$ but there was no effect of task (semantic vs size judgement) $F(1,5) = 2.3$, $P = 0.2$. There was an interaction between task and media $F(1,5) = 8.69$, $P = 0.04$. The size judgement was performed more quickly $F(1,5) = 13.6$, $P = 0.02$. Character tasks were completed more quickly $F(1,5) = 18.9$, $P = 0.01$. There were no interaction effects.

Comparison of Baseline Conditions: Effect of Media and Task

At both the pooled data and individual levels of analysis, there was no significant difference in BOLD signal between the size judgement tasks involving characters and pictures, words and pictures or between characters and words (data not shown). When activation arising from both tasks employing characters was compared to both tasks using pictures (Fig. 2d), the

TABLE 1
Behavioral Data

	Accuracy (% correct)		Reaction time (ms)	
	Mean	SD	Mean	SD
Chinese vs pictures ($n = 6$)				
Character semantics	68	8.7	2052	193
Character size	80.2	9.9	1718	231
Picture semantics	80.6	2.8	1819	109
Picture size	84.1	9.2	1769	272
English vs pictures ($n = 6$)				
Word semantics	74.2	3.8	1759	206
Word size	73.4	8.4	1529	216
Picture semantics	81	6.4	1677	103
Picture size	76.6	10.4	1630	211
English vs Chinese ($n = 5$)				
Character semantics	74.1	9.5	1678	260
Character size	82.2	7.8	1419	189
Word semantics	87.5	4.3	1429	159
Word size	85.3	6.7	1292	211

result was similar to that obtained from parallel comparisons of character semantic judgement vs character size judgement and picture semantic judgement vs picture size judgement (Fig. 2a). These findings were mirrored in the word and picture comparisons (Fig. 2e) and indicate that most of the BOLD signal changes observed in these experiments arise from the semantic judgment tasks and that differences in the BOLD signal generated by the control tasks are small and probably not significant.

Character and Picture Semantic Processing

The pooled data derived from a GLM where character semantic processing was compared to character size judgement and where picture semantic processing was compared to picture size judgement, revealed that a common network of areas was activated for character and picture semantic processing (Figs. 2a and 3). This included the left prefrontal (BA 9,44,47), midline frontal (anterior SMA), left mid/posterior temporal (BA 21, 22), inferior temporal (BA 37), and left parietal (BA 7) regions.

This spatial location of activation was relatively consistent across individuals in the left prefrontal and midline frontal regions. Although all participants demonstrated temporal activation, this varied in location between participants (Fig. 4). The most consistent activation occurred in the left posterior temporal region (BA21, 22). Midtemporal activation was observed in two participants and left fusiform gyrus activation in three participants. The inferior temporal activation for pictures was weaker and located somewhat superior to that for characters.

Analysis of time courses in the temporal and prefrontal ROI showed significantly greater BOLD signal

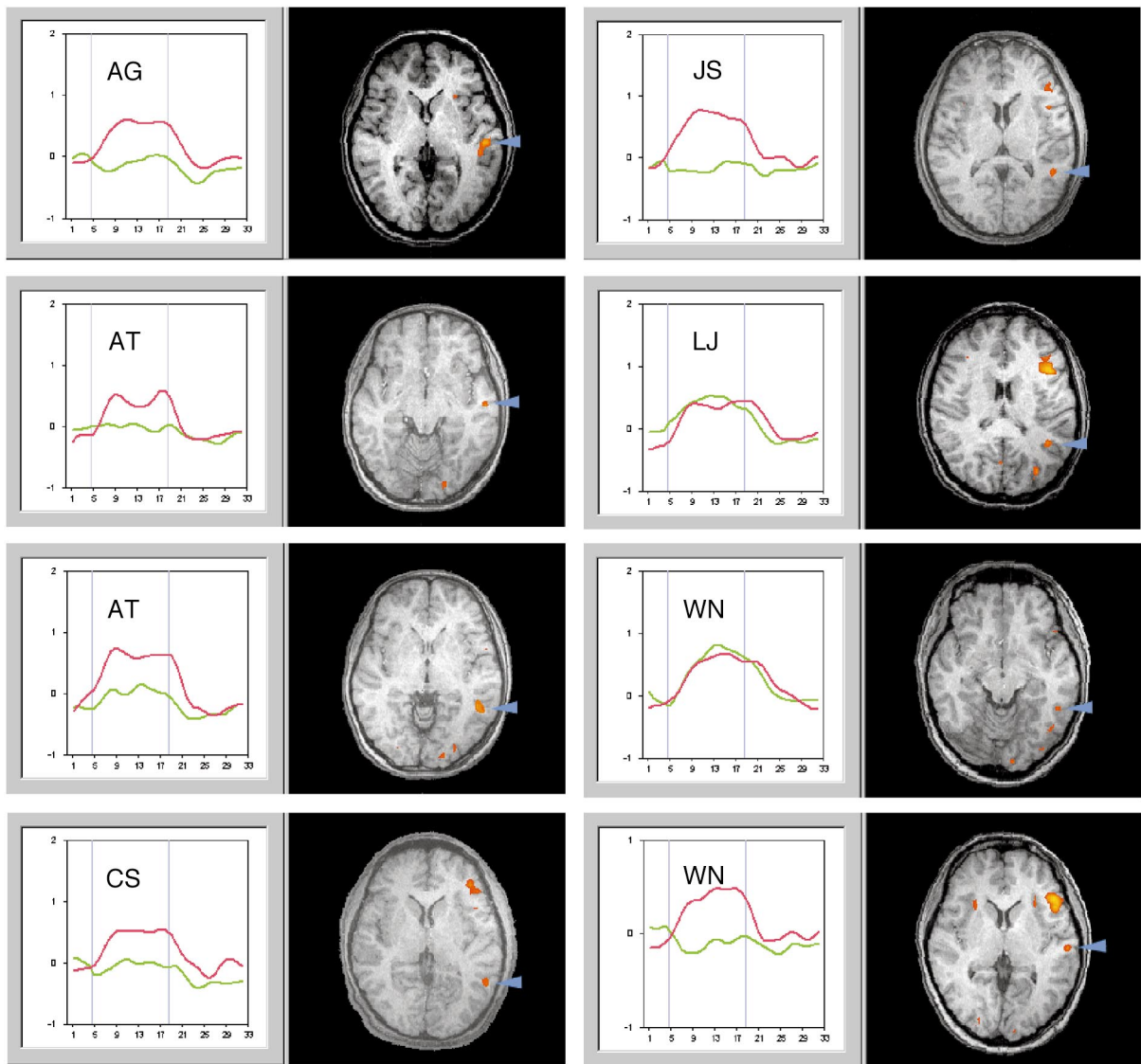


FIG. 4. Axial images oriented in Talairach space demonstrating the spatial variability of left mid and posterior temporal activation in six subjects in the Character semantic vs size judgement. Time courses from the region highlighted in the axial slice showing the percent signal change appear alongside. Each pair of letters denotes an individual subject's initials. "Character semantics" is coded red and "Picture semantics" green. Light blue arrow denotes the region of interest. The left half of the brain is displayed on the right half of each image.

change in the character semantic condition in the pooled data (Table 5, Fig. 5). Five of six participants showed this difference in activation (Fig. 4). Within the left temporal region, the middle and posterior temporal regions most consistently showed greater signal change with character semantic compared to picture semantic processing. In the lateral occipital regions, especially on the right side, signal change was greater in the picture semantic condition (Table 5, Figs. 2a, 2d, and 5).

Word and Picture Semantic Processing

The pooled data showed a common network of areas activated for word and picture semantic processing

that was similar to that seen in the character and picture comparison (Figs. 2b and 3). The Talairach coordinates of these activations were spatially congruent with those identified in the experiment involving characters and pictures (Table 3).

This spatial location of activation was consistent across individuals in the left prefrontal and midline frontal regions. Five participants demonstrated temporal activation and this varied in location between participants. The most consistent activation occurred in the mid/posterior temporal region (BA21, 22).

Analysis of time courses in the temporal ROI showed significantly greater BOLD signal change in the word semantic condition (Table 5, Fig. 5). As with the char-

TABLE 2
Character and Picture Semantic Comparisons

Subject	Characters					Pictures				
	Brodmann's area	cc	<i>x</i>	<i>y</i>	<i>z</i>	Brodmann's area	cc	<i>x</i>	<i>y</i>	<i>z</i>
Left temporal cortex										
AG	BA 22	0.72	-53	-20	6	—	—	—	—	—
AT	BA 37	0.65	-44	-59	-11	—	—	—	—	—
AT	BA 21	0.65	-48	-46	3	—	—	—	—	—
CS	BA 21	0.65	-52	-50	7	—	—	—	—	—
CS	BA 37	0.54	-50	-63	-8	—	—	—	—	—
JS	BA 21	0.54	-45	-45	8	—	—	—	—	—
LJ	BA 22	0.68	-40	-46	17	BA 22	0.64	-41	-46	17
WN	BA 21/37	0.56	-49	-45	-8	BA 21/37	0.63	-55	-44	-8
WN	BA 22	0.57	-56	-17	8	—	—	—	—	—
WN	BA 37	0.68	-43	-63	-9	—	—	—	—	—
Pooled	BA 37	—	-46	-60	-10	—	—	—	—	—
Pooled	BA 21	—	-46	-46	3	—	—	—	—	—
Left prefrontal cortex										
AG	BA 46	0.7	-33	35	11	BA 45	0.62	-26	22	6
AG	BA 9	0.8	-39	12	37	BA 9	0.71	-38	17	33
AT	BA 6/8	0.7	-42	4	36	BA 6/8	0.68	-43	5	34
AT	BA 9	0.7	-38	21	20	BA 9/45	0.81	-43	24	18
CS	BA 45	0.8	-40	26	13	BA 45	0.64	-39	38	6
CS	BA 9	0.8	-46	21	28	BA 9	0.74	-44	21	28
JS	BA 45	0.7	-43	20	4	BA 45	0.71	-36	28	15
JS	BA 6/8	0.8	-36	5	36	—	—	—	—	—
LJ	BA 44	0.9	-36	10	30	BA 44	0.76	-31	8	32
LJ	BA 45/46	0.8	-37	26	12	BA 45	0.79	-34	19	23
WN	BA 45	0.8	-44	25	8	BA 45	0.78	-45	27	9
WN	BA 8	0.8	-43	8	37	BA 9/44	0.84	-37	12	25
Pooled	BA 45	—	-28	28	3	BA 45	—	-26	26	3
Pooled	BA 44	—	-36	8	31	BA 8	—	-42	11	33
Right and left occipital cortex										
AG	—	—	—	—	—	BA 19/37	0.31	39	-78	1
AG	—	—	—	—	—	BA 37	0.39	-45	-71	-3
AT	—	—	—	—	—	BA 37	0.47	37	-73	4
CS	—	—	—	—	—	BA 37	0.48	-42	-65	-4
LJ	—	—	—	—	—	BA 19/37	0.36	34	-76	0
LJ	—	—	—	—	—	BA 19/37	0.52	-39	-78	0
WN	—	—	—	—	—	BA 37	0.33	50	-64	4
WN	—	—	—	—	—	BA 37	0.3	-45	-70	3
Pooled	—	—	—	—	—	BA 37	—	40	-73	2
Pooled	—	—	—	—	—	BA 37	—	-43	-71	-1

Note. Individual subjects are denoted by their initials. "Pooled" refers to the pooled dataset. Parietal activations were not tabulated.

acter and picture comparison, these changes were seen in a majority of participants and a majority of temporal locations. With English words, there was no significant difference between words and pictures in the prefrontal regions at the pooled level of analysis. In the lateral occipital region, signal change was greater in the picture semantic condition (Figs. 2b and 2e).

Word and Character Semantic Processing

There was a spatial overlap in the locations of peak activation for character and word semantic processing in all the areas where activation was present (Table 4), but overall, activation was more extensive during character semantic processing. Within-group analysis of

time courses in the left prefrontal ROI showed greater BOLD signal change in the character semantic condition. At the individual level these differences appeared to parallel the participant's relative performance in the two languages (data not shown).

Effects Across Experiments

When normalized percent signal change data from ROIs in the left prefrontal, left posterior temporal and lateral occipital regions were combined for analysis, significantly higher BOLD signal was observed for character and word semantic processing compared to pictures for the posterior temporal region

TABLE 3
Word and Picture Semantic Comparisons

Subject	Words					Pictures				
	Brodmann's area	cc	x	y	z	Brodmann's area	cc	x	y	z
Left temporal cortex										
IL	BA 21	0.54	-56	-49	-4	BA 21	0.55	-56	-49	-5
KY	BA 37	0.71	-39	-64	-10	—	—	—	—	—
KY	BA 21	0.6	-48	-53	4	—	—	—	—	—
LL	BA 21	0.57	-55	-48	-4	—	—	—	—	—
RH	BA 21	0.72	-37	-41	-4	—	—	—	—	—
RH	BA 21	0.61	-51	-40	7	—	—	—	—	—
YZ	BA 37	0.49	-43	-57	-16	—	—	—	—	—
YZ	BA 21	0.71	-49	-49	0	—	—	—	—	—
YZ	BA 21/22	0.67	-50	-28	0	—	—	—	—	—
Pooled	BA 37	—	-41	-63	-12	BA 21	—	-41	-66	-2
Pooled	BA 21	—	-48	-47	3	BA 21	—	-50	-50	-4
Left prefrontal cortex										
IL	BA 9	0.76	-42	12	33	BA 9	0.79	-40	16	32
KY	BA 45	0.59	-41	19	7	BA 45	0.72	-44	19	22
KY	BA 44	0.76	-44	17	25	BA 8	0.58	-38	9	30
LD	BA 45	0.72	-35	26	17	BA 45	—	-33	28	16
LD	BA 6/8	0.74	-30	6	34	BA 6	0.71	-28	8	32
LL	BA 9/44	0.79	-41	12	31	BA 8	0.72	-41	15	33
RH	BA 9/44	0.73	-37	7	30	BA 8	—	-41	6	30
YP	BA 6/8	0.71	-41	10	43	BA 8	0.71	-41	12	41
YZ	BA 9	0.72	-42	31	17	BA 9	0.66	-41	29	17
YZ	BA 6	0.72	-32	1	40	BA 9	0.68	-34	2	39
Pooled	BA 45	—	-43	19	5	BA 45	—	-38	30	9
Pooled	BA 8	—	-36	10	32	BA 8	—	-39	11	34
Right and left occipital cortex										
IL	—	—	—	—	—	BA 37	0.54	42	-72	-7
IL	—	—	—	—	—	BA 19/37	0.32	-40	-74	-6
KY	—	—	—	—	—	BA 19/37	0.33	35	-76	4
KY	—	—	—	—	—	BA 37	0.42	-40	-68	2
LL	—	—	—	—	—	BA 37	0.42	39	-65	-1
RH	—	—	—	—	—	BA 37	0.58	41	-70	2
RH	—	—	—	—	—	BA 19/37	0.6	-41	-75	4
YP	—	—	—	—	—	BA 37	0.5	41	-67	-12
YP	—	—	—	—	—	BA 37	0.41	-44	-70	-5
YZ	—	—	—	—	—	BA 37	0.5	40	-69	-3
YZ	—	—	—	—	—	BA 37	0.48	-36	-68	-4
Pooled	—	—	—	—	—	BA 37	—	40	-70	-4
Pooled	—	—	—	—	—	BA 37	—	40	-66	-4

Note. Individual subjects are denoted by their initials. "Pooled" refers to the pooled dataset. Parietal activations were not tabulated.

(Table 5). Significantly higher BOLD signal was observed in both left and right occipital regions for the picture semantic task compared to either character or word processing. The left prefrontal region showed significantly higher BOLD signal change for characters compared to pictures but not when characters were compared to words or when words were compared to pictures.

DISCUSSION

We found that character, word, and picture semantic processing relative to their respective size judgement tasks activate a common network that includes the left

prefrontal (BA 9, 44, 45), left posterior temporal (BA 21, 22), left fusiform gyrus (BA 37), and the left parietal region (BA 7). However, there was selectively more BOLD signal change in the left middle temporal gyrus/superior temporal sulcus (BA 21/22) for character semantic processing compared to picture semantic processing. There was more signal change in the right occipital and to a lesser extent, left occipital region (BA 19/37; temporal-occipital in some publications) during picture semantic processing. The key finding in this study is that while character and picture processing activate many common areas, there are modality dependent differences in activation. Chinese character semantic processing shares greater similarities with

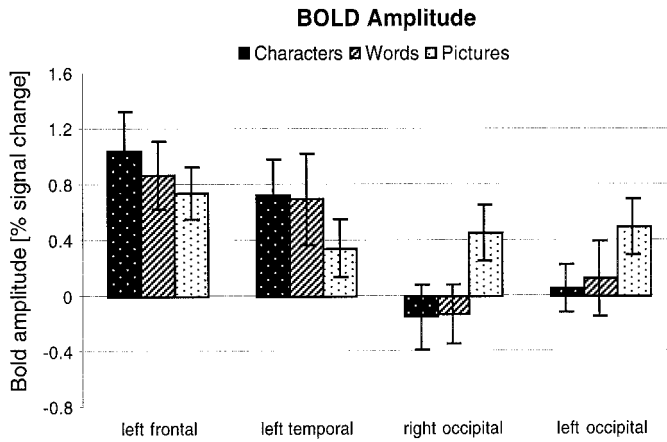


FIG. 5. Bar plot with error bars showing the mean and standard deviation of BOLD signal change in the left prefrontal, left temporal, and lateral occipital regions as a function of task. The data on which the plots were based was pooled across all three experiments (see Table 5).

English word semantic processing than with picture semantic processing.

In the present study, the left temporal region activated by the semantic processing of characters (and words) is similar to that reported in a semantic comparison task using fMRI (Thompson-Schill *et al.*, 1997) but lies about 1.6 cm posterior to that reported in the Vandenberghe study. Although all these studies test semantics, the use of different investigative modalities

(fMRI vs PET) as well as the specific choice of items used may have affected the location of temporal activation via category effects (Moore and Price, 1999). While we cannot be certain that identical processing modules are revealed in the different studies, we note that the word specific effect for the left mid/posterior temporal region has been replicated for character processing. In addition to semantic access, activation of the posterior portion of the left middle and superior temporal gyri has been related to phonological processing of words (Bavelier *et al.*, 1997; Bookheimer *et al.*, 1995; Demonet *et al.*, 1992; Fiez and Petersen, 1998). Behavioral studies demonstrate that access to meaning for English words (Van Orden *et al.*, 1988) as well as Chinese characters (Perfetti and Tan, 1998) involves obligatory phonological processing. Picture naming, according to one model, takes place after accessing structural descriptions and semantic representations of the object (Humphreys *et al.*, 1999). An alternative explanation for the higher activation with characters/words is that somehow the task is more difficult given the differential in accuracy favoring picture semantic judgement. This "difficulty" cannot be directly related to the choice of task items, since identical items in picture and character (or word) form were used in each subject. As such, it is likely that modality-related differences in processing routes account for the higher activation. Specifically, we propose that the greater left posterior temporal activation for words reflects

TABLE 4

Character and Word Semantic Comparisons

Subject	Characters					Words				
	Brodmann's area	cc	x	y	z	Brodmann's area	cc	x	y	z
Left temporal cortex										
CM	BA 21	0.48	-44	-50	-7	BA 21	0.48	-44	-50	-7
CW	BA 22	0.67	-59	-45	10	BA 22	0.73	-59	-44	8
CW	BA 37	0.53	-41	-54	-13	BA 37	0.52	-41	-54	-13
KR	BA 21	0.52	-39	-55	-3	BA 21	0.53	-38	-55	-4
KR	BA 37	0.6	-48	-66	-18	BA 37	0.55	-46	-64	-17
ZX	BA 21	0.68	-56	-47	-2	BA 21	0.61	-48	-43	-5
ZX	BA 21	0.6	-57	-19	4	—	—	—	—	—
Pooled	BA 37	—	-41	-56	-15	BA 37	—	-41	-53	-10
Pooled	BA 21	—	-56	-48	-1	BA 21	—	-60	-48	-1
Left prefrontal cortex										
CM	BA 45	0.41	-28	26	13	BA 45	0.46	-31	27	13
CM	BA 6	0.82	-37	8	38	BA 6	0.72	-39	8	39
CW	BA 9	0.72	-42	15	28	BA 9	0.78	-40	17	26
CW	BA 45	0.52	-36	17	8	BA 45	0.78	-41	23	17
KR	BA 9	0.81	-41	10	36	BA 9	0.8	-41	11	35
YK	BA 9	0.52	-40	23	21	BA 9	0.56	-38	21	21
ZX	BA 45	0.82	-41	27	17	BA 45	0.83	-42	25	17
ZX	BA 9	0.83	-37	9	38	BA 9	0.85	-35	11	36
Pooled	BA 9	—	-42	13	35	BA 9	—	-44	16	36
Pooled	BA 9	—	-44	16	36	—	—	—	—	—

Note. Individual subjects are denoted by their initials. "Pooled" refers to the pooled dataset. Parietal activations were not tabulated.

TABLE 5
BOLD Signal Change as a Function of Task

	Characters			Words			Pictures		
	BOLD	SD	<i>N</i>	BOLD	SD	<i>N</i>	BOLD	SD	<i>N</i>
Left prefrontal	1.04	±0.29	11	0.88	±0.24	11	0.74	±0.19	12
Left temporal	0.73	±0.25	10	0.70	±0.33	10	0.35	±0.20	12
Right occipital	-0.15	±0.24	4	-0.13	±0.21	6	0.46	±0.20	10
Left occipital	0.06	±0.17	4	0.13	±0.27	5	0.50	±0.20	9

	Characters-Words		Characters-Pictures		Words-Pictures	
	Difference	<i>P</i> value	Difference	<i>P</i> value	Difference	<i>P</i> value
Left prefrontal	0.17	0.161	0.30*	0.009	0.14	0.149
Left temporal	0.03	0.806	0.38*	0.001	0.35*	0.011
Right occipital	-0.02	0.908	-0.61*	0.007	-0.59*	<0.001
Left occipital	-0.07	0.642	-0.44*	0.005	-0.37*	0.034

Note. "BOLD" refers to mean percentage signal change derived from "*N*" subjects data; "difference" refers to the difference in mean BOLD signal between the two conditions contrasted in that column. Paired *t* tests were performed on each pair of differences.

enhanced access to phonological representations in comparison to that required for picture processing (Vandenberghe *et al.*, 1996).

We demonstrated a predominantly right occipital effect for picture semantic processing compared to either word or character semantic processing. Vandenberghe *et al.* reported that this area was more active for all picture tasks compared to word tasks but that it did not specifically relate to semantic processing. The basis for the difference is that in the present study no differences emerged when the size judgement tasks were directly compared. In a similar study where picture semantics were of interest, activation of this occipital region was highest during semantic judgement, intermediate with size judgement and lowest with a perceptual task (Ricci *et al.*, 1999). As such enhanced activation of picture-specific structural descriptions may underlie the observed modulation of occipital activation.

That characters are processed like words, relating more to lexical processing than object recognition is in agreement with case reports showing that character processing can remain intact when picture processing is impaired (Hu *et al.*, 1986; Weekes *et al.*, 1997). The experimental design used here does not allow us to address the issue as to whether modality specificity exists at the presemantic or semantic levels if indeed such a distinction exists.

The colocalization of peak activation for Chinese characters and English words in the left perisylvian cortex, lends further support to the idea that lexico-semantic processing may be independent of script in fluent or relatively fluent bilinguals (Chee *et al.*, 1999a, 1999b). Parallel evidence from studies on the Japanese language inform us that there may be word-category specific differences in locus of activation (Kansaku *et*

al., 1998). However differences do not exist between Kanji and Kana word naming (Koyama *et al.*, 1998) nor between visual processing of Kanji characters and English words (Uchida *et al.*, 1999).

Character compared to word processing was associated with greater BOLD signal change in the left prefrontal areas and a possible inference is that character meaning is more difficult to access. Even though some subjects first used Mandarin (Chinese) in childhood, the study cohort is more fluent in English as reflected by the behavioral data. As such, conceptual links between English words and the concepts they represent are probably stronger than conceptual links for Chinese characters (Kroll and deGroot, 1997). In preliminary data obtained from studying citizens of the People's Republic of China, left prefrontal BOLD signal change was equal or slightly greater during English word processing compared to Chinese. Modulation in left prefrontal activation relating to relative fluency resembles that of word frequency for English readers (Fiez *et al.*, 1999).

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