NeuroImage

www.elsevier.com/locate/ynimg
NeuroImage 23 (2004) 975–982

Semantic processing of Chinese in left inferior prefrontal cortex studied with reversible words

John X. Zhang,[a,*] Jie Zhuang,[a] Lifei Ma,[b] Wei Yu,[c] Danling Peng,[d] Guosheng Ding,[d] Zhaoqi Zhang,[c] and Xuchu Weng[b]

[a]*Department of Linguistics, The University of Hong Kong, Hong Kong*
[b]*Laboratory for Higher Brain Function, Institute of Psychology, Chinese Academy of Sciences, Beijing 100101, China*
[c]*Anzhen Hospital, Beijing, China*
[d]*Institute of Cognitive Neuroscience and Learning, Beijing Normal University, Beijing, China*

Received 21 January 2004; revised 11 June 2004; accepted 2 July 2004
Available online 13 October 2004

This study utilized fast event-related fMRI with reversible words to examine the role of left inferior prefrontal cortex (PFC) in semantic processing of Chinese. As a special linguistic phenomenon in Chinese, a reversible word is a two-character word (AB) that, when read from right to left (BA), opposite to the normal left to right reading direction, is also a real word. The two words, AB and BA, can have very different meanings. Fourteen native Chinese saw a reversible word (BA) and were asked to read it backward silently to obtain the meaning of AB, defined as the target meaning. They then saw two test words and decided which of the two was semantically related to the target meaning. Activity in a subregion of BA47 was found to be modulated by the extent to which irrelevant semantic activation of the distractor word BA interfered with semantic retrieval of the target word AB. This finding demonstrated the involvement of the left inferior PFC in the control processes of semantic retrieval in Chinese. In addition, comparing conditions using reversible with that using nonreversible words, we found evidence suggesting a semantic/phonological functional subdivision in left inferior PFC, consistent with that in English.

Keywords: Semantic retrieval; Executive control; Phonological processing; fMRI

Introduction

One of the robust findings in neuroimaging research over the past decade is the involvement of the left inferior prefrontal cortex (PFC) in semantic processing (Buckner et al., 2000; Copland et al., 2003; Demb et al., 1995; Fiez, 1997; Gabrieli et al., 1998; Kapur et al., 1994; Petersen et al., 1988; Poldrack et al., 1999; Thompson-Schill et al., 1997; Wagner et al., 2000, 2001). Both the temporal lobe and the frontal lobe seem to be involved in the semantic processing network; however, it is generally agreed that the left inferior PFC has a domain-general role for executive control in semantic retrieval (Bookheimer, 2002; Copland et al., 2003; Fletcher and Henson, 2001; Thompson-Schill, 2003). There have been different ways to characterize such executive processes, such as the selection hypothesis (Fletcher et al., 2000; Thompson-Schill et al., 1997) and the guided control hypothesis (Wagner et al., 2001). A related issue is whether this area represents a specific mechanism for semantic retrieval per se or can be generalized to a wider context (Thompson-Schill et al., 1997, 1998). Recently, a metaanalysis suggests a functional subdivision in left inferior frontal gyrus (IFG) so that an anterior, inferior portion of left IFG in Brodmann area 47 was hypothesized to be responsible for semantic processing and a posterior, superior portion of left IFG in Brodmann area 44/45 for phonological processing (Bookheimer, 2002; see also Poldrack et al., 2001).

Most studies on this topic have been with English, an alphabetical language. There have been only a few studies with semantic tasks in Chinese, which, in contrast to English, is a pure logographic script. With a Pyramids and Palm Trees (PPT) paradigm, Chee et al. (2000, 2001) found left middle frontal gyrus (BA9/44) and left inferior frontal gyrus (BA45) activation in a semantic judgment task, and the activation pattern was comparable for both Chinese character stimuli and English word stimuli. Tan et al. (2000, 2001a), using semantic generation and semantic-relatedness judgment tasks, reported strong activation in left middle frontal gyrus BA9 for Chinese words, with weak left inferior frontal activations. The mixed results may be due to the fact that Chee et al. used bilingual subjects and Tan et al. used native Chinese speakers. Apparently, more evidence is needed to examine whether semantic processing involves similar neural correlates across languages with distinct linguistic structures, such as English and Chinese.

In studies of semantic processing, a semantic task is often contrasted with a nonsemantic control task, such as passive viewing

* Corresponding author. Fax: +852 2549 6253.
E-mail address: jxzhang@hku.hk (J.X. Zhang).
Available online on ScienceDirect (www.sciencedirect.com.)

1053-8119/$ - see front matter © 2004 Elsevier Inc. All rights reserved.
doi:10.1016/j.neuroimage.2004.07.008

or size judgment. However, given that the activation of phonology, orthography, and semantics is highly interrelated in reading Chinese, such comparisons, as pointed out by Tan and Siok (2003), may not highlight activations specific to the semantic component. In addition, semantic processing may be modulated by the level of demand for executive control so that automatic semantic retrieval may not always involve a strong activation of the left inferior PFC (Wagner et al., 2001). With these considerations, in the present study, we took advantage of a unique feature of Chinese to manipulate the level of semantic interference and compared two semantic tasks differing in their demand for control processes.

The basic unit in the Chinese script is monosyllabic characters. Words are represented either by a single character or by a combination of two or more single characters. Two-character words account for a predominant 64% of the total vocabulary. A curious phenomenon from such word construction is the existence of a special category of two-character word pairs that differ only in the order of their constituting characters. For example, 领带 (tie) and 带领 (guide), composed of the same two characters, have quite different meanings. These words are called reversible words as one gets a legitimate word by reading either from the normal left to right direction (forward reading) or from the reversed right to left direction (backward reading). Analogous constructs do not exist in English. For example, toady [t∂u’di] and ditto [di’t∂u] look like containing the same two syllables in reversed order. However, the vowel qualities change as they shift from a stressed to an unstressed syllable. Reversible words have been used in behavioral studies but not in imaging studies (Peng et al., 1999; Taft et al., 1999).

As shown in the left two columns in Fig. 1, we presented participants with a reversible word (called the target item for easy reference) in each trial and asked them to read the word backward, that is, from right to left, to get the corresponding meaning (note the direction in everyday Chinese reading is always from left to right). For example, when seeing the word 领带 (meaning tie), participants should read it as 带领 (meaning guide) and focus on “guide” as the relevant target meaning while ignoring “tie” as the irrelevant distractor meaning. They then saw two test words, one on each side, and had to decide which word was semantically related to the target meaning. We distinguished between a “High-conflict” (left column) and a “Low-conflict” condition (middle column). In both conditions, one of the test words signified the correct response; that is, it was semantically related to the target meaning. The other test word, however, was semantically related to the distractor meaning in the High-conflict condition but unrelated to the distractor meaning in the Low-conflict condition.

When retrieving the meaning of the presented word in its backward order, participants were subject to interference from the automatic semantic activation of the word in its forward order, which was the normal reading direction. Relative to the Low-conflict condition, such interference was stronger in the High-conflict condition since the incorrect test word would be more likely to prime an incorrect response given that it was semantically

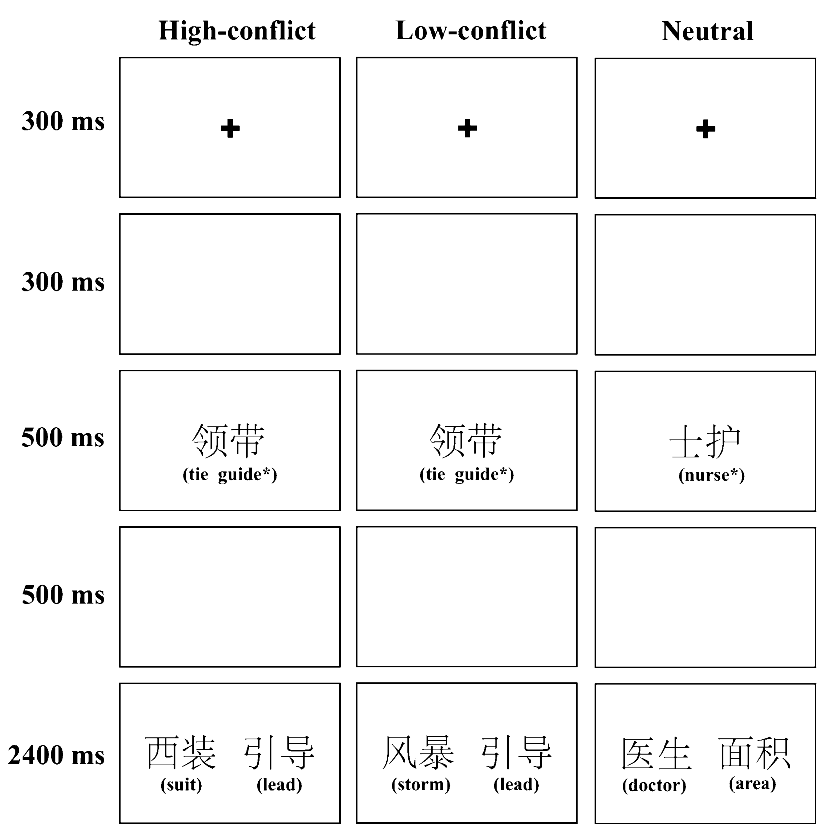

Fig. 1. Illustration of the experimental task. Following a fixation, participants saw a target item and read it from right to left to obtain the backward meaning, referred to as the target meaning. They then saw two test words and decided whether the left or the right one was semantically related to the target meaning and pressed a key on the corresponding side. The bracketed English words, not present in real experiment, indicate the meaning of the above items when read forward (no asterisk) and backward (with asterisk). The forward meaning of the target item, 领带 (tie) was semantically related to the incorrect test word, 西装 (suit), in the High-conflict condition but unrelated to the incorrect test word, 风暴 (storm), in the Low-conflict condition. For the neutral condition, the forward reading of the target item was a nonword.

related to the distractor meaning. Therefore, for the High-conflict condition, we expected that there was an increased demand for selecting the correct meaning as relevant for semantic retrieval (Thompson-Schill et al., 1997) or increased demand for guiding the retrieval process in the presence of heightened distraction (Wagner et al., 2001). Consequently, if the left inferior PFC were involved in the executive control process of semantic retrieval in Chinese, as in English, we would expect this region to be more activated in the High-conflict condition, compared to the Low-conflict condition.

Previous literature indicates that, when our participants read the reversible words in their backward order, in addition to automatic semantic activation, there is obligatory phonological activation of the words in their forward order as well (Perfetti and Tan, 1999; Tan and Perfetti, 1997, 1999). This provided an opportunity to test whether the Bookheimer (2002) hypothesis regarding the involvement of the superior/posterior subregion of left inferior PFC (BA44/45) in phonological processing applies to Chinese.

To this end, we added a third "Neutral" condition using nonreversible words. An example was shown in Fig. 1, right column. As in the two conditions with reversible words, participants first read a two-character item 士护 backward to obtain the relevant target meaning, that is, 护士 (nurse), and then made semantic-relatedness judgment upon seeing the two test words. However, here, the two-character item was not a reversible word: its backward reading was a real word, but its forward reading was a pseudoword.

In the High- and Low-conflict conditions, although our participants were required to focus only on the backward reading of the presented word, the forward form of the word, given that it was in the normal reading direction, would still lead to automatic activation of its corresponding phonological representations. Such representations, however, would not exist for the presented target item in the Neutral condition because it was not a real word when reading from left to right. Therefore, more automatic phonological processing should occur in the reversible word conditions (i.e., the High- and Low-conflict conditions) than in the nonreversible word condition (i.e., the Neutral condition).[1] Briefly, if the Bookheimer (2002) hypothesis was true for Chinese, we expected to see greater activation in the posterior/superior region of left inferior prefrontal cortex in the former conditions relative to the latter condition.

Methods

Pilot study

A group of 20 native Chinese speakers (15 female, mean age 22.3 years, age range 20 to 27 years) participated in a pilot study to test the task design. There were three types of trials, for the High-conflict, the Low-conflict, and the Neutral conditions, respectively. Each participant, following practice, completed six blocks of 24 trials. Within each block, there were eight trials for each trial type, randomly intermixed.

Shown in Fig. 1, each trial started with a fixation cross on for 300 ms and then off for another 300 ms, followed by a two-character item presented for 500 ms. Participants were required to silently read the item backward (from right to left), which would always be a real word and obtain the corresponding meaning, that is, the target meaning. They then saw two test words, one to each side of the screen center and had to decide which one was semantically related to the target meaning. They pressed their left or right index finger depending on whether the left or the right test word was the correct choice. They made their response within a 1.5-s time window following test words onset. Following the response window, there was a 0.9-s blank screen, which turned off the test words. The length of each trial was 4 s. A fixed intertrial interval (ITI) of 1.5 s was used. Each character in the presented two-character items was $1.5° \times 1.5°$ in visual angle with a center-to-center distance of 2.0°. The center-to-center distance between the left and the right test words was 5.5°. The stimuli were presented on a 17-in. monitor.

The stimulus set included 40 reversible words (mean word frequency 11.81 per million with a standard error of 2.95) and 40 neutral words (mean word frequency 11.76 per million with a standard error of 3.00). For each participant, 20 reversible words were randomly taken from the pool of 40 items and used in the High-conflict condition. The remaining 20 were used in the Low-conflict condition. As the reversed reading of a reversible word is also a reversible word itself, for better counterbalancing, for each reversible word, we used either its forward reading or its backward reading as the target item with equal probability across participants. Such counterbalancing produced balanced frequency values across all participants for the forward and the backward readings of the reversible items (11.84 per million vs. 11.78 per million). The strength of semantic association between the target meaning and the correct test word was also comparable and thus counterbalanced across the reversible words and the neutral words [3.40 vs. 3.49, two-tailed paired t test, $t(9) = 0.90$, $P = 0.4$], as judged by an independent group of 10 native Chinese speakers on a 1 to 5 scale (1 for remotely semantically related and 5 strongly semantically related).

Mean accuracy and RT (reaction time) were 88.5% and 780 ms. Item analyses indicate that the High-conflict condition was significantly worse than the Low-conflict condition [mean error rate, 23.6%, SE = 1.7 vs. 7.1%, SE = 1.0, $t(39) = 9.70$, $P < 0.0000$; mean RT, 837 ms, SE = 15.4 vs. 781 ms, SE = 13.8, $t(39) = 2.86$, $P < 0.01$]. The Low-conflict condition was significantly worse than the Neutral condition [mean error rate, 7.1%, SE = 1.0 vs. 3.8%, SE = 0.7, $t(78) = 2.73$, $P < 0.01$; mean RT, 781 ms, SE = 13.8 vs. 723 ms, SE = 9.8, $t(78) = 3.42$, $P < 0.001$]. The High-conflict condition was also significantly worse than the Neutral condition [mean error rate, $t(78) = 10.55$, $P < 0.0001$; mean RT, $t(78) = 6.20$, $P < 0.0001$]. There were two different degrees of freedom, 39 and 78 in these tests. This was because the first two were paired t tests in which the same group of 40 items, that is, reversible words, was used in both the High-conflict and the Low-conflict conditions (across subjects but not within each individual subject), whereas the others were two-sampled t tests in which two different groups of 40 items, that is, reversible and nonreversible words, were used in the Low-conflict condition and the Neutral condition, respectively.

Participants

Fourteen native Chinese speakers (five female, mean age 22.5 years, age range 19 to 25 years) participated in the imaging study. None of them participated in the pilot study. All were strongly right-handed as judged by a handedness inventory (Snyder and

[1] There should also be more semantic processing in the reversible word conditions (i.e., the High- and Low-conflict conditions) than in the nonreversible word condition (i.e., the Neutral condition). Please refer to the Discussion section.

Harris, 1993). Informed consent was obtained in accordance with guidelines from the Institute of Psychology of China.

Imaging procedure

The task was the same as in the pilot study. The design was a fast event-related design. After some practice trials, participants went in the scanner and completed five functional runs. Excluding the first five dummy scans, each run was 5 min and 4 s long, containing 152 scans (TR = 2 s) or 3D volumes. Among these 152 scans, the first and the last 16 were for resting periods in which participants passively viewed a central fixation. The middle 120 scans were for a test period of 24 trials, 8 for each condition. The ITI was pseudorandomized with a mean length of about 6 s and a range from 2 to 12 s. Due to limited scan time, the stimulus set was reduced to 32 items from the 40 items in the pilot study.

Imaging was conducted on a 1.5 T Siemens SONATA MRI scanner at Anzhen Hospital of Capital Medical University (Beijing, China). Twenty axial slices covering the whole brain were acquired with a T2*-weighted gradient-echo EPI pulse sequence (TR = 2000 ms, TE = 60 ms, flip angle = 90°) for the functional scans (acquisition matrix 64 × 64, FOV = 19.2 × 19.2 cm, slice thickness = 5 mm, skip = 1 mm). Coplanar anatomical images (acquisition matrix 256 × 256) were acquired with a T1-weighted spin echo pulse sequence (TR = 442 ms, TE = 15 ms).

Participants lay supine inside the scanner and were fit with plastic ear-canal molds. Their head was restrained with pillows and a tape running across their forehead. They were also told to keep their head still when doing the task inside the scanner. Participants made their responses with a button box. All visual stimuli were white on a black background, projected onto a screen positioned at the front of the magnet bore opening. The screen was made visible to the participants through a mirror mounted above their eyes on a head coil. Stimulus presentation was controlled with a PC computer using the *Inquisit* software package from Millisecond Inc. (http://www.millisecond.com).

Imaging analysis

Image analysis was conducted with the *SPM2* package (Wellcome Department of Cognitive Neurology, London). Functional images from each participant were slice acquisition-corrected, motion-corrected, and coregistered to the coplanar anatomical image from that participant. The T1 images were normalized to the standard SPM/MNI template with the transformation matrix applied to the coregistered functional images. Such normalized functional images, interpolated to 3-mm isotropic voxels and spatially smoothed with a Gaussian filter (6-mm kernel), were entered into a regression analysis using the general linear model for event-related designs in *SPM2* (Friston et al., 1995).

In constructing regressors for multiple regression, each trial was modeled with a square-waved epoch of two TRs, convolved with the canonical hemodynamic response function in SPM. Three regressors were constructed for the High-conflict, the Low-conflict, and the Neutral conditions, respectively. Session-specific effects were modeled as confound variables, and low frequency noise in the signal was removed before the regression analysis.

Following the regression analysis, two linear contrasts were constructed, and subject-specific estimates of these contrasts were obtained. They were the High-conflict versus Low-conflict contrast, and the Low-conflict versus Neutral contrast. Only the Low-conflict but not the High-conflict condition was included in the second contrast to focus more on phonological processing but not semantic processing.

The contrast estimates were entered into a standard SPM second-level analysis with subject treated as a random effect, using one-sampled t test (df = 14 − 1). The expected mean difference value for the t tests was set to zero. A voxelwise intensity threshold (uncorrected $P < 0.005$) and a spatial extent threshold (cluster size greater than 20 voxels) were combined to control for multiple comparisons (Forman et al., 1995; Poline et al., 1997) in the generation of the t maps. All coordinates reported were in Talairach space converted from MNI space based on an algorithm at www.mrccbu.cam.ac.uk/Imaging/mnispace.html. Percentage of signal change was calculated by averaging the BOLD signal from all voxels in each identified region of activation, separated for different trial conditions and relative to the resting baseline.

Results

Behavioral results

Participants showed a similar performance pattern as in the pilot study. Overall mean accuracy and RT were 92.7% and 865 ms, slower but more accurate than the pilot group. The High-conflict condition was significantly worse than the Low-conflict condition [mean error rate, 17.6%, SE = 1.8 vs. 3.1%, SE = 1.0, $t(31) = 6.55$, $P < 0.0000$; mean RT, 907 ms, SE=10.9 vs. 884 ms, SE = 12.7, $t(31) = 1.32$, $P = 0.2$]. The Low-conflict condition was significantly worse than the Neutral condition [mean error rate, 3.1%, SE = 1.0 vs. 1.4%, SE = 0.4, $t(62) = 1.56$, $P = 0.1$; mean RT, 884 ms, SE = 12.7 vs. 804 ms, SE = 8.1, $t(62) = 5.13$, $P < 0.000$]. The High-conflict condition was also significantly worse than the Neutral condition [mean error rate, $t(62) = 8.63$, $P < 0.0001$; mean RT, $t(62)=7.28$, $P < 0.0001$]. The degrees of freedom were different for pilot study group and the scanned group because we used 40 items for the first group but 32 items for the second group. Subject analyses showed a pattern of results similar to that in item analyses.

Imaging results

Shown in Fig. 2 (top panel), the contrast between the High-conflict condition and the Low-conflict condition revealed a significant activation in left inferior prefrontal cortex at BA47. Comparing with the range of activations in the Bookheimer (2002) metaanalysis for semantic activation, $x = -33$ to -49, $y = 15$ to 34, and $z = -12$ to 30, the peak activation found here was at (−24, 22, −13), shifted towards the midline. The percentage signal change of the BOLD signal in this region is plotted in Fig. 3a for the two involved conditions. The homologous region in the right hemisphere was also activated with a reduced volume of activation (Table 1) but virtually identical percentage of signal change (Fig. 3a). Anterior cingulate was also found activated in this contrast. Shown in Fig. 2 (middle panel), the contrast between the Low-conflict condition and the Neutral condition revealed two significant activations, both in left inferior prefrontal cortex, one at BA44/45 and the other at BA47. The percentage signal changes of the BOLD signal in these two regions are plotted in Fig. 3b for the two involved conditions. Summary information about these activations is reported in Table 1. Activation in the High-conflict versus Neutral contrast included all four activated regions in the

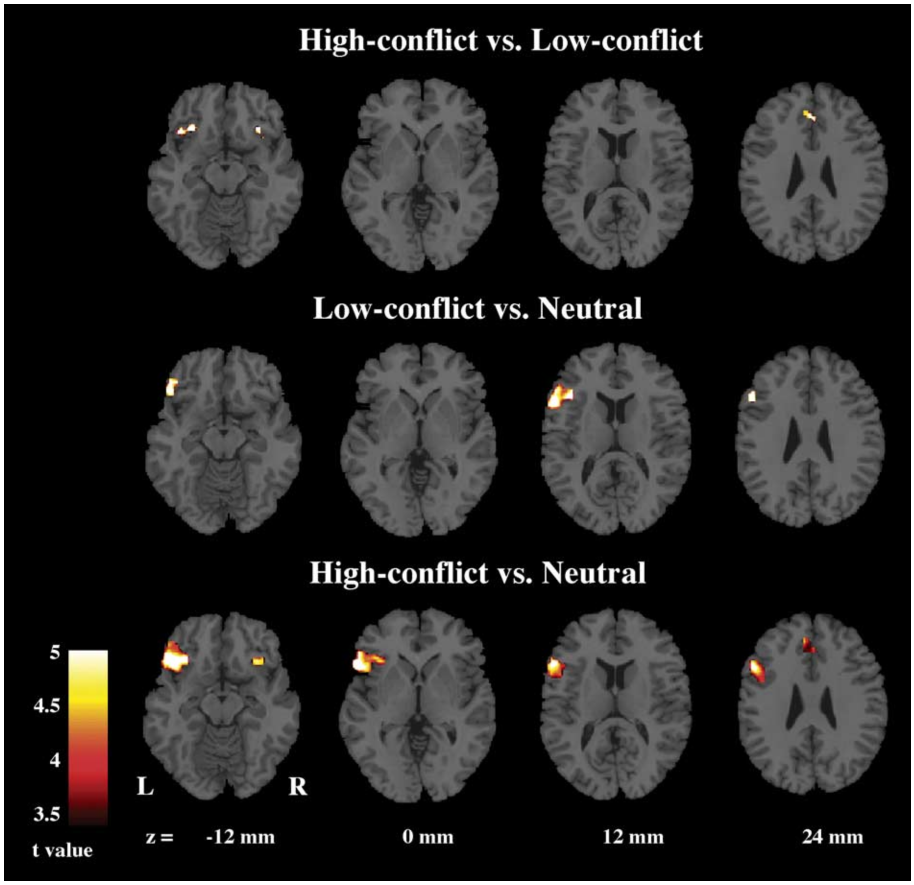

Fig. 2. Axial t maps of brain activation ($P < 0.005$, minimum 20 contiguous voxels) for the High-conflict versus Low-conflict comparison (top), the Low-conflict versus Neutral comparison (middle), and the High-conflict versus Neutral comparison (bottom). The images were superimposed on a standard SPM anatomical template brain in neurological convention with z coordinate for each slice shown in Talairach space.

above two contrasts, with greater spatial extents (Fig. 2, bottom panel). For any of the three contrasts, no other brain regions were found significantly activated. Nor did any region show any significant suppression.

Discussion

Consistent with participants' posttest interview report, performance was significantly poorer in the High-conflict condition than in the Low-conflict condition. This indicates that varying the semantic relatedness of the incorrect test word with the automatically activated distractor meaning of the reversible word did manipulate the level of interference in this semantic judgment task. Accompanying this behavioral difference, the contrast between the High-conflict and the Low-conflict conditions revealed a significant activation in the left inferior PFC.

We take this result as the critical finding of the present study. It strongly suggests that the left inferior prefrontal cortex, as in English, is associated with the control processes in semantic processing in Chinese. As discussed in the introduction, the imaging literature on semantic processing of Chinese is small with some study reporting weak left inferior PFC activity. We were able to demonstrate a clear left inferior PFC activation in the present study as the two conditions we contrasted were both semantic tasks, which were highly comparable in visual stimulation, overall amount of semantic activation, and general response requirements. The manipulation to vary the level of interference tapped into control processes, the core function attributed to the left inferior prefrontal cortex in semantic processing (Bookheimer, 2002; Buckner et al., 2000; Gabrieli et al., 1998; Thompson-Schill et al., 1997; Wagner et al., 2001). The irrelevant meaning of the reversible words in its forward order competed for response in the High-conflict condition but not in the Low-conflict condition. This competition may be resolved either through a selection mechanism to separate the relevant from the irrelevant meaning representations (Thompson-Schill et al., 1997; Zhang et al., 2004) or through a guided control mechanism to bias the retrieval process to be more specific to the relevant meaning representation (Wagner et al., 2001).

The contrast between the High-conflict and the Low-conflict conditions also revealed a right inferior frontal activation, homologous to the left BA47 activation, suggesting the involvement of the right hemisphere in the semantic processing of Chinese. No strong claim, however, is made about this result as related findings in the literature have been mixed. For example, Tan et al. (2000) found both left and right BA47 activation in a semantic-relatedness judgment task, but only when the items used were two-character Chinese words. When the items were single-character words with precise meaning, the left but not the right BA47 was activated. When the items were single-character words with vague meaning, neither the left nor the right BA47 was activated. Tan et al. (2001b) found right but not left BA47

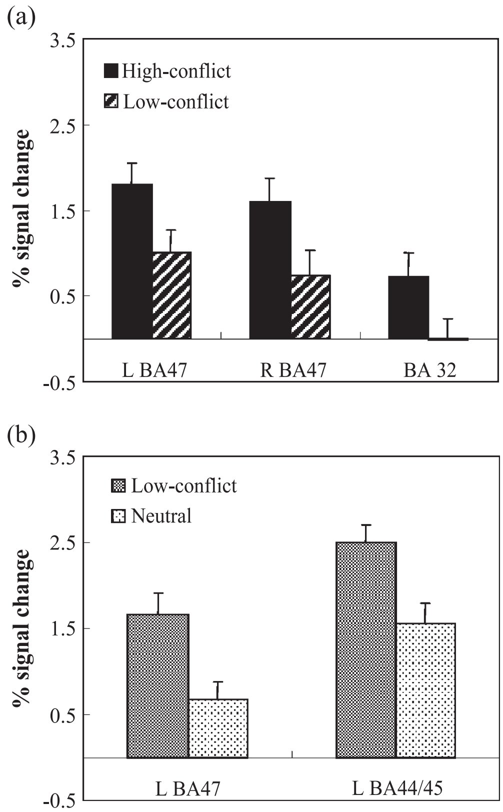

Fig. 3. Mean percentage BOLD signal change in activated regions for (a) left BA47, right BA47, and BA32 in the High-conflict and the Low-conflict conditions; and (b) left BA47 and left BA44/45 in the Low-conflict and the Neutral conditions.

activation in a semantic task with single-character Chinese words. Chee et al. (2000, 2001) used both single-character and two-character Chinese words in semantic tasks but reported neither left nor right BA47 activation.

The anterior cingulate also showed greater activity in the High-conflict condition than in the Low-conflict condition. This area has been generally recognized to be responsible for conflict monitoring (Botvinick et al., 1999; Carter et al., 1998). Therefore, its activation signifies the different levels of interference/conflict in the response phase across the two conditions. This is consistent with our assumption that more control processes were recruited to overcome the greater semantic interference in the High-conflict condition, relative to the Low-conflict condition.

If BA47 is involved in semantic processing, as we hypothesize here, one may expect the BOLD signal in this region for the High-conflict condition (relative to the Low-conflict condition) to be correlated with participants' performance, that is, reaction time and/or accuracy in the same condition (also with the Low-conflict condition as the reference condition). However, failing to support this expectation, such correlations did not reach significance level ($P > 0.1$) for either left or right BA47. One interpretation is that, since the High-conflict and the Low-conflict conditions are highly comparable, differences across the two, with either the BOLD signal measure or the performance measure, may not have enough range of variation to expose the correlation between the two measures, even if they do exist. When we used the Neutral condition (as opposed to the Low-conflict condition) as the reference condition, a significant correlation was found between the fMRI signal and the RT data for the High-conflict condition in left BA47 ($r = 0.53$, $P < 0.05$). Presumably, differences between the High-conflict and the Neutral conditions offer more cross-subject variations.

As we discussed in the introduction, contrast between the Low-conflict and the Neutral conditions, consistent with the significant performance differences between the two, should reveal regions associated with increased phonological processing in the former condition than in the latter condition. Such a contrast indeed identified activation in a more posterior/superior part of the left inferior frontal cortex at BA44/45. Critically, this region fell within the spatial cluster range hypothesized for phonological processing in the metaanalysis of Bookheimer (2002).

The same contrast also identified a second activation, located in the left inferior PFC, more anterior and inferior at BA47. This region fell within the spatial cluster range for semantic processing in the Bookheimer (2002) analysis. It is also close, although not identical, to the left inferior PFC activation identified for semantic processing in the High- versus Low-conflict contrast. We interpret this activation to be associated with the processing of the irrelevant meaning (the forward form) of the reversible words in the Low-conflict condition, relative to the Neutral condition where the forward items were not real words. Although without a separate peak, this posterior/superior left inferior PFC (BA44/45) activation extended to the middle frontal gyrus BA9, an area that plays a critical role in fine analysis of complex spatial configuration of Chinese characters (Chee et al., 2000; Tan et al., 2000, 2001a; Xiang et al., 2003). This may be due to increased reliance on orthography to facilitate selection of relevant semantic and phonological representations from irrelevant ones in the Low-conflict condition than in the Neutral condition, although the

Table 1
Summary information for regions of activation in the three statistical contrasts

Contrast	Anatomical structure	~Brodmann areas	Stereotaxic Coordinates			Peak *Z* score	Volume (voxel)
High-conflict >	Left inferior frontal gyrus	47	−24	22	−13	4.46	41
Low-conflict	Right inferior frontal gyrus	47	35	19	−13	4.37	23
	Anterior cingulate	32	4	31	23	4.26	21
Low-conflict >	Left inferior frontal gyrus	44/45	−45	17	13	4.50	248
Neutral	Left inferior frontal gyrus	47	−41	26	−11	4.30	55
High-conflict >	Left inferior frontal gyrus	47	−39	21	−7	5.38	477
Neutral	Left inferior frontal gyrus	44/45	−43	11	21	4.82	372
	Anterior cingulate	32	0	19	36	4.89	354
	Right inferior frontal gyrus	47	35	18	−10	4.17	46

Note. Coordinates shown in Talairach space for the center of mass of each activated region.

physical properties of the visual stimuli were comparable across the two conditions.

Briefly, the Low-conflict versus Neutral contrast revealed two distinct activations in the left inferior prefrontal cortex. Given the differential involvement of phonological and semantic processing across the two conditions, we take this pattern of results as evidence consistent with the Bookheimer (2002) analysis that the anterior/inferior subregion in left inferior PFC was related to semantic processing and the posterior/superior subregion to phonological processing, suggesting that such a functional subdivision was also present in processing Chinese. Results from the High-conflict versus Neutral comparison also provided consisting evidence as the activated regions in this contrast coincided with those in the High-conflict versus Low-conflict and the Low-conflict versus Neutral contrasts.

A line of imaging research contrasting pseudowords with real words has found that they activate the same set of regions in left prefrontal cortex (among other brain lobes), and within these regions, there is greater activation for pseudowords than real words (Fiebach et al., 2002; Hagoort et al., 1999; Price et al., 1996; Xu et al., 2001). This finding, albeit subject to some inconsistent evidence (Newman and Twieg, 2001), has been confirmed in a recent study specifically designed to address cross-study inconsistencies (Mechelli et al., 2003). This finding poses a challenge to the hypothesis the present study supports, as we would expect the real words, which have meaning, to engage brain regions for semantic processing more than pseudowords, which do not have meaning. One possibility is that some components in semantic processing, for example, a control mechanism as in Wagner et al.'s (2001) or a selection mechanism as in Thompson-Schill (2003), may be general cognitive processes that are also heavily employed by pseudowords processing.

None of the three comparisons we conducted revealed any activation in the temporal lobe, which has been implicated as component of the semantic memory network (Binder et al., 1996; Demonet et al., 1992; Pugh et al., 1996; Wise et al., 1991). This, in our view, is due to the fact that the three task conditions in the present study were highly comparable. They did not differ in the amount of semantic knowledge that had to be intentionally retrieved. Therefore, the temporal and parietal regions, which are supposed to be mainly for storage functions, may not have been differentially taxed. Although the amount of automatic semantic activation was different across the Low-conflict and the Neutral conditions, such a difference may have been overshadowed by the intentional semantic retrieval process.

One feature of this study was that our participants were first asked to manipulate or transform the stimuli presented and then made judgment based on the transformed representation. Although this is not usually seen in language studies, it has been a common technique in memory and attention research (D'Esposito et al., 1999; Zhang et al., 2003). We adopted this technique to augment the interference between automatically and intentionally activated semantic representations to facilitate examination of the effect with fMRI. Taft et al. (1999) used a lexical decision task and found that reaction time for reversible words was slower than that for nonreversible words, suggesting an interference effect from the backward word form. Similarly, with a priming paradigm, Peng et al. (1999) showed that simply asking participants to read a reversible word AB in its forward order was sufficient to activate its backward meaning BA. We did not adopt their paradigms as we intended to focus on semantic processing with a semantic task. In comparing the High-conflict and the Low-conflict conditions, we employed a rationale to control for the amount of activated representations and vary the relevance of such representations in the response stage. This rationale has also been used in some recent studies such as Bunge et al. (2002).

Conclusions

In this study, we took advantage of the presence of reversible words, a unique linguistic feature in Chinese, and compared two semantic tasks that involved similar activation of semantic representations but differed in the extent to which irrelevant semantic activation interfered with intentional semantic retrieval of relevant meaning. Focusing more on the executive control of semantic retrieval, such comparison revealed activation in a subregion of the left inferior PFC, providing evidence that the left inferior frontal lobe was involved in the semantic processing of Chinese. Comparing reversible words with nonreversible words, we also reported evidence suggesting that a semantic/phonological functional subdivision in left inferior PFC, as proposed by Bookheimer (2002), generalizes to the processing of Chinese.

Acknowledgments

This research was supported by a Research Grants Council Central Allocation Vote (RGC CAV) group research grant (HKU 3/02C) awarded to L.H. Tan, a China National Natural Science Foundation grant (NNSFC 30128005) and a China Ministry of Science and Technology grant (G1999054000) awarded to X.C. Weng, and a China National Pandeng Project (95-special-09) awarded to D.L. Peng. We thank Claudia Wong for help with preparation of the experimental materials, and Xiaoyi Wang and Congyu Lin for data conversion.

References

Binder, J.R., Frost, J.A., Hammeke, T.A., Rao, S.M., Cox, R.W., 1996. Function of the left planum temporale in auditory and linguistic processing. Brain 119, 1239–1247.

Bookheimer, S., 2002. Functional MRI of language: new approaches to understanding the cortical organization of semantic processing. Annu. Rev. Neurosci. 25, 151–188.

Botvinick, M., Nystrom, L.E., Fissell, K., Carter, C.S., Cohen, J.D., 1999. Conflict monitoring versus selection-for-action in anterior cingulate cortex. Nat. Neurosci. 402, 179–181.

Buckner, R.L., Koutstaal, W., Schacter, D.L., Rosen, B.R., 2000. Functional MRI evidence for a role of frontal and inferior temporal cortex in anodal components of priming. Brain 123, 620–640.

Bunge, S.A., Hazeltine, E., Scanlon, M.D., Rosen, A.C., Gabrieli, J.D., 2002. Dissociable contributions of prefrontal and parietal cortices to response selection. NeuroImage 17, 1562–1571.

Carter, C.S., Braver, T.S., Barch, D.M., Botvinick, M.M., Noll, D., Cohen, J.D., 1998. Anterior cingulate cortex, error detection, and the online monitoring of performance. Science 280, 747–749.

Chee, M.W., Weekes, B., Lee, K.M., Soon, C.S., Schreiber, A., Hoon, J.J., Chee, M., 2000. Overlap and dissociation of semantic processing of Chinese characters, English words, and pictures: evidence from fMRI. NeuroImage 12, 392–403.

Chee, M.W., Hon, N., Lee, H.L., Soon, C.S., 2001. Relative language proficiency modulates BOLD signal change when bilinguals perform semantic judgments. Blood oxygen level dependent. NeuroImage 13, 1155–1163.

Copland, D.A., Zubicaray, G.I.d., McMahon, K., Wilson, S.J., Eastburn, M., Chenerya, H.J., 2003. Brain activity during automatic semantic priming revealed by event-related functional magnetic resonance imaging. NeuroImage 20, 302–310.

Demb, J.B., Desmond, J.E., Wagner, A.D., Vaidya, C.J., et al., 1995. Semantic encoding and retrieval in the left inferior prefrontal cortex: a functional MRI study of task difficulty and process specificity. J. Neurosci. 15, 5870–5878.

Demonet, J.F., Chollet, F., Ramsay, S., Cardebat, D., Nespoulous, J.L., Wise, R., Rascol, A., Frackowiak, R., 1992. The anatomy of phonological and semantic processing in normal subjects. Brain 115, 1753–1768.

D'Esposito, M., Postle, B.R., Ballard, D., Lease, J., 1999. Maintenance versus manipulation of information held in working memory: an event-related fMRI study. Brain Cogn. 41, 66–86.

Fiebach, C.J., Friederici, A.D., Muller, K., von Cramon, D.Y., 2002. fMRI evidence for dual routes to the mental lexicon in visual word recognition. J. Cogn. Neurosci. 14 (1), 11–23.

Fiez, J.A., 1997. Phonology, semantics, and the role of the left inferior prefrontal cortex. Hum. Brain Mapp. 5, 79–83.

Fletcher, P.C., Henson, R.N.A., 2001. Frontal lobes and human memory—Insights from functional neuroimaging. Brain 124, 849–881.

Fletcher, P.C., Shallice, T., Dolan, R.J., 2000. "Sculpting the response space"—An account of left prefrontal activation at encoding. NeuroImage 12, 404–417.

Forman, S.D., Cohen, J.D., Fitzgerald, M., Eddy, W.F., Mintun, M.A., Noll, D.C., 1995. Improved assessment of significant activation in functional magnetic resonance imaging (fMRI): use of a cluster-size threshold. Magn. Reson. Med. 33, 636–647.

Friston, K.J., Holmes, A.P., Poline, J.B., Grasby, P.J., Williams, S.C., Frackowiak, R.S., Turner, R., 1995. Analysis of fMRI time-series revisited. NeuroImage 2, 45–53.

Gabrieli, J.D., Poldrack, R.A., Desmond, J.E., 1998. The role of left prefrontal cortex in language and memory. Proc. Natl. Acad. Sci. U. S. A. 95, 906–913.

Hagoort, P., Indefrey, P., Brown, C., Herzog, H., Steinmetz, H., Seitz, R.J., 1999. The neural circuitry involved in the reading of German words and pseudowords: a PET study. J. Cogn. Neurosci. 11 (4), 383–398.

Kapur, S., Rose, R., Liddle, P.F., Zipursky, R.B., et al., 1994. The role of the left prefrontal cortex in verbal processing: semantic processing or willed action? NeuroReport: An International Journal for the Rapid Communication of Research in Neuroscience 5, 2193–2196.

Mechelli, A., Gorno Tempini, M.L., Price, C.J., 2003. Neuroimaging studies of word and pseudoword reading: consistencies, inconsistencies, and limitations. J. Cogn. Neurosci. 15 (2), 260–271.

Newman, S.D., Twieg, D., 2001. Differences in auditory processing of words and pseudowords: an fMRI study. Hum. Brain Mapp. 14 (1), 39–47.

Peng, D., Ding, G., Wang, C., Marcus, T., Zhu, X., 1999. The processing of Chinese reversible words: the role of morphemes in lexical access. Acta Psychol. Sin. 31, 36–46.

Perfetti, C.A., Tan, L.H., 1999. The constituency model of Chinese word identification. In: Wang, J., Inhoff, A.W., Chen, H.C. (Eds.), Reading Chinese script: A cognitive analysis. Lawrence Erlbaum Associates, Publishers, Mahwah NJ, US.

Petersen, S.E., Fox, P.T., Posner, M.I., Mintun, M., Raichle, M.E., 1988. Positron emission tomographic studies of the cortical anatomy of single-word processing. Nature 331, 585–589.

Poldrack, R.A., Wagner, A.D., Prull, M.W., Desmond, J.E., Glover, G.H., Gabrieli, J.D., 1999. Functional specialization for semantic and phonological processing in the left inferior prefrontal cortex. NeuroImage 10, 15–35.

Poldrack, R.A., Temple, E., Protopapas, A., Nagarajan, S., Tallal, P., Merzenich, M., Gabrieli, J.D., 2001. Relations between the neural bases of dynamic auditory processing and phonological processing: evidence from fMRI. J. Cogn. Neurosci. 13, 687–697.

Poline, J.B., Worsley, K.J., Evans, A.C., Friston, K.J., 1997. Combining spatial extent and peak intensity to test for activations in functional imaging. NeuroImage 5, 83–96.

Price, C.J., Wise, R.J.S., Frackowiak, R.S.J., 1996. Demonstrating the implicit processing of visually presented words and pseudowords. Cereb. Cortex 6 (1), 62–70.

Pugh, K.R., Shaywitz, B.A., Shaywitz, S.E., Constable, R.T., Skudlarski, P., Fulbright, R.K., Bronen, R.A., Shankweiler, D.P., Katz, L., Fletcher, J.M., Gore, J.C., 1996. Cerebral organization of component processes in reading. Brain 119, 1221–1238.

Snyder, P.J., Harris, L.J., 1993. Handedness, sex and familiar sinistrality effects on spatial tasks. Cortex 29, 115–134.

Taft, M., Zhu, X., Peng, D., 1999. Positional specificity of radicals in Chinese character recognition. J. Mem. Lang. 40, 498–519.

Tan, L.H., Perfetti, C.A., 1997. Visual Chinese character recognition: does phonological information mediate access to meaning? J. Mem. Lang. 37, 41–57.

Tan, L.H., Perfetti, C.A., 1999. Phonological activation in visual identification of Chinese two-character words. J. Exper. Psychol., Learn., Mem., Cogn. 25, 382–393.

Tan, L.H., Siok, W.T., 2003. How does the brain reads the Chinese language: recent neuroimaging findings. In: Li, P., Tan, L.H., Bates, E., Tzeng, O. (Eds.), Handbook of Chinese Psycholinguistics. Cambridge Univ. Press, Cambridge, UK.

Tan, L.H., Spinks, J.A., Gao, J.H., Liu, H.L., Perfetti, C.A., Xiong, J., Stofer, K.A., Pu, Y., Liu, Y., Fox, P.T., 2000. Brain activation in the processing of Chinese characters and words: a functional MRI study. Hum. Brain Mapp. 10, 16–27.

Tan, L.H., Feng, C.M., Fox, P.T., Gao, J.H., 2001a. An fMRI study with written Chinese. NeuroReport: For Rapid Communication Of Neuroscience Research 12, 82–88.

Tan, L.H., Liu, H.L., Perfetti, C.A., Spinks, J.A., Fox, P.T., Gao, J.H., 2001b. The neural system underlying Chinese logograph reading. NeuroImage 13, 836–846.

Thompson-Schill, S.L., 2003. Neuroimaging studies of semantic memory: inferring "how" from "where". Neuropsychologia 41, 280–292.

Thompson-Schill, S.L., D'Esposito, M., Aguirre, G.K., Farah, M.J., 1997. Role of left inferior prefrontal cortex in retrieval of semantic knowledge: a reevaluation. Proc. Natl. Acad. Sci. U. S. A. 94, 14792–14797.

Thompson-Schill, S.L., Swick, D., D'Esposito, M., Knight, R.T., Kan, I.P., Farah, M.J., 1998. Lesions of the left inferior frontal gyrus impair selection, not retrieval, of semantic knowledge. J. Cogn. Neurosci., 53.

Wagner, A.D., Koutstaal, W., Maril, A., Schacter, D.L., Buckner, R.L., 2000. Task-specific repetition priming in left inferior prefrontal cortex. Cereb. Cortex 10, 1176–1184.

Wagner, A.D., Pare Blagoev, E.J., Clark, J., Poldrack, R.A., 2001. Recovering meaning: left prefrontal cortex guides controlled semantic retrieval. Neuron 31, 329–338.

Wise, R., Chollet, F., Hadar, U., Friston, K., Hoffner, E., Frackowiak, R., 1991. Distribution of cortical neural networks involved in word comprehension and word retrieval. Brain 114, 1803–1817.

Xiang, H., Li, C., Ma, X., Zhang, Z., Bower, J., Weng, X., Gao, J.H., 2003. Involvement of the cerebellum in semantic discrimination: an fMRI study. Hum. Brain Mapp. 18, 208–214.

Xu, B., Grafman, J., Gaillard, W.D., Ishii, K., Vega Bermudez, F., Pietrini, P., Reeves Tyer, P., DiCamillo, P., Theodore, W., 2001. Conjoint and extended neural networks for the computation of speech codes: the neural basis of selective impairment in reading words and pseudowords. Cereb. Cortex 11 (3), 267–277.

Zhang, J.X., Leung, H.-C., Johnson, M.K., 2003. Frontal activations associated with accessing and evaluating information in working memory: an fMRI study. NeuroImage 20, 1531–1539.

Zhang, J.X., Feng, C.M., Fox, P., Gao, J.H., Tan, L.H., 2004. Is left inferior frontal gyrus (LIFG) a general mechanism for working memory selection? NeuroImage (in press).