Brain Activation in the Processing of Chinese Characters and Words: A Functional MRI Study

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Abstract: Functional magnetic resonance imaging was used to identify the neural correlates of Chinese character and word reading. The Chinese stimuli were presented visually, one at a time. Subjects covertly generated a word that was semantically related to each stimulus. Three sorts of Chinese items were used: single characters having precise meanings, single characters having vague meanings, and two-character Chinese words. The results indicated that reading Chinese is characterized by extensive activity of the neural systems, with strong left lateralization of frontal (BAs 9 and 47) and temporal (BA 37) cortices and right lateralization of visual systems (BAs 17–19), parietal lobe (BA 3), and cerebellum. The location of peak activation in the left frontal regions coincided nearly completely both for vague- and precise-meaning characters as well as for two-character words, without dissociation in laterality patterns. In addition, left frontal activations were modulated by the ease of semantic retrieval. The present results constitute a challenge to the deeply ingrained belief that activations in reading single characters are right lateralized, whereas activations in reading two-character words are left lateralized. *Hum. Brain Mapping 10:16–27, 2000.* © **2000 Wiley-Liss, Inc.**

Key words: MRI; fMRI; neuroimaging; reading; Chinese reading; lateralization; semantic vagueness; hemispheric dominance; word recognition; language

INTRODUCTION

Does the surface form of written languages influence reading processes and cerebral organization? For investigating such a question, the Chinese writing system presents a sharp contrast to English and other alphabetic writing systems. Whereas alphabetic systems are based on the association of phonemes with graphemic symbols, Chinese is based inherently on the association of meaningful morphemes with graphic units. Moreover, alphabetic words have a linear structure whereas Chinese writings (i.e., characters) have a square, nonlinear configuration. It has been suggested that cognitive processes underlying the reading of Chinese characters may differ from those underlying the reading of English words. For example, Rozin et al. [1971] found that when American children who had difficulty reading English were taught to read the English words represented by Chinese characters, they were able to master the reading quite quickly.

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Likewise, prior research has suggested that the neuroanatomical mechanism of Chinese reading is unlike that of English word reading. In particular, studies using the visual hemifield paradigm have demonstrated that the right cerebral hemisphere is more efficient in processing single Chinese characters than the left cerebral hemisphere, whereas there is a reverse tendency in processing two-character Chinese words [Cheng & Yang, 1989; Tzeng et al., 1979]. This result has led to a Chinese character-word dissociation hypothesis in laterality patterns [see Fang, 1997 for review], a hypothesis that has attracted extensive attention because of its departure from the conclusion that the left hemisphere is a dominant hemisphere in processing alphabetic languages [Beaumont, 1982; Binder et al., 1995; Desmond et al., 1995; Gabrieli et al., 1996; Howard et al., 1992; Knecht et al., 2000; Paulesu et al., 2000; Petersen et al., 1988; Price et al., 1994; Springer et al., 1999; Xiong et al., 1998].

It has been assumed that the orthographic structure of single Chinese characters is responsible for the right hemisphere dominance [Tzeng et al., 1979]. Specifically, the Chinese character, as a basic writing unit, possesses a number of strokes that are packed into a square shape. Thus, the character as a whole is a salient perceptual unit. As the right hemisphere is specialized at holistic and spatial processing [Bryden, 1982; Ellis et al., 1988; Jonides et al., 1993; Kosslyn et al., 1993; McCarthy et al., 1994; Smith et al., 1995], it is supposed to be more involved in single character identification than the left hemisphere. As for the two-character Chinese word, it contains two separate characters and its identification undergoes a constituent analysis and assembly process [Tan and Perfetti, 1999]. This coincides with the specialty of the left hemisphere as a temporal, sequential analyzer. Studies with Japanese Kanji and Kana indicated a right hemisphere advantage for processing Kanji (a script highly similar to Chinese characters) and a left hemisphere advantage for processing Kana (a phonetic-based script similar to English), providing a corroboration of the character-word dissociation hypothesis [Hatta, 1977]. Thus, the surface form of writing systems seems to influence cerebral lateralization. The idea that some languages have special processing requirements has also been supported by research on American Sign Language (ASL) that shows that ASL is associated with right hemisphere activations, in addition to left hemisphere activations [Neville et al., 1998].

Subsequent investigations have reported converging evidence for left lateralization in recognizing two-character words [see Fang, 1997], whereas the evidence for right lateralization in recognizing single characters has been mixed. In particular, some studies using the visual hemifield procedure suggested either no difference for the two hemispheres or a left hemispheric superiority [e.g., Besner et al., 1982; Fang, 1997; Leong et al., 1985]. More recently, a neuroimaging study of Chinese character processing by Chee et al. [1999] reported peak activations in the left hemisphere (e.g., Brodmann's area BA 44/45, BAs 46/9 and 37) and strong activations in bilateral occipital and bilateral parietal regions (BA 7). Hence, Chee et al. [1999] found no evidence for right hemisphere dominance. Clinical reports of selective impairments also indicate that Japanese Kanji and Kana are processed by similar neural pathways and that script differences may provide no constraints in cerebral specialization [Koyama et al., 1998; Sugishita et al., 1992].

Obviously, the Chinese character-word dissociation view has over-emphasized the visual-orthographic property of Chinese characters but ignored other dimensions. As noted earlier, written Chinese is a morphemic system that is based on the association of meanings with graphic forms. Moreover, all Chinese characters are pronounceable units, though they map onto phonology at the syllable level (rather than at the phonemic level as English words do). Cognitive research on Chinese reading has well documented that, during identification of a Chinese character, both its visual-orthographic component and its phonological and semantic attributes are activated quite rapidly [Chua, 1999; Perfetti & Zhang, 1995; Pollatsek et al., 2000; Tan et al., 1996; Weekes et al., 1998; Ziegler et al., 2000]. Thus, the left hemisphere, which is usually thought to specialize in analytic, semantic, and phonetic processing, should be at least relevant to the activation of the single character's phonological and meaning components. In this sense, the visual recognition of Chinese characters may engage activations and integrations of the large-scale cortical neural systems responsible for visual-orthographic, phonologic, and meaning attributes. This idea agrees with the proposal that there is a stimulus-related dynamic reconfiguration of large-scale neural networks [Bressler, 1995; Kock & Davis, 1994].

The goal of the present study was to investigate the neural correlates of Chinese single character and two-character word reading using functional magnetic resonance imaging. We were particularly interested in assessing the Chinese character-word dissociation hypothesis of cerebral laterality. Stimuli in this study contained single characters and two-character words. A word generation task was utilized, in which subjects were required to generate a word that was semantically related to the word that they just viewed. This task is similar to the verb generation task developed by Petersen et al. [1988, 1989], with the exception that we did not specify to our subjects that a verb must be generated. Rather, a semantic associate of any type was allowed. This is based on our understanding of the Chinese language that for many characters and two-character words, it is difficult to categorize them into some word class.

Single Chinese characters vary in their semantic precision, which has been demonstrated to influence visual recognition and meaning activation [Tan et al., 1996]. Therefore, in this study, we used two types of characters: characters with vague meanings, and characters with precise meanings. The single character stimuli used were from our previous study [Tan et al., 1996], in which the semantic vagueness-precision of characters was assessed by 25 subjects in terms of a 7-point rating scale ranging from very vague (1), to very precise (7). Chinese two-character words usually have well-defined, precise meanings; thus, we only used one set of two-character words in the present study.

MATERIALS AND METHODS

Subjects

Six male volunteers participated in this functional magnetic resonance imaging (fMRI) study. They gave informed consent in accordance with guidelines set by the University of Texas Health Science Center at San Antonio (UTHSCSA). All subjects were native Chinese (Mandarin) speakers from mainland China, ranging in age from 29 to 39 years and living in the U.S. no more than 6 years.

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 nine 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.

Apparatus and procedure

Experiments were performed on a 1.9 T GE/Elscint Prestige whole-body magnetic resonance imaging (MRI) scanner (GE/Elscint Ltd., Haifa, Israel) at the Research Imaging Center at UTHSCSA. Prior to fMRI imaging, the subject was visually familiarized with the procedures and the experimental conditions to minimize anxiety and enhance task performance. Following this familiarization, the subject lay supine on the scanning table that was supported by a body-length, vinyl-upholstered, dense foam pad. The subject was then fit with plastic ear-canal molds. The subject's head was immobilized by a tightly fitting, thermally molded, plastic facial mask that extended from hairline to chin [Fox et al., 1985].

A T_2*-weighted gradient-echo echo planar imaging (EPI) sequence was used for fMRI scans, with the slice thickness = 6 mm, in-plane resolution = 2.9 mm $\times$ 2.9 mm, and TR/TE/θ = 2000 ms/45 ms/90°. The field of view was 372 mm $\times$ 210 mm, and the acquisition matrix was 128 $\times$ 72. Twenty contiguous axial slices were acquired to cover the whole brain. For each slice, 225 images were acquired with a total scan time of 450 s in a single run. The anatomical MRI was acquired using a T_1-weighted, three-dimensional, gradient-echo pulse-sequence. This sequence provided high-resolution (1 mm $\times$ 1 mm $\times$ 1 mm) images of the entire brain.

Materials and behavioral performance

Three types of stimuli were used for this study, each with 60 items: (a) semantically vague Chinese single characters, (b) semantically precise Chinese single characters, and (c) two-character Chinese words. Figure 1 illustrates the examples of experimental materials. Single characters' semantic vagueness/precision was assessed by 25 subjects. Characters with an average rating greater than 5.5 were classified as semantically precise characters, whereas characters with an average rating less than 4.0 were classified as semantically vague characters. The ratings for the vague characters ranged from 1.92 to 3.96, with an average of 3.0 (SD = 0.58). For the precise characters, the ratings ranged from 5.51 to 7.00, with an average of 6.21 (SD = 0.47). Our cognitive experiments using these isolated characters have reported that the semantic dimension of vague- and precise-meaning characters is activated asynchronously [Tan et al., 1996], implicating that the two sorts of characters used in the present study might well assess the brain activity during reading.

(a)	(b)	(c)
济	雨	加速
cross a river relieve many help aid benefit	rain	acceleration

Figure 1.
Examples of the Chinese characters and words used in the present study: semantically vague Chinese single-character (**a**), semantically precise Chinese single-character (**b**), and two-character Chinese word (**c**). The meaning of each character and word, in English, is also shown in this figure.

Both single-character and two-character words were commonly used and had the frequency of occurrences no fewer than 30 per million according to the *Modern Chinese Frequency Dictionary* [1986]. To control for the possible influence of orthographic properties [Weekes et al., 1998], visual complexity and the ratio of simple and compound characters were matched across the two sets of single characters.

The stimuli were shown through a LED projector system. The experimental task was that the subject silently generated a Chinese word that was semantically related to the Chinese stimulus they just viewed. Each single character or two-character word was presented for 250 ms, followed by fixation for 1,250 ms. Blocks of 20 Chinese stimuli (30 sec) were separated by 20 sec of fixation on a small crosshair. The experiment was conducted in a single run, which consisted of three blocks of vague-meaning characters, three blocks of precise-meaning characters, three blocks of two-character words, and nine blocks of crosshair fixation. Different Chinese characters or words were displayed in each block to avoid any practice effect. Presentation of the three sorts of Chinese items was counterbalanced for each subject and randomized across subjects. During each scan, the subject repeatedly performed the word generation task, a demanding task given that the exposure duration was short.

Data analysis

We used Matlab (The Math Works, Inc., Natick, MA, USA) and in-house software for image data processing [Xiong et al., 1995], including corrections for head motion and global MRI signal shift. Skull stripping of the 3D MRI T_1-weighted images was performed using Alice software (Perceptive Systems, Inc., Boulder, CO, USA). These images were spatially normalized to the Talairach brain atlas [Talairach and Tournoux, 1988] using a Convex Hull algorithm [Downs, 1994; Lancaster et al., 1999].

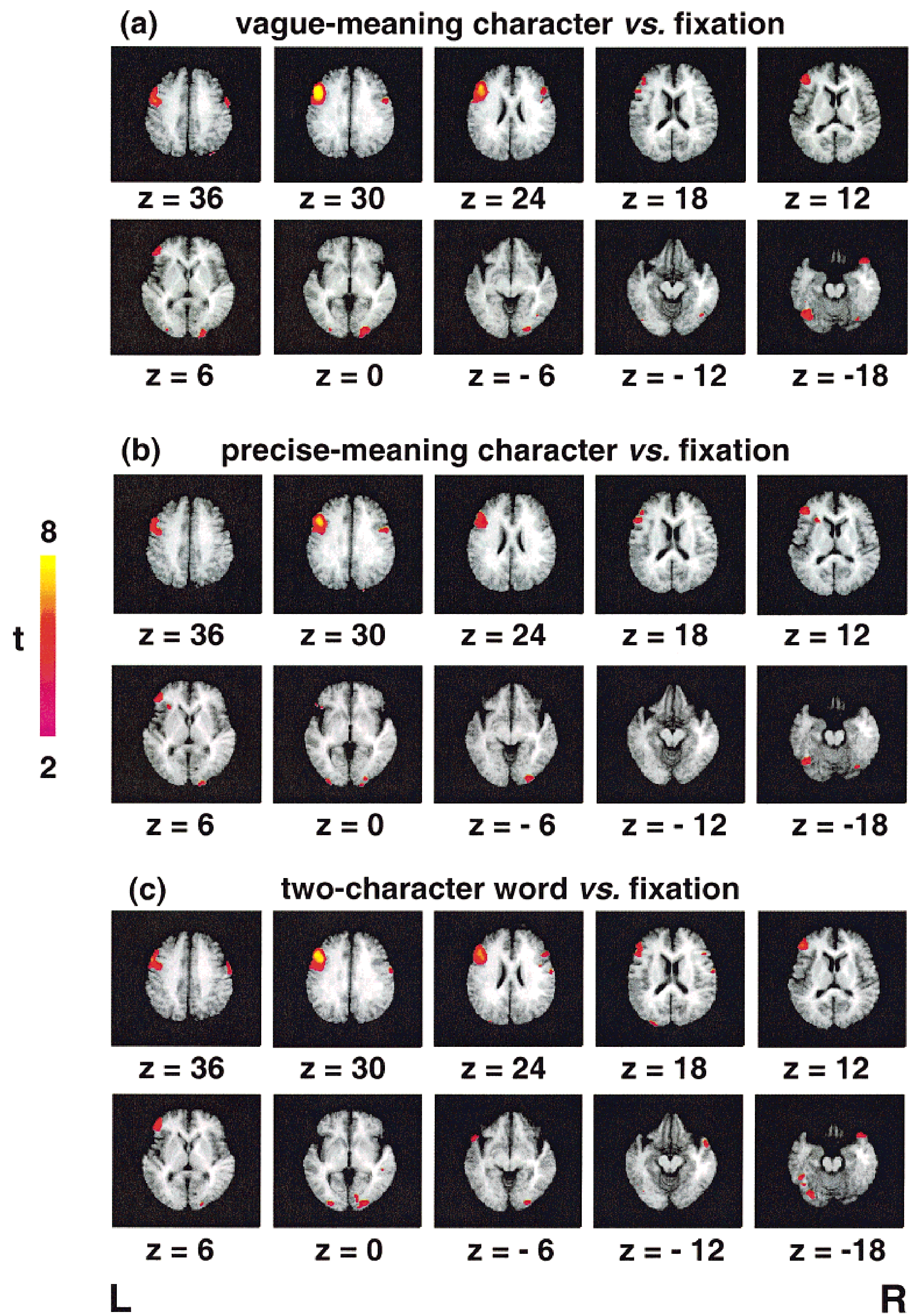
Functional images were grouped into vague-meaning character, precise-meaning character, two-character word, and fixation groups. Images from the first 8 sec of each condition were excluded from further functional data processing, to minimize the transit effects of hemodynamic responses. Activation maps were calculated by comparing images acquired during each task state (vague-meaning characters, precise-meaning characters, and two-character words) with those acquired during the control state (fixation), using a students' group *t*-test. Like T_1-weighted anatomical images, activation maps were also spatially normalized into Talairach space using the Convex Hull algorithm. The averaged activation maps across the six subjects with a t value threshold of 2.0 ($p < 0.025$) 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, gyre) and Brodmann area (BA) designations were applied automatically using a 3-D electronic brain atlas [Lancaster et al., 1997].

To evaluate the intersubject consistency of brain activations associated with Chinese character and word reading, we created penetrance maps by combining binary individual functional maps [Fox et al., 1996]. Penetrance maps were then overlaid on the subjects' group-mean T_1-weighted images to demonstrate the voxels with significant activation in three or more subjects. The binary functional maps were determined using a t value threshold of 2.4 [$p < 0.01$] for each subject.

Laterality was evaluated from the functional maps (Fig. 2): vague-meaning characters vs. fixation, precise-meaning characters vs. fixation, and two-character words vs. fixation. Activation voxels in regions-of-interest (ROIs) were checked to calculate an asymmetry index (AI) for each condition [AI = sum (voxels (L – R)) / sum (voxels (L + R)); Binder et al., 1995; Chee et al., 1999; Desmond et al., 1995]. The value of AI ranges from -1 to $+1$, with a negative value indicating right hemispheric dominance and a positive value indicating left hemispheric dominance.

RESULTS

Brain activation fMRI images averaged across the six subjects for vague-meaning characters vs. fixation,



(a) vague-meaning character *vs.* fixation
z = 36
z = 30
z = 24
z = 18
z = 12
z = 6
z = 0
z = - 6
z = - 12
z = -18
(b) precise-meaning character *vs.* fixation
z = 36
z = 30
z = 24
z = 18
z = 12
z = 6
z = 0
z = - 6
z = - 12
z = -18
(c) two-character word *vs.* fixation
z = 36
z = 30
z = 24
z = 18
z = 12
z = 6
z = 0
z = - 6
z = - 12
z = -18
8
t
2
L
R

Figure 2.

precise-meaning characters vs. fixation, and two-character words vs. fixation are shown in Figure 2. Significant areas of activation for these comparisons are summarized in Table I. The intersubject consistency of regional brain activations for each of the three comparisons is shown in Figure 3 as penetrance images.

Comparisons of each of the three experimental conditions (vague-meaning characters, precise-meaning characters, and two-character words) with fixation showed peak activations in the left middle frontal gyrus (BA 9), left temporal fusiform gyrus (BA 37), right postcentral parietal gyrus (BA 3/1), and right occipital lingual gyrus or cuneus (BA 17/18). The patterns of peak activation were consistent for all three comparisons. Significant activations were also found in the left supplementary motor area (BA 6) for all three comparisons. The vague-meaning character vs. fixation comparison further indicated significant activations in right inferior and middle frontal gyri (BAs 46/9 and 47), whereas the precise-meaning character vs. fixation comparison and the two-character word vs. fixation comparison revealed significant activations in bilateral inferior frontal gyri (BAs 47 and 9). Other activated regions included the right temporal fusiform gyrus for vague-meaning characters, the right superior and middle temporal gyri for two-character words, left superior parietal lobule (BA 7) and left middle occipital gyrus (BA 18) for all three types of Chinese stimuli, and the bilateral fusiform gyrus (BA 19) for the vague-meaning characters. In addition, the right cerebellum was strongly activated in the processing of both single characters and two-character words, a finding that is consistent with the results from the studies of English word reading [Petersen et al., 1988, 1989] and sensory acquisition [Gao et al., 1996; Liu et al., 1999].

Although the locations of significant activations for the three types of Chinese items largely coincided, the extent of activations varied across conditions. We summed the total extent of all activated clusters for each of the three sorts of Chinese items in the frontal, parietal, temporal, and occipital lobes, respectively. Figure 4 illustrates the mean activated voxels across the six subjects in the left and right cerebral hemisphere. Statistical analysis indicated that in the left frontal cortex, the extent of activations was significantly greater for vague-meaning characters and two-character words than for precise-meaning characters; $p < .04$ when the vague-meaning character was compared with the precise-meaning character; and $p < .05$ when the two-character word was compared with the precise-meaning character. Similar patterns were seen in the left temporal and right parietal cortices, although statistical analyses did not approach significance.

Finally, to quantify the asymmetry in functional activation, regions-of-interest (ROIs) were selected a priori based on past findings of language processing foci as described by Petersen et al. [1988, 1989], Wise et al. [1991] and Chee et al. [1999]. We first selected middle and inferior frontal regions (BAs 46, 47, and 9) to calculate the asymmetry index. AIs were, respectively, 0.88, 0.85, and 0.89 for vague-meaning characters, precise-meaning characters, and two-character words. Thus, it is evident that the left frontal lobe is dominant during semantic generation. Considering the salient feature of the Chinese character as a nonlinear square-shaped configuration, we also calculated the AIs for temporal, occipital, and parietal lobes and cerebellum. The results indicated that the left temporal lobe was more strongly activated: AIs were 0.92, 1.00, and 0.82 for vague-meaning characters, precise-meaning characters, and two-character words, respectively. However, the right occipital and parietal cortices were more involved into Chinese word generation in the present study: For the occipital cortex, AIs were −0.77, −0.55, and −0.36 for the three types of stimuli, whereas in the parietal lobe, AIs were −0.39, −0.56, and −0.74, respectively. The AIs were −1.00, −0.42, and −1.00 in cerebellum, indicating that activations in cerebellum were also right lateralized.

Figure 2.
Functional maps. Averaged brain activations involved in the word generation task. Normalized activation brain maps averaged across six subjects demonstrate the statistically significant activations ($p < 0.025$) in the vague-meaning character vs. fixation comparison (**a**), the precise-meaning character vs. fixation comparison (**b**), and the two-character word vs. fixation comparison (**c**). All of the functional maps (in color) are overlaid on the corresponding T_1 images (in gray scale). Planes are axial sections, labeled with the height (mm) relative to the bicommissural line. L = the left hemisphere; R = the right hemisphere.

DISCUSSION

Our results indicate that both the left and the right hemisphere were engaged during the processing of Chinese single-character and two-character words. The left frontal regions (BAs 9, 47) were much more strongly activated than the right frontal regions, demonstrating left hemispheric dominance in the frontal lobe. In the literature on English word reading, it has been implicated that the left frontal gyri contribute to the semantic processing of words [Blaxton et al., 1996; Buckner and Petersen, 1996; Buckner et al., 1995;

TABLE I. Stereotactic coordinates, *t* values, and corresponding Brodmann areas for regions showing significant activations (the region is also given a mnemonic anatomical name associated with the coordinates)[a]

	Vague-meaning characters vs. fixation				Precise-meaning characters vs. fixation				Two-character words vs. fixation			
		Coordinates				Coordinates				Coordinates		
Regions activated	BA	(X, Y, Z)	Vol.	*t*	BA	(X, Y, Z)	Vol.	*t*	BA	(X, Y, Z)	Vol.	*t*
Frontal												
Left middle frontal gyrus	9	(−47, 12, 34)	2476	3.15***	9	(−47, 19, 26)	1352	2.87***	9	(−47, 13, 34)	2906	2.99***
Left medial/middle frontal gyrus	6	(−2, 2, 52)	620	2.87***	6	(−3, 2, 51)	479	2.73***	6	(−3, 0, 55)	477	2.85***
	6	(−36, −3, 45)	4	2.04*		—			6	(−4, 16, 44)	1	2.00*
Left precentral gyrus		—			6	(−45, −6, 54)	359	2.79***		—		
Left inferior frontal gyrus		—			47	(−53, 30, −1)	15	2.12*	47	(−52, 21, −4)	95	2.35*
		—			47	(−43, 25, 0)	4	2.05*		—		
Right middle frontal gyrus	46	(48, 21, 23)	83	2.43**	46	(48, 21, 22)	9	2.06*	46	(51, 22, 24)	93	2.30*
Right inferior frontal gyrus					9/44	(51, 5, 32)	98	2.40**	47	(42, 25, −18)	72	2.40**
	9/44	(45, 4, 25)	7	2.07*		—			9/44	(43, 3, 24)	4	2.05*
Temporal												
Left temporal fusiform gyrus	37	(−42, −61, −12)	261	2.38**	37	(−48, −56, −14)	1	2.05*	37	(−40, −58, −12)	366	2.37**
	37	(−44, −43, −10)	13	2.11*		—				—		
Right temporal fusiform gyrus	37	(42, −59, −11)	12	2.13*		—				—		
Right superior/middle gyrus		—				—			38	(52, 10, −11)	33	2.30*
		—				—			21	(49, −33, 0)	4	2.10*
Parietal												
Left superior parietal lobule	7	(−40, −65, 52)	259	2.55**	7	(−38, −66, 54)	74	2.28*	7	(−38, −65, 51)	132	2.45**
Left precuneus	19	(−28, −78, 44)	37	2.23*		—				—		
Right postcentral gyrus	3	(51, −13, 48)	660	2.44**	3	(49, −16, 53)	175	2.29*	1	(52, −17, 47)	880	2.53**
Right precuneus	19	(35, −82, 36)	7	2.06*						—		
		—			19	(33, −80, 34)	2	2.04*		—		
Right inferior parietal lobule		—			40	(50, −37, 54)	78	2.23*		—		
Occipital												
Left middle occipital gyrus	18	(−31, −88, 3)	38	2.18*	18	(−32, −95, 0)	72	2.15*	19	(−28, −90, 20)	48	2.21*
		—				—			18	(−28, −89, 1)	44	2.25*
Left fusiform	19	(−45, −72, −12)	2	2.04*		—			19	(−40, −68, −12)	1	2.10*
Left superior occipital gyrus					19	(−40, −82, 32)	1	2.01*		—		
Right cuneus or lingual gyrus	17	(22, −91, 1)	281	2.43**	18	(22, −94, −1)	246	2.27*	17	(22, −88, −1)	176	2.45**
		—			19	(19, −91, 30)	3	2.12*	18	(10, −79, 0)	17	2.09*
		—				—			18	(9, −97, 10)	4	2.11*
Right fusiform gyrus	19	(41, −64, −9)	23	2.14*		—				—		
Right middle occipital gyrus	18	(22, −94, 20)	1	2.02*		—				—		
Cerebellum												
Left declive		—				(−40, −60, −22)	275	2.48**		—		
Right pyramis/uvula		(27, −63, −27)	476	2.53**		(27, −63, −27)	672	2.58**		(26, −73, −23)	65	2.25*
Right cerebellar tonsil		—				—				(32, −53, −31)	24	2.11*

[a] Vol = Activation volume (voxels), BA = Brodmann's area.
* $P < .025$ uncorrected for multiple comparisons; ** $P < .01$ uncorrected; *** $P < .005$ uncorrected.

Demb et al., 1995; Gabrieli et al., 1996; Kapur et al., 1994; Petersen et al., 1988, 1989; Poldrack et al., 1999; Ricci et al., 1999; Roskies et al., 1996; Wagner et al., 1997; see Fiez, 1997 for a summary]. The word-generation task used in our study required explicitly semantic retrieval of a Chinese item; we infer that the left frontal regions are relevant to the semantic activation of both Chinese single characters and two-character words. Peak activations were localized within the left prefrontal region (BA 9) for single-character as well as two-character words, implicating that common regions are recruited to maintain access to semantic information in reading Chinese.

Activations in the occipital and parietal cortices were right-lateralized. The activated occipital areas, such as the lingual gyrus and the fusiform gyrus (BAs 17–19), are supposed to be relevant to the processing of the visual properties of Chinese characters and words. The reason why the right parietal regions (BAs 3 and 1) were strongly activated is not clear.

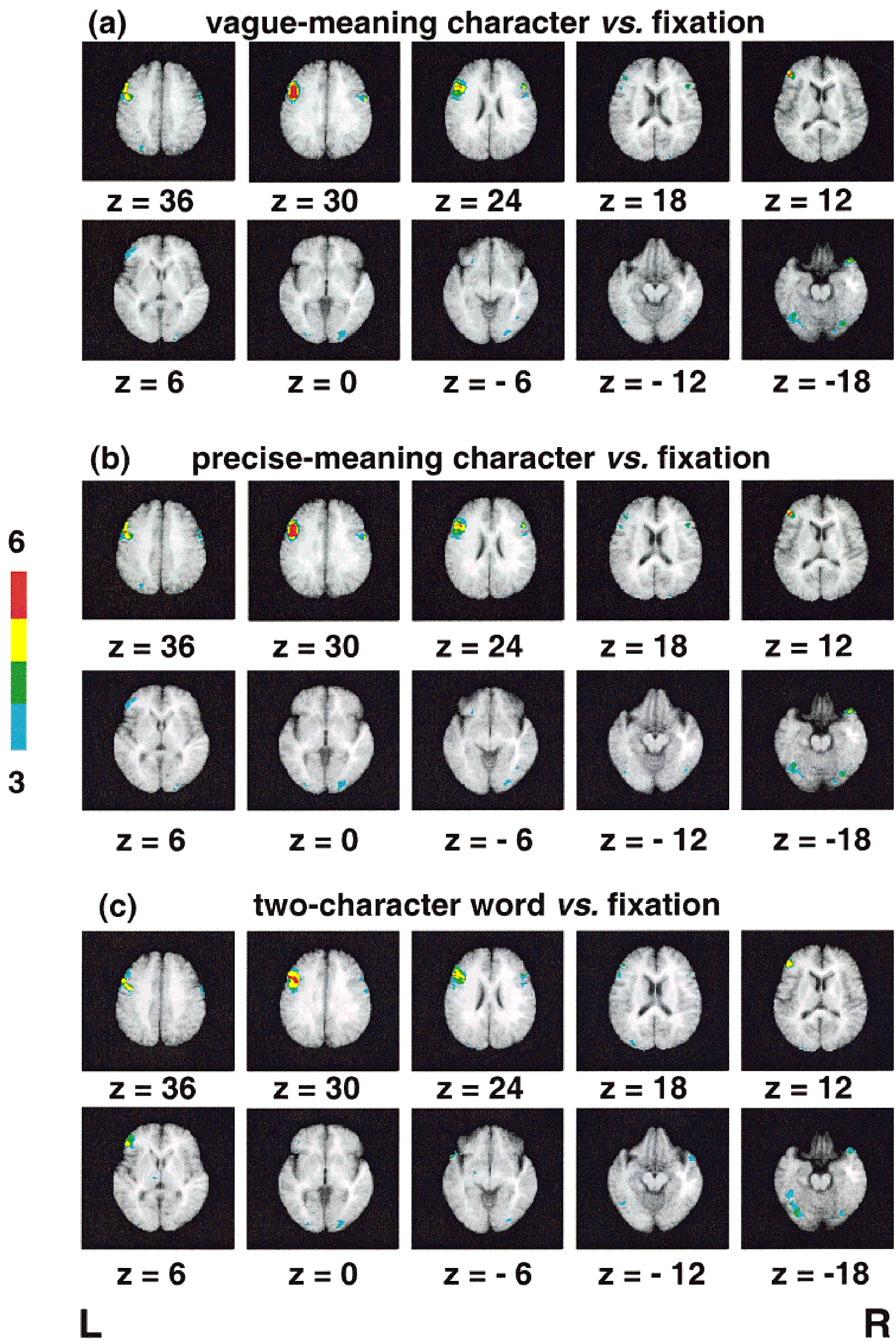
Our results do not support the Chinese character-word dissociation hypothesis that assumes right lateralization in recognizing single characters and left lateralization in recognizing two-character words. We found that the activations in the frontal and temporal lobes were left-lateralized, whereas the activations in the visual cortex were right-lateralized both for single-character as well as for two-character words. There was no dissociation between the regions responsible for isolated characters and the regions responsible for two-character words.

Another important finding is that the total extent of the activations in the left frontal cortex was significantly larger for vague-meaning characters and two-character words than for precise-meaning characters. There is no quantifiable difference between the former two kinds of Chinese stimuli. This pattern of brain activation indicates that the comprehension of visually presented Chinese characters and words generates cortical activations that increase with the retrieval difficulty of the meaning of characters and words. Semantically precise characters have well-defined meanings that are easy to retrieve out of context. Semantically vague characters,[1] however, have too many distinct and frequently used meanings that often cause retrieval difficulty when the reader is asked to explain those characters' meanings out of context. Two-character Chinese words have a well-specified meaning, but their recognition undergoes a constituent character assembly process, a process that increases processing complexity and is not necessary for single precise-meaning characters [Tan & Perfetti, 1999]. Hence, it is plausible that the volume of brain activations varied across the three types of Chinese stimuli. Our results provide neural evidence for the construct of semantic precision/vagueness. They are also in line with the results reported by Just et al. [1996] that the linguistic complexity of the English sentence modulated the extent of brain activation.

One may argue that the aforementioned result that brain activations varied across the three types of stimuli indicates that the activation in the left frontal regions might be relevant to phonological but not semantic processing. This is because phonological processing is more involved with vague-meaning characters and two-character words [relative to precise-meaning characters; see Tan and Perfetti, 1999; Tan et al., 1996], which, in turn, leads to stronger brain activities. We believe that this argument is highly speculative, because the word-generation task we used in the present study is, after all, based on the explicit retrieval of the "meaning" of the stimuli. As we discussed in the preceding section, there is ample evidence implicating the importance of the left frontal regions in semantic processing and memory of English words.

The basal temporal area (BA 37) was consistently activated both for single-character and for two-character words. This provides a corroboration of Chee et al.'s [1999] finding with a generation task that required the subject to complete a Chinese compound word or a character after they viewed a cued character or character component. It also agrees with results from non-Chinese reading studies that show that this area participates in word recognition [Brunswick et al., 1999; Demonet et al., 1992; Fiez et al., 1996; Herb-

[1]Semantic information about Chinese characters is not as readily accessed as is widely assumed [Tan et al., 1996]. One possible reason is that each Chinese character has acquired multiple frequently-used meanings because of a limited number of characters (approximately 4,500, according to the *Modern Chinese Frequency Dictionary*, 1986) being used in the present day. As a consequence, when readers are required to retrieve the meaning of some characters in isolation, they often have difficulty. A comparison of Chinese and English may help to elucidate why Chinese characters must acquire rich meanings. Cheng [1982] indicated that only 2,460 characters are needed to amount to 99% of a 1,177,984-character Chinese corpus, whereas 40,000 English words are needed to account for the same proportion of a one million-word English corpus. Another reason for the difficulty in accessing the meaning of some Chinese characters in isolation is that two-character words amount to 64% of all Chinese words, whereas single characters that can be used independently (as a "word") make up only 34%. Some Chinese characters have lost their independent and distinctive meanings during the formation of two-character words.



(a) vague-meaning character vs. fixation
z = 36
z = 30
z = 24
z = 18
z = 12
z = 6
z = 0
z = - 6
z = - 12
z = -18
(b) precise-meaning character vs. fixation
6
3
z = 36
z = 30
z = 24
z = 18
z = 12
z = 6
z = 0
z = - 6
z = - 12
z = -18
(c) two-character word vs. fixation
z = 36
z = 30
z = 24
z = 18
z = 12
z = 6
z = 0
z = - 6
z = - 12
z = -18
L
R

Figure 3.

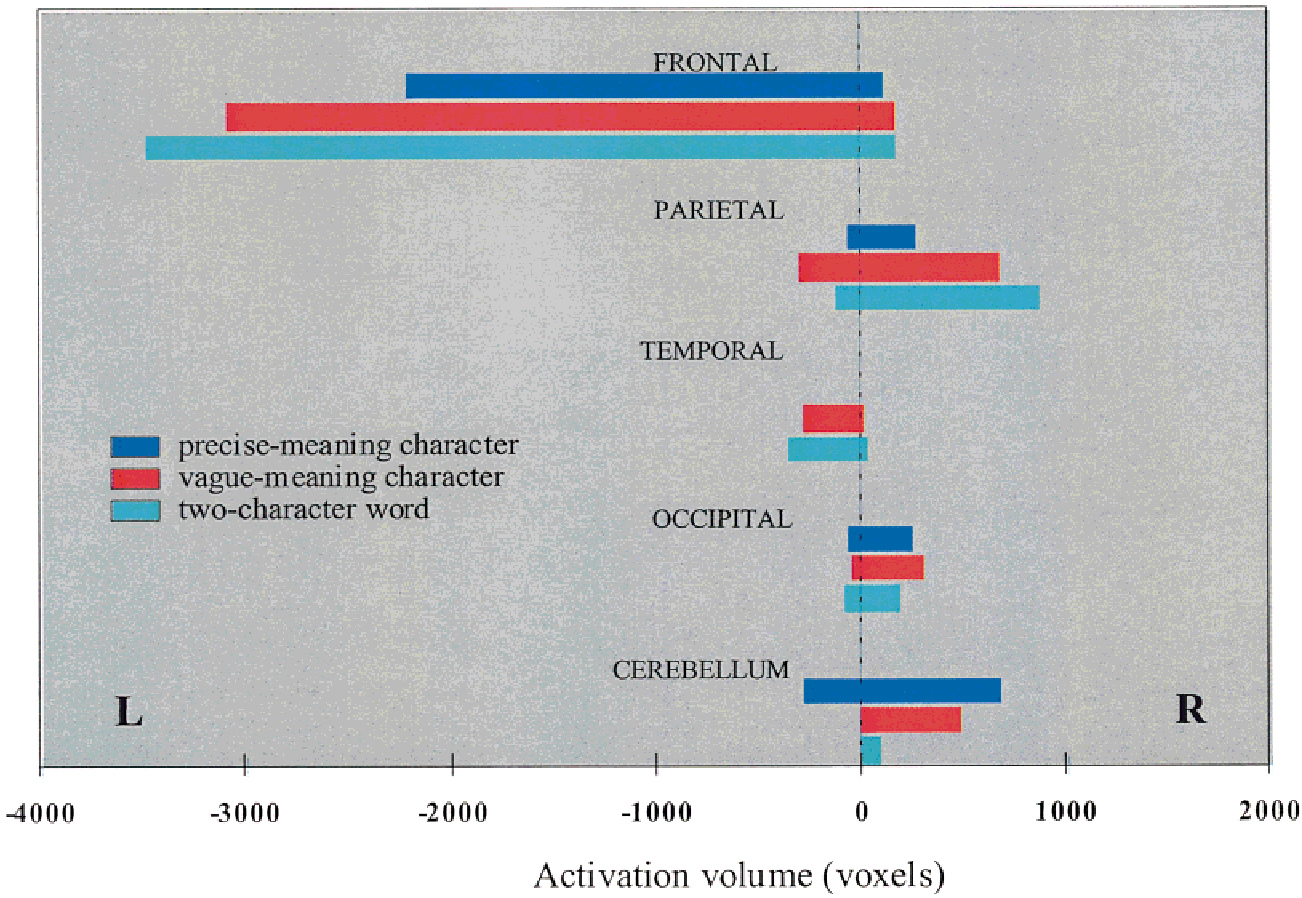


Figure 4.

Volume (mm^3) of total activations. Based on the averaged activation maps, the volume of the total statistically significant activations ($p < 0.025$) in frontal, parietal, temporal, and occipital cortices and cerebellum are shown in this figure. As shown in this figure, the volume of cortical activations was modulated by the complexity of meaning retrieval in reading Chinese. L = the left hemisphere; R = the right hemisphere.

ster et al., 1997; Koyama et al., 1998; Makabe et al., 1997; Nobre et al., 1994; Wise et al., 1991] and is an association region that integrates converging inputs from many regions [Buchel et al., 1998].

In summary, our findings indicate that the processing of written Chinese characters and words is left lateralized in the frontal and temporal cortices and right lateralized in the visual systems, parietal cortex, and cerebellum. Regional activations were modulated by the ease of semantic retrieval as assessed by isolated characters' semantic vagueness. The strongly activated brain regions coincided nearly completely both for single-character and for two-character words, without dissociation in laterality.

Figure 3.

Penetrance maps. By combining binary individual functional maps ($p < 0.01$), the penetrance maps demonstrate the voxels with significant activation in three or more subjects, with the conditions of vague-meaning character vs. fixation (**a**), precise-meaning character vs. fixation (**b**) and two-character word vs. fixation (**c**). All of the penetrance maps (in color) are overlaid on the corresponding T_1 images (in gray scale). Planes are axial sections, labeled with the height (mm) relative to the bicommissural line. L = the left hemisphere; R = the right hemisphere.

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