Functional Anatomy of Syntactic and Semantic Processing in Language Comprehension

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Abstract: A functional magnetic resonance imaging (fMRI) study was conducted to map syntactic and semantic processes onto the brain. Chinese-English bilingual subjects performed two experimental tasks: a syntactic plausibility judgment task in which they decided whether a viewed verb phrase was syntactically legal, and a semantic plausibility judgment task in which they decided whether a viewed phrase was semantically acceptable. A font size judgment task was used as baseline. It is found that a large-scale distributed neural network covering the left mid-inferior frontal and mid-superior temporal cortices was responsible for the processing of Chinese phrases. The right homologue areas of these left cortical sites were also active, although the brain activity was obviously left-lateralized. Unlike previous research with monolingual English speakers that showed that distinct brain regions mediate syntactic and semantic processing of English, the cortical sites contributing to syntactic analysis of Chinese phrases coincided with the cortical sites relevant to semantic analysis. Stronger brain activity, however, was seen in the left middle frontal cortex for syntactic processing (relative to semantic processing), whereas for semantic processing stronger cortical activations were shown in the left inferior prefrontal cortex and the left mid-superior temporal gyri. The overall pattern of results indicates that syntactic processing is less independent in reading Chinese. This is attributable to the linguistic nature of the Chinese language that semantics and syntax are not always clearly demarcated. Equally interesting, we discovered that when our bilingual subjects performed syntactic and semantic acceptability judgments of English phrases, they applied the cerebral systems underlying Chinese reading to the processing of English. *Hum. Brain Mapping 16:133–145, 2002.* © 2002 Wiley-Liss, Inc.

Key words: fMRI; syntactic processing; language comprehension; Chinese reading

INTRODUCTION

Human languages are structured at multiple levels involving phonology, syntax, and semantics. Language comprehension integrates information at the different levels of structure through an on-line cognitive process. An important question in the cognitive neuroscience of language is whether the human brain possesses distinct cortical regions that specialize in the processing of different linguistic elements such as syntax (sentence structure) and semantics (meaning).

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Past lesion studies of alphabetic languages with relatively well-defined syntactic structures suggest that anterior cortical areas in the left cerebral hemisphere are associated with syntactic analysis [Caplan et al., 1985; Zurif et al., 1972]. This hypothesis has been buttressed by recent investigations measuring event-related potentials (ERPs) [Ainsworth-Darnell et al., 1998; Friederici et al., 1998]. More recently, the development of brain imaging techniques of high spatial resolution such as positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) has enabled researchers to map syntactic and semantic functions onto the intact living brain. Using visually presented sentences and a sentence plausibility judgment task, PET studies have implicated Broca area (i.e., Brodmann area, BA 44 and 45 on the left) in explicit syntactic analysis [Caplan et al., 1998, 2000; Stromswold et al., 1996]. The role of Broca's pars opercularis in syntactic processing have also been demonstrated by recent fMRI work with other reading comprehension tasks [Dapretto and Bookheimer, 1999; Friederici et al., 2000; Kang et al., 1999; Moro et al., 2001; Nichelli et al., 1995].

The aforementioned studies have implicated the left inferior frontal cortex in syntactic analysis. This finding agrees with the modular view of the human mind and brain that assumes that separate, informationally encapsulated modules are dedicated to the processing of different levels of linguistic representation [Fodor, 1983]. Several other neuroimaging studies, however, have suggested that syntactic processing may take place at multiple interconnected cortical regions including the inferior prefrontal, mid-superior temporal and inferior parietal cortices in the left hemisphere [Just et al., 1996; Keller et al., 2001; Mazoyer et al., 1993]. According to this view, the interaction and collaboration of these brain regions are pivotal to syntactic analysis in a coherent language-processing neural network [Horwitz et al., 1999a, 2000].

Our picture of the brain mechanisms underlying semantic processing is not very clear. A large body of neuroimaging research has implicated the left inferior prefrontal cortex in semantic memory and meaning processing [Bokde et al., 2001; Buckner and Petersen, 1996; Buckner et al., 1995, 2000; Dapretto and Bookheimer, 1999; Demb et al., 1995; Donaldson et al., 2001; Gabrieli et al., 1996; Maril et al., 2001; Petersen et al., 1988; Poldrack et al., 1999; Ricci et al., 1999; Roskies et al., 1996; Thompson-Schill et al., 1999; Wagner et al., 1997, 2001]. Other research, however, has indicated that semantic processing is served by more posterior temporal and/or occipital cortices [Alexander et al., 1987; Demonet et al., 1992; Martin et al., 1996; Mesulam, 1990; Tranel et al., 1997]. To solve this dispute, more recent work has assumed that the posterior temporal regions are responsible for the maintenance of semantic knowledge, whereas the inferior prefrontal cortex is relevant to the executive processes of retrieving semantic information [see Fiez, 1998, for a review].

One of the aims of the present study is to identify the cortical regions responsible for syntactic and semantic processing of Chinese. Like any other language, Chinese relies on syntax and semantics to express meanings through phrases and sentences. The roles that syntax and semantics play in Chinese, however, differ significantly from English. In English, an SVO (Subject-Verb-Object) language, all other things being equal, a noun phrase coming before the main verb is normally the subject; a noun phrase coming after the main verb is normally the object. Thus, it is clear from subject-verb agreement what the subject is in sentences (1) and (2) below:

1. He has invited the students.
2. The students have invited him.

The different forms of the third personal singular pronoun ('he' vs. 'him') lend further support to the correct identification of the subject of each sentence.

When the verb is in its passive form, as in examples (3) and (4), the subjects can similarly be readily identified, but their semantic roles are now different: instead of agents (in Sentences 1 and 2), they are now the theme (i.e., recipients of the invitations).

3. The students have been invited (by him).
4. He has been invited (by the students).

Thus, in English, the syntactic status of a noun or a pronoun is independent of its semantic status in a sentence. Syntax and semantics are relatively clearly demarcated.

Chinese is also a SVO language. But syntax and semantics are not as clearly separated as in English. The Chinese sentences (5) and (6) below parallel the English sentences (1) and (2) above.

5. Ta qinglaile xuesheng.
   He/Him invited students
   'He has invited the students'.

6. Xuesheng qinglaile ta.
   Students invited he/him
   'The students have invited him'.

Despite the apparent parallelism, however, there are two important differences. First, in the Chinese sentences, there is no requirement for the verb ('qinglaile,' invited) to agree with the subject ('ta' or 'xuesheng,' he or students). Second, the form of the third person singular pronoun ('ta,' he/him) remains the same whether it is in subject or object position.

The significance of these differences can be more clearly seen when we try to construct parallel examples of (3) and (4), the passive sentences. The most common way of conveying similar meanings in Chinese is:

7. Xuesheng qinglaile.
   Students invited
   'The students have been invited (someone)'

8. Ta qinglaile.
   He/him invited
   'He has been invited.'

Unlike the comparable English sentences, the verb here ('qinglaile,' invited) is not in a passive form, nor is it in agreement with any noun phrase in the sentence. Syntactically, one might refer to the initial NPs as the subjects. Semantically, however, they are understood to be the theme (the recipient of the invitation). But this reading cannot possibly be signaled by the syntax, because the same NPs in the same syntactic position preceding precisely the same verb form in the previous two examples (5 and 6) had a completely different semantic interpretation: they were agents.

To make matters worse, this interpretation turns out to be but one of two possible readings. In an appropriate context (e.g., when sentence (7) is said in answer to the question 'Have the students invited Mr. Chan?'), it is equally possible to read 'xuesheng,' the initial NP in (7), as the agent (the patient, 'Mr. Chan,' would have been omitted from the object position, which is very common in Chinese). Similarly, the third person singular pronoun in (8) can be interpreted as the agent in an appropriate discourse context. In other words, the same NP in the same syntactic position in the same sentence (with an identical form of the same verb) can receive diametrically different semantic interpretations. Thus, unlike English, semantics and syntax are not always clearly demarcated. The former (together with pragmatics) plays a very important role in sentence comprehension in Chinese.

Research on Chinese syntax has, from very early on, but particularly so in recent years, moved steadily in the direction of a much closer engagement with semantics. Many Chinese linguists [e.g., Lu, 1997; Ma, 1998; Shao, 1998; Xing, 1995] believe that syntax is intimately tied to semantics, and cannot be fully understood independently of it. One leading linguist [Xu, 2000] goes even further: he believes that Chinese is typologically different from Indo-European languages, in that semantics plays a core role in the structure of the language. Because the Chinese language differs from English in syntax and semantics, research with Chinese will add important information to our understanding of the universality and specificity of the neural mechanisms underlying language processing.

A second goal of this fMRI study was to determine neural substrates responsible for syntactic and semantic analyses of English by Chinese-English bilinguals who learn English as a second language. To date the findings of the cortical mechanisms of bilinguals have been conflicting. Imaging data from studies of lexical processing and language production have either indicated a dissociation of regions during processing the two languages [e.g., Dehaene et al., 1997; Gandour et al., 2000; Hsieh et al., 2001; Klein et al., 2001; Mazoyer et al., 1993; Perani et al., 1996], or shown that common areas were activated in within- and across-language word tasks [Chee et al., 1999; Kim et al., 1997; Klein et al., 1995, 1999; Pu et al., 2001; Tan et al., 2001a]. There is yet no available research to address how bilinguals process the syntactic structure of a second language.

Our study used fMRI and intransitive verb phrases (VPs) to map syntactic and semantic processes onto the brain. Two experimental tasks were devised: a syntactic plausibility judgment which required subjects to decide whether a viewed VP phrase was syntactically legal, and a semantic plausibility judgment that required subjects to decide whether a viewed phrase was semantically acceptable. We used font size judgment as baseline, in which subjects decided whether all constituent words in a presented phrase had the same physical size. Based on our understanding of the nature of Chinese syntax and its relationship with semantics, we predicted that there would be a largely overlapping neural network associated with syntactic and semantic analyses of written Chinese.

MATERIALS AND METHODS

Subjects

Seven male volunteers participated in this study. They gave informed consent in accordance with guidelines set by Chang Gung Medical Center in Taiwan. All subjects were native Chinese (Mandarin) speakers, ranging in age from 20–31 years. They started to learn English as a second language after age 10.

A language experience questionnaire was devised to obtain measures of self-reported current fluency in English and amount of schooling in English. The first section of the questionnaire asked subjects about their language history. On average, subjects began speaking their second language at 12 years and already received a minimum of 10 years of formal training in English throughout primary school, high school and college in Taiwan. In the second section, the questionnaire contained two rating scales for Chinese and English fluency, respectively. The endpoints of the rating scale were 1 and 7, with 1 being *not fluent* and 7 being *very fluent*. Subjects were required to rate the fluency with which they could currently perform each skill by ticking the appropriate number. The average rating scores of fluency in the subjects' Chinese and English were 6.43 (Chinese reading, SD = 0.79), 5.86 (English reading, SD = 0.90), 6.57 (Chinese speaking, SD = 0.79), and 5.29 (English speaking, SD = 1.60). The difference in proficiency of the two languages is statistically significant, $P < 0.05$.

All subjects were strongly right handed as judged by the handedness inventory devised by Snyder and Harris [1993]. In this inventory, we adopted nine items involving unimanual tasks (tasks that can be done by only one hand). A 5-point Likert-type scale was used, with "1" representing exclusive left-hand use and "5" representing exclusive right-hand use. The items were: writing a letter, drawing a picture, throwing a ball, holding chopsticks, hammering a nail, brushing teeth, cutting with scissors, striking a match, and opening a door. The scores on the 9 items were summed for each subject, with the lowest score (9) indicating exclusive left-hand use for all tasks, and the highest score (45) indicating exclusive right-hand use. All subjects had scores higher than 40.

Behavioral Performance and Materials

We devised two experimental tasks: the syntactic plausibility judgment task, in which subjects judged whether a viewed Chinese or English phrase was syntactically acceptable, and the semantic plausibility judgment task, in which subjects decided whether a viewed Chinese or English phrase was semantically reasonable. The experimental stimuli used in this study consisted of 15 syntactically plausible Chinese phrases, 15 syntactically plausible English phrases, 15 semantically plausible Chinese phrases, and 15 semantically plausible English phrases. All Chinese and English words contained in the phrases were commonly used according to the frequency corpus of Chinese and English (Beijing Language Institute, 1986; Francis and Kucera, 1982). For Chinese phrases, each VP was either preceded or followed by an adverb (ADV). As ADV-V is the normal order in Chinese and V-ADV is not allowed, we were able to construct pairs of VPs consisting of the same words (a verb and an adverb) in two different orders. Syntactically ADV-V (that is legal) is evidently different from V-ADV (that is illegal); semantically, however, it is possible to read off identical semantic interpretations from the two syntactically different strings. For example, in the phrase 'congcong likai' (literally 'quickly left'), the adverb (congcong) comes before the verb (likai), which is legal in Chinese syntax. In the other phrase 'likai congcong,' however, the adverb comes after the verb. This is ungrammatical in Chinese: the syntax is illegal and unacceptable. Semantically, however, the latter string is not uninterpretable. It is possible (with extra effort) to read off a similar semantic interpretation as the legal string. Other examples include 'si suishi' (die anytime) and 'xiao limaodi' (smile politely). For Chinese semantically unacceptable phrases, we used a verb that was preceded or followed by an adverb but the combination of the verb and the adverb was meaningless (e.g., 'shangle men,' hurt the door; 'changle zi,' sang a character; 'nianle qiche,' read a car).

For English phrases, we followed Kang et al. [1999] and also constructed three types of stimuli: a) normal (e.g., 'grew plants'); b) syntactically unacceptable ('forgot made'); and (c) semantically anomalous ('heard shirts'). All verbs were in the past tense to avoid an imperative meaning ('drive cars').

The stimuli were shown through a LED projector system. On each trial, a phrase was exposed for 1,500 msec. After the presentation of a phrase, a fixation crosshair was exposed for 1,500 msec. Subjects were asked to perform the experimental task as quickly and accurately as possible. A block design was adopted in this study. The experimental materials for the syntactic plausibility judgment were randomized within 30 sec blocks comprised of five syntactically "legal" and five syntactically "illegal" phases. Likewise, the experimental materials for the semantic plausibility judgment were also randomized within 30 sec blocks comprised of five semantically reasonable and five semantically unreasonable phases. A 3 sec brief instruction was presented before each block.

In the control scan, the subject performed a font size decision task, in which they decided whether all Chinese characters (or English words) in a viewed phrase that was both semantically and syntactically acceptable had a same physical size. We believe that the use of the font size judgment as baseline would control for activations provoked by visual-orthographic and phonological components of a written phrase [Tan et al., 2001a]. Therefore, the syntactic judgment task minus font size judgment task isolates cortical regions for explicit syntactic analyses, whereas the semantic judgment task minus the font size judgment task reveals brain areas involved in explicit semantic processing.

The experiment was conducted in two separate runs, one for the Chinese stimuli and the other for the English stimuli. Each run consisted of three blocks of syntactic judgment, three blocks of semantic judgment, and three blocks of font size judgment. The Chinese stimuli were exposed before English stimuli. Within each of the two languages, presentation of the syntactic phrases, the semantic phrases and the control phrases was counterbalanced.

Apparatus and Procedure

The fMRI experiment was performed using a 1.5 T Siemens Vision MRI scanner (Erlangen, Germany). Before fMRI imaging, the subject was visually familiarized with the procedures and the experimental conditions to minimize anxiety and enhance task performance. After this familiarization, the subject lay supine on the scanning table and was fitted with plastic ear-canal molds. The subject's head was immobilized by a tightly fitting, thermally molded, plastic facial mask that extended from the hairline to the chin [Fox et al., 1985].

A single shot, T_2*-weighted gradient-echo echo planar imaging (EPI) sequence was used for the fMRI scans, with the slice thickness = 7 mm, in-plane resolution = 3 mm × 3 mm, and TR/TE/θ = 2,000 msec/60 msec/90°. The field of view was 192 mm × 192 mm, and the acquisition matrix was 64 x 64. Seventeen contiguous axial slices were acquired to cover the whole brain. For each slice, 153 images were acquired with a total scan time of 306 sec in a single run. The anatomical MRI was acquired using a T_1-weighted, 3D, gradient-echo pulse-sequence. This sequence provided high resolution (1 mm × 1 mm × 1 mm) images of the entire brain.

Data Analysis

We used Matlab (The Math Works, Inc., Natick, MA) and in-house software for image data processing [Xiong et al., 1995], which included corrections for head motion and global MRI signal shift. Skull stripping of the 3D MRI T_1-weighted images was done using Alice software (Perceptive Systems, Inc., Boulder, CO). These images were then spatially normalized to the Talairach brain atlas [Talairach and Tournoux, 1988] using the Convex Hull algorithm [Lancaster et al., 1997, 1999].

Functional images were grouped into syntactic decision, semantic decision, and font-size decision groups for each of the two languages. Images from the first 8 sec of each block were excluded from further functional data processing to minimize the transit effects of hemodynamic responses. Activation maps were calculated by comparing images acquired during each task state (syntactic judgment and semantic judgment) with those acquired during the control state (font-size judgment), using a Student's group t-test. Like the T_1-weighted anatomical images, the activation maps were also spatially normalized into Talairach space using the Convex Hull algorithm. The averaged activation maps across the 7 subjects with a t-value threshold of 2 ($P < 0.025$) were then overlaid on the corresponding T_1 images. For each condition, Talairach coordinates of the center-of-mass and volume (mm^3) of the activation clusters were determined based on the averaged activation maps. Anatomical labels (lobes, gyri) and Brodmann area (BA) designations were applied automatically using a 3D electronic brain atlas [Lancaster et al., 1997].

RESULTS

Syntactic and Semantic Processing of Chinese Phrases

The fMRI images averaged across subjects for the syntactic and semantic plausibility judgments of Chinese phrases (both relative to the font size judgment) are shown in Figure 1a,b. Coordinates of significant activations are presented in Table I. In essence, brain areas associated with syntactic analysis in reading Chinese coincide with brain areas associated with semantic analysis. The activity of the left mid-inferior frontal cortex covering BAs 9, 46, 47, 45, and 44 was dominant for both types of processing. The left supero-medial frontal gyrus (BA 10), right inferior prefrontal cortex near BA 45 and 46 and right superomiddle frontal sites (BAs 10 and 9) also contributed to syntactic and semantic processes. In the occipital lobe, strong activity was observed in the left lingual (BA 17) or fusiform gyrus (BA 37). The right inferior occipital cortex also mediated syntactic and semantic processing in reading Chinese. In the temporal cortex, activations were seen in the left middle temporal (BA 21) and bilateral anterior superior temporal cortices (BA 38).

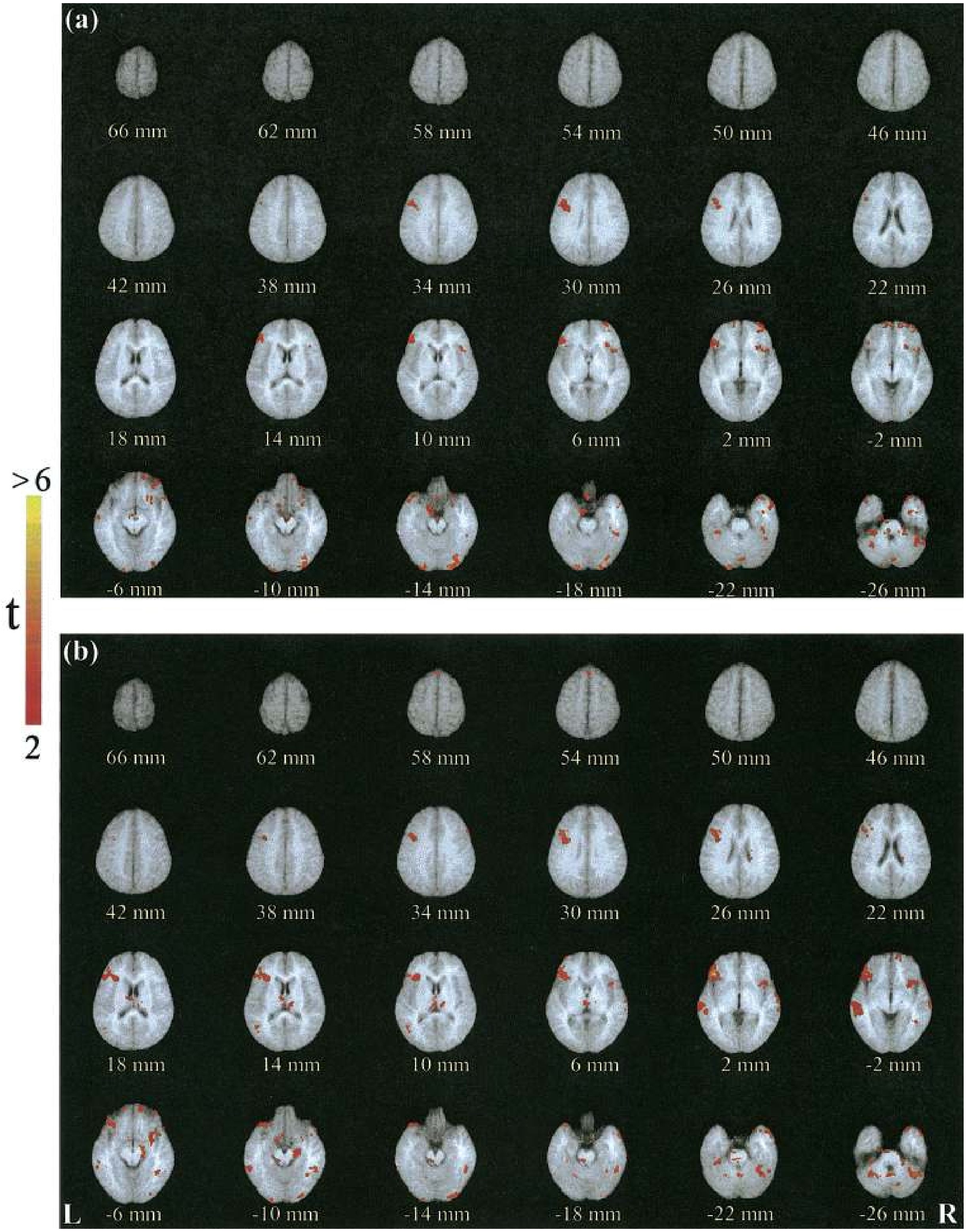

Figure 1.

Averaged brain activations provoked by syntactic and semantic analyses of Chinese (**a**,**b**). Normalized t-maps (in color) pooled from seven subjects are overlaid on the corresponding T_1 images (in gray scale), demonstrating statistically significant activations ($P < 0.025$). Planes are axial sections, labeled with the height (mm) relative to the bicommissural line (L, left hemisphere; R, right hemisphere). (a) Activations in syntactic processing. (b) Activations in semantic processing.

TABLE I. Regions of significant activation in syntactic and semantic processing of Chinese*

	Chinese syntax−Chinese font						Chinese semantics−Chinese font					
		Coordinates						Coordinates				
Regions activated	BA	X	Y	Z	Activation volume	P	BA	X	Y	Z	Activation volume	P
Frontal												
L middle frontal gyrus	9	−45	26	27	4532	0.006	9/46	−47	19	30	2500	0.006
	46	−45	42	17	3507	0.004	—	—	—	—	—	—
L inferior frontal cortex	47	−56	36	−9	752	0.010	45/46	−45	34	8	19704	0.005
	44	−50	10	28	708	0.013	44	−50	10	28	257	0.013
L supero-medial gyri	10	−8	68	−4	1312	0.009	8	−1	33	55	536	0.012
	25	−2	26	−18	632	0.009	10	−18	60	−8	272	0.009
L subcallosal gyrus	34	−11	3	−14	1456	0.009	—	—	—	—	—	—
L rectal gyrus	—	—	—	—	—	—	11	−7	50	−27	264	0.009
R superior frontal gyrus	10	33	58	−4	1520	0.008	—	—	—	—	—	—
R inferior frontal gyrus	45	55	25	17	304	0.009	46	59	41	7	1680	0.009
R middle frontal gyrus	—	—	—	—	—	—	10	34	54	−9	512	0.011
	—	—	—	—	—	—	9	55	19	35	248	0.011
Temporal												
L superior temporal gyri	38	−45	21	−29	304	0.003	38	−51	18	−12	340	0.007
L middle temporal gyrus	21	−62	−9	−8	240	0.007	21	−61	−28	−2	3000	0.007
	—	—	—	—	—	—	39	−47	−59	13	376	0.013
R superior temporal gyri	38	43	15	−24	299	0.012	22	64	−14	1	688	0.011
	—	—	—	—	—	—	38	50	17	−27	220	0.009
Occipital												
L lingual gyrus	17	−21	−97	−7	2944	0.006	—	—	—	—	—	—
L fusiform	—	—	—	—	—	—	18	−23	−96	−12	320	0.010
R inferior occipital gyrus	18	30	−87	−13	3584	0.005	18	29	−88	−13	1008	0.007
Other areas												
L thalamus	—	—	—	—	—	—		−4	−14	12	1136	0.009
R thalamus	—	—	—	—	—	—		10	−19	13	608	0.009
L sub-lobar caudate	—	—	—	—	—	—		−11	9	−10	400	0.012
Cerebellum												
L anterior lobe		−27	−48	−30	2872	0.009		−35	−30	−24	616	0.012
L cerebellar tonsil		—	—	—	—	—		−29	−54	−31	2528	0.009
Right culmen		44	−44	−26	2296	0.010		42	−48	−24	3168	0.004
R pyramis		3	−78	−24	416	0.009		12	−70	−30	272	0.010

* L, left; R, right.

Interestingly, we found that the left sub-lobar caudate and thalamus participated in semantic, rather than syntactic, processing of Chinese. As with previous research on language processing, cerebellum was heavily involved in subjects' reading performance.

Despite the partial overlap of activation sites for semantic and syntactic analyses, the volume of brain activities was significantly different between the two kinds of processing in the following areas of interest (in terms of Student's *t*-test at $P < 0.05$ corrected, unless specified) (Fig. 2). For syntactic processing, the activation volume was 5.5 times greater in the middle frontal gyrus than in the inferior prefrontal regions. For semantic processing, however, there was an opposite activation pattern; the activation volume was 8 times greater in the inferior frontal areas than in the middle frontal gyrus. This implicates the relative significance of middle and inferior frontal regions in syntactic and semantic analyses of Chinese, respectively. The activation volume of the left middle-superior temporal gyri (BAs 21 and 38) was significantly larger in the semantic judgment task than in the syntactic judgment.

Syntactic and Semantic Processing of English Phrases by Chinese-English Bilinguals

The pattern of brain activations relevant to syntactic and semantic analyses during reading English par-

TABLE II. Brain regions of significant activation in syntactic and semantic processing of English by Chinese-English bilinguals

	English syntax−English font						English semantics−English font					
		Coordinates			Activation			Coordinates			Activation	
Regions activated	BA	X	Y	Z	volume	*P*	BA	X	Y	Z	volume	*P*
Frontal												
L middle frontal gyrus	9	−51	20	30	19970	0.003	9/46	−31	20	28	29160	0.003
	10	−40	48	−1	2100	0.004	10	−30	62	8	1877	0.009
L inferior frontal cortex	45	−45	35	1	2034	0.007	47/45	−50	19	1	47552	0.002
	44	−55	10	29	841	0.011	44	−55	8	32	699	0.006
	47	−20	13	−18	4200	0.004	—	—	—	—	—	—
L mid-medial frontal gyri	6	−7	0	52	656	0.007	6	−25	5	55	23340	0.004
R inferior frontal gyri	46	50	31	11	1970	0.004	47	51	26	−11	600	0.008
	45	51	18	20	1780	0.014	45	50	18	21	823	0.007
R superior frontal gyrus	—	—	—	—	—	—	10	15	59	−8	3072	0.003
R mid-medial frontal gyri	6	49	−9	43	776	0.009	6	48	−2	42	2400	0.009
	6	19	5	47	328	0.013	—	—	—	—	—	—
Temporal												
L (supero-)middle gyri	21	−57	8	−16	1440	0.006	22	−53	−45	20	1056	0.004
	21	−44	−26	−10	344	0.008	38/21	−49	1	−12	9032	0.003
	22	−55	−33	12	310	0.009	—	—	—	—	—	—
R fusiform fyrus	37	46	−38	−16	688	0.008	37	43	−45	−13	1343	0.004
L temporal sub-gyral	28	−31	1	−29	712	0.005	—	—	—	—	—	—
Parietal												
L precuneus	19	−29	−63	41	320	0.012	19	−30	−65	42	1160	0.004
L inferior parietal cortex	40	−55	−36	24	728	0.007	—	—	—	—	—	—
R precuneus	—	—	—	—	—	—	19	33	−70	41	400	0.010
Occipital												
L lingual gyrus	—	—	—	—	—	—	18	−15	−79	0	536	0.007
L inferior occipital gyrus	—	—	—	—	—	—	19	−24	−74	−1	704	0.012
R fusiform gyrus	—	—	—	—	—	—	19	29	−78	−11	424	0.007
Other areas												
L thalamus		−13	−17	15	3736	0.009		−6	−15	16	2219	0.004
L parahippocampal gyrus	34	−19	0	−20	1346	0.006	34	−20	0	−15	608	0.013
L cingulate cortex	—	—	—	—	—	—	32	−1	18	41	430	0.011
R parahippocampal gyrus	28	22	−4	−24	944	0.008	35	19	−30	−12	336	0.011
Cerebellum												
L anterior lobe (culmen)		−38	−33	−25	568	0.011		−39	−30	−26	5568	0.006
R nodule		4	−51	−28	19240	0.006		—	—	—	—	—
R culmen	—	—	—	—	—	—		6	−51	−17	47500	0.005

* L, left; R, right.

tially overlapped with that during reading Chinese (Fig. 3a,b). Peak activations occurred in the left middle and inferior frontal cortex. Right inferior and mid-medial frontal gyri contributed to both types of processing. As shown in Figure 2, for syntactic processing, greater cortical activity was obtained in the middle frontal gyri (BAs 9 and 10) than in the inferior prefrontal cortex (BAs 45, 47, and 44). For semantic processing, however, the left inferior prefrontal cortex was more immensely involved than the left middle frontal cortex. Cortical activation in the left medial-middle frontal gyrus near BA 6 was also stronger in semantic than in syntactic judgments. These differences were statistically significant.

Activations in the temporal cortex were left-lateralized, heavily housed in the (supero)-middle gyri at BAs 38 and 21, with a pattern that there was a greater activation volume for the semantic processing relative to syntactic analysis. This converges on the finding of Chinese syntactic and semantic analyses. The right fusiform cortex was found to mediate English syntactic and semantic processes.

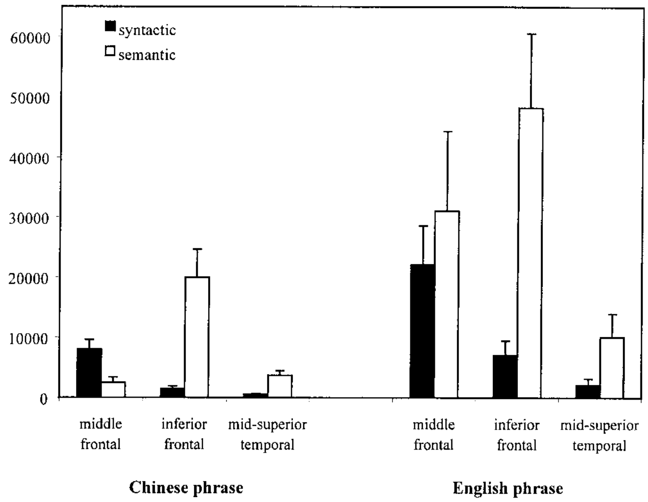

Figure 2.
Activation volume (mm^3) in regions of interest in the left hemisphere.

Of interest is that the left precuneus (BA 19) and the inferior parietal region (BA 40), two areas that were inactive in reading Chinese in the present study, were found to mediate syntactic as well as semantic processes in reading English. The occipital cortex near the left lingual and inferior gyri and the right fusiform contributed to English semantic, rather than syntactic, analysis. This also departs from the result of processing Chinese phrases, because the occipital activity was responsible for both semantic and syntactic judgments in Chinese.

Other important brain activations were observed in thalamus and bilateral parahippocampal gyri for English syntactic and semantic processes. Cerebellum was involved in both tasks as well.

Also observed are greater cortical activities in processing English than Chinese phrases. The cross-linguistic differences in the regions of interest illustrated in Figure 2 were all statistically significant, $P < 0.05$.

DISCUSSION

Three important findings have been demonstrated by the present fMRI study. First, we found that the cortical sites contributing to syntactic analysis of Chinese phrases coincided with the cortical sites relevant to semantic analysis, indicating that syntactic processing is less independent in reading Chinese. Second, we discovered that when our bilingual subjects performed syntactic and semantic acceptability judgments of English phrases, they applied the cerebral systems underlying Chinese reading to the processing of English. Third, the processing of English provoked significantly stronger brain activities in the left frontal and temporal cortex, suggesting that the proficiency of second language reading influences cortical activation. Below we discuss our major findings in detail.

Interaction of Syntactic and Semantic Processes in Reading Chinese

A large-scale distributed neural network covering the left mid-inferior frontal and mid-superior temporal cortices was responsible for the processing of Chinese phrases. The right homologue areas of these left cortical sites were also active, although the brain activity was obviously left-lateralized. Unlike previous research with monolingual English speakers that showed that distinct brain regions mediate syntactic and semantic processing of English [Caplan et al., 1998; Dapretto and Bookheimer, 1999; Friederici et al., 2000; Just et al., 1996; Kang et al., 1999; Moro et al., 2001; Nichelli et al., 1995; Stromswold et al., 1996], the present study found no specific cortical sites that served syntactic, to the exclusion of semantic, analysis of Chinese. Instead, compared to syntactic processing in Chinese, semantic processing activated a larger neural system even involving the left caudate and thalamus.

Although we did not observe a cortical area specialized at syntactic functions, our findings indeed revealed the relative importance of the left middle and inferior frontal regions and the left superior and middle temporal cortex in the two sorts of processing. Stronger brain activity was seen in the left middle frontal cortex for syntactic processing relative to semantic processing. For semantic processing, however, the left inferior prefrontal cortex including BAs 45 and 47 and the left middle-superior temporal gyri (BAs 21 and 38) showed greater activations. This pattern of results implied that (a) the left middle frontal cortex is more involved in syntactic parsing and (b) the left inferior prefrontal and mid-superior temporal regions are more relevant to semantic analysis.

This pattern of data suggests that syntactic processing in Chinese proceeds fundamentally in integration with semantic processing: the syntax of a construction is analyzed in conjunction with semantic processing, indeed, as an integral part of semantic processing. Unlike in English where syntax and semantics are handled essentially separately, in Chinese, syntax is handled under the semantic umbrella, the two components being largely in overlap. Our results indicate that the semantic process is a dominant process, whereas syntactic parsing is secondary and less independent in comprehending Chinese than in comprehending English by native speakers. Hypothetically, although syntactic processing occurs in reading Chinese, it heavily interacts with semantic processing. This possibility is in consonance with recent findings in Chinese linguistic research (as discussed in Introduction) that have highlighted the intimate relationship between syntax and semantics and the analysis of Chinese phrases and sentences.

Our finding of the strong activation of the left middle prefrontal cortex at BA 9 and 46 in syntactic and semantic processing is important. It converges with our previous fMRI findings that showed that this region plays an important role in reading Chinese in several tasks involving word generation, rhyme decision, naming, homophone decision, and semantic judgments [Tan et al., 2001a–c]. Our findings have been buttressed by a recent 3 T fMRI study using Chinese words [Kuo et al., 2001]. We have assumed that the square-shaped intricate visuo-spatial features of Chinese characters demand the activation of the left middle prefrontal cortex, a region that mediates visual-spatial processing of objects [Courtney et al., 1998; D'Esposito et al., 1995; McCarthy et al., 1994; Owen wt al., 1996; Smith and Jonides, 1998]. Our present study further demonstrated that the middle frontal cortex contributes to semantic, in particular syntactic analysis in reading in Chinese.

The heavy involvement of the left inferior prefrontal and supero-middle temporal cortices in semantic processing of Chinese is in line with considerable evidence from alphabetic languages [Chen et al., 2002; Fu et al., 2002]. Thus, it seems that the semantic functioning of these cortical sites is general across languages.

Comprehending English by Chinese-English Bilinguals

Syntactic and semantic processing of English phrases by our bilingual subjects peaked in the left middle and inferior prefrontal cortices. The left middle and superior temporal gyri were also heavily involved. Similar to the two types of processing in Chinese, we found that the left middle frontal gyrus played a greater role in syntactic parsing than the left inferior frontal and temporal cortices. Semantic processing, on the other hand, showed an opposite pattern of activation.

Our results lend additional support to the theory that the neural (and cognitive) system of second language learning is dominated by the learners' first language. Although Chinese-English bilinguals may have a command of English grammar and syntax, as indexed by their high TOEFL scores, nevertheless, as users of English as a foreign language, Chinese students may still heavily rely on a semantics-dominant strategy in understanding English. Thus, like reading in Chinese, syntactic processing in the reading of English might strongly interact with semantic analysis. As a result, the Broca area at BA 44 that is responsible for native English users' syntactic parsing) was not found to be specialized at syntactic processing of English by our bilingual subjects.

Another finding of interest is that the left precuneus and the inferior parietal region at BA 40 contributed to the semantic and syntactic processing of English but not Chinese. As these regions are known to mediate attentional resource allocation [see Smith and Jonides, 1998], their contribution might be due to semantic and syntactic judgments of English phrases being more difficult than those of Chinese phrases for our subjects. We also note, however, that the left inferior parietal cortex has been shown to be relevant to syntactic parsing of English phrases and sentences by native English users [Kang et al., 1999; Keller et al., 2001]. Thus, our result of the involvement of the parietal cortex may suggest that English syntactic analysis requires the activation of this cortical region, whether such a syntactic analysis is performed by native speakers or foreign language users.

Brain Activation is Modulated by Language Proficiency

Our bilingual subjects were more fluent in Chinese than in English, as described in the Method section. Not surprisingly, brain activations in the key sites including left mid-inferior frontal and mid-superior temporal cortices were much stronger in reading English than in reading Chinese. This was true for semantic as well as for syntactic judgments, as illustrated in Figure 3. Therefore, it is obvious that language proficiency modulates brain activity. In a broad sense, we can say that less proficient use of the second language leads reading tasks to be more difficult, which, in turn, results in greater cortical activation volume. It is well established that brain activation increases with task difficulty [Carpenter et al., 1999; Just et al., 1996; Moro et al., 2001; Tan et al., 2000].

In summary, it was found in this study that the comprehension of Chinese constructions proceeds in a way quite different from the comprehension of English constructions as reported in the literature. Unlike English and other languages such as German, the task of comprehending Chinese is strongly oriented to-

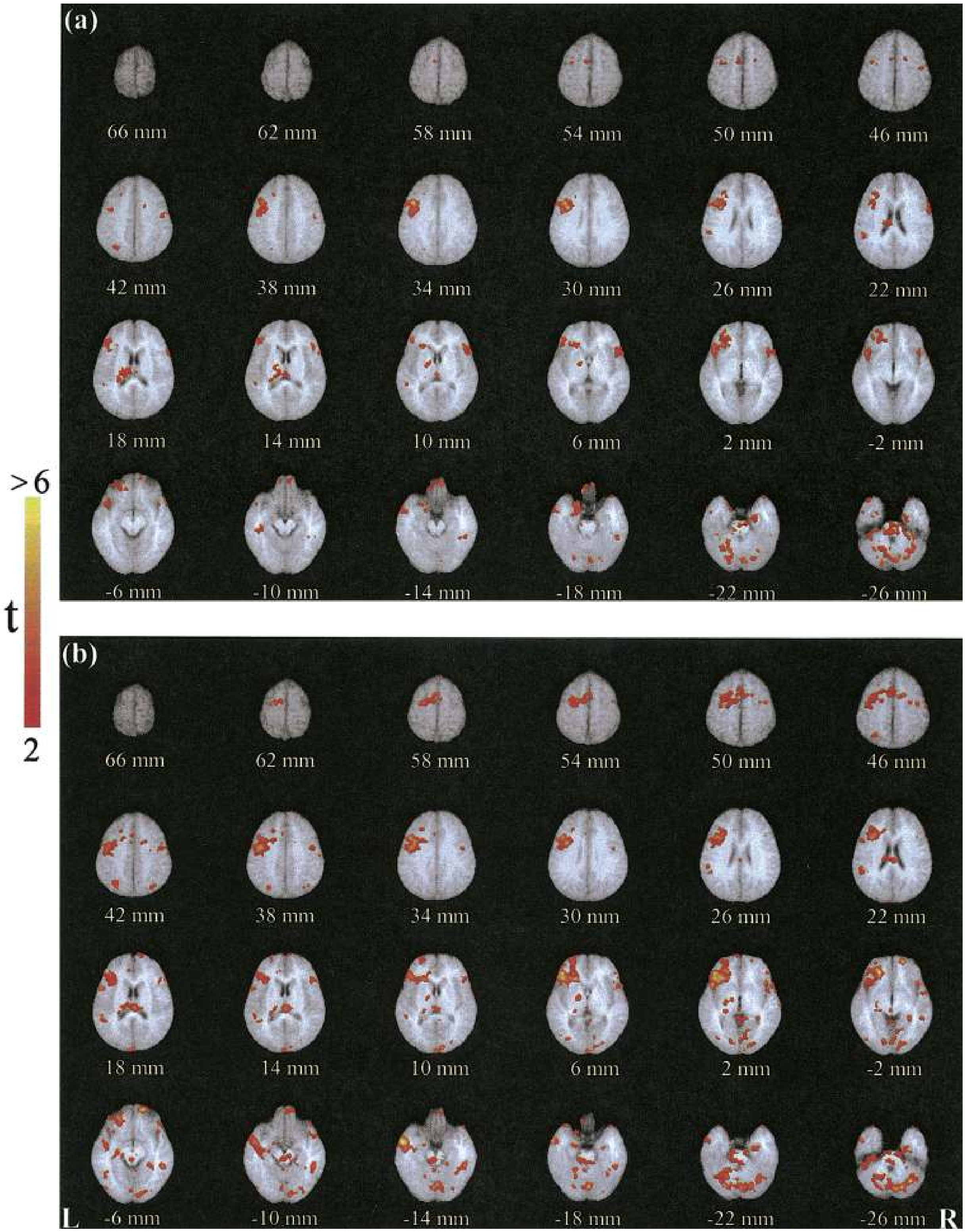

Figure 3.

Averaged brain activations provoked by syntactic and semantic analyses of English by Chinese-English late bilinguals (**a**,**b**). Normalized t-maps (in color) pooled from seven subjects are overlaid on the corresponding T_1 images (in gray scale), demonstrating statistically significant activations ($P < 0.025$). Planes are axial sections, labeled with the height (mm) relative to the bicommissural line (L, left hemisphere; R, right hemisphere). (a) Activations in syntactic processing. (b) Activations in semantic processing.

ward semantics. Syntactic processing does have an important role to play, but it is performed in very close conjunction with, and possibly subsumed under, semantic analysis. In addition, it is interesting that late Chinese-English bilinguals, even if their proficiency level in English is very high, seem nevertheless to resort to "the Chinese strategy" when confronted with the task of comprehending English constructions: they ground syntactic processing in semantic analysis, to which much weight is given. Further research might turn up even more points of interest that would enhance our understanding of the ways in which speakers' processing of linguistic information at the levels of syntax and semantics are affected/determined by the grammatical organization of different languages.

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