

The Neural System Underlying Chinese Logograph Reading

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Written Chinese as logographic script differs notably from alphabets such as English in visual form, orthography, phonology, and semantics. Thus, research on the Chinese language is important to advance our understanding of the universality and particularity of the organization of language systems in the brain. In this study, we examine the neural systems associated with logographic reading using functional magnetic resonance imaging. Two experimental tasks were devised, one based on semantic decision and the other on homophone decision. Compared to the fixation baseline, peak activations resulting from semantic as well as homophony decisions were localized in the left middle frontal gyrus (BA 9). Left inferior frontal cortex also mediated Chinese processing. In addition, more right hemisphere cortical regions (i.e., BAs 47/45, 7, 40/39, and the right visual system) were involved in reading Chinese relative to reading English. This is attributed to the square shape of the logograph which requires an elaborated analysis of the spatial information and locations of various strokes comprising the logographic character. We suggest that the left middle frontal area (BA 9) coordinates and integrates the intensive visuospatial analysis demanded by logographs' square configuration and the semantic (or phonological) analysis required by the present experimental tasks. Our study has implicated brain regions common to both logographic and alphabetic languages as well as brain regions specialized in processing logographs. © 2001 Academic Press

Key Words: fMRI; reading; reading Chinese; BA 9; word recognition; Chinese character identification.

INTRODUCTION

Recent research measuring task-related changes in regional cerebral blood flow and oxygenation with positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) has yielded impor-

tant insights into the neural systems underlying word recognition and reading in the human brain. A large-scale distributed cortical network, including left frontal, temporal, and occipital cortices, has been suggested to mediate the processing of visuo-orthographic, phonologic, semantic, and syntactic constituents of alphabetic words (Binder *et al.*, 1995; Bookheimer *et al.*, 1995; Brunswick *et al.*, 1999; Caplan *et al.*, 2000; Demonet *et al.*, 1992; Desmond *et al.*, 1995; Fiez *et al.*, 1999; Gabrieli *et al.*, 1996; Howard *et al.*, 1992; Just *et al.*, 1999; More and Price, 1999; Petersen *et al.*, 1988; Poldrack *et al.*, 1999; Price *et al.*, 1994; Shaywitz *et al.*, 1996). Due to the variety of written languages, investigations with different written scripts have added to the challenge of mapping language functions onto the brain. There are several studies implicating distinct cortical areas that are associated with the processing of different languages (Dehaene *et al.*, 1997; Gandour *et al.*, 2000; Kim *et al.*, 1997; Mazoyer *et al.*, 1993; Neville *et al.*, 1998; Paulesu *et al.*, 2000; Perani *et al.*, 1996). Other studies, however, have reported that common neural networks are recruited during the recognition of various written scripts (Hagoort *et al.*, 1999; Illes *et al.*, 1999; Klein *et al.*, 1994, 1995).

Research on written Chinese will advance our understanding of the commonality and particularity of the organization of language systems in the brain, as the design principle of the Chinese writing system differs markedly from the design principle of alphabetic systems such as English and French. Written Chinese is considered to be a logographic system, in which characters as a basic writing unit possess a number of strokes that are packed into a square shape. Chinese characters map onto meaningful morphemes rather than phonemes in the spoken language, implying that regular or quasi-regular grapheme-phoneme conversions that exist in all alphabetic languages (e.g., the letter *b* is pronounced /b/) are impossible in Chinese (Plaut *et al.*, 1996; Tan and Perfetti, 1998). Rather, a

Chinese characters' pronunciation is defined at the syllable level and must be learned through rote memory of the association of visual character form and sound, occasionally with the aid of subcharacter units that are themselves real characters. These unique characteristics imply that some of the neurocognitive mechanisms underlying Chinese logographic reading may differ from those underlying alphabetic word reading (Tan and Perfetti, 1998; Weber-Fox and Neville, 1996).

Most of the past research with Chinese has adopted the visual hemifield paradigm in an attempt to ascertain whether a Chinese characters' unique square configuration leads to the dominance of the right cerebral hemisphere. So far, the conclusions have been contentious (Cheng and Yang, 1988; Fang, 1997; Naeser and Chan, 1980; Tzeng *et al.*, 1979). More recent investigations with fMRI suggest that, although brain activations during reading aloud of Chinese characters are bi-lateralized (Tan *et al.*, 2001), silent reading of Chinese is dominated by the activity of the left hemisphere (Chee *et al.*, 1999a, 1999b; Tan *et al.*, 2000). Neuroimaging findings with Japanese Kanji, which is similar to Chinese characters in orthography, seem to provide a corroboration of the results from Chinese reading (Fujimaki *et al.*, 1999; Uchida *et al.*, 1999).

Despite the absence of an interhemispheric difference in processing logographic Chinese and alphabetic English, reading in Chinese results in some important neural activity that is rarely observed during the reading of English. In our previous research (Tan *et al.*, 2000; Xiong *et al.*, 2000) with single characters and two-character Chinese words, subjects covertly generated a word that was semantically related to each viewed stimulus. While the left inferior prefrontal areas (Brodmann's areas [BA] 47 and 45) were involved in the semantic generation of Chinese stimuli, a finding that agrees with the finding of the loci of semantic processing and meaning retrieval of English words (e.g., Buckner and Petersen, 1996; Buckner *et al.*, 1995; Demb *et al.*, 1995; Gabrieli *et al.*, 1996; Petersen *et al.*, 1988; Ricci *et al.*, 1999; Roskies *et al.*, 1996; Wagner *et al.*, 1997; reviewed by Price, 1997 and Gabrieli *et al.*, 1998), peak activation during Chinese reading was localized in the middle frontal lobe (BA 9), a region that is rarely reported in neuroimaging studies of the processing of alphabetic words.

Our previous results (Tan *et al.*, 2000) implicated a possible segregation of the cortical organization of written Chinese and alphabets. However, the word generation responses of each subject were not monitored during the fMRI study. Thus, cognitive processes involved in that task are not clear.

The objective of the present study was to further elucidate the neural system that contributes to reading Chinese. We used two experimental tasks: a semantic judgment task and a homophone judgment task. In the semantic task, subjects were asked to judge whether a

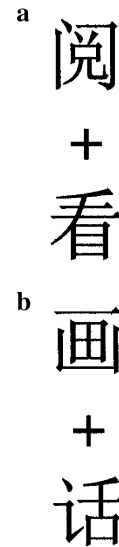


FIG. 1. Examples of experimental stimuli used in the experiment. In a, the subject judged whether the two Chinese characters were semantically related or not. The character above the fixation crosshair is pronounced /yue/, with a meaning of "view" and "read." The character below the fixation crosshair is pronounced /kan/, meaning "look" and "view." In b, the subject judged whether the two Chinese characters were homophones or not. The character above the fixation crosshair is pronounced /hua/, with a meaning of "draw." The character below the fixation crosshair is also pronounced /hua/, meaning "talk" and "words." From these examples, we find that Chinese characters look very different from English words. Each Chinese character is made up of a number of strokes, the smallest writing unit of Chinese logographs. These strokes are assembled into a square shape according to stroke sequence rules that readers learn in primary school. For example, the character 阅 consists of the following 10 strokes: | \ 丿 丨 丨 丨 丨 丨 丨 丨 丨. The modern Chinese uses approximately 5000 characters and 420 distinct syllables (i.e., pronunciations, disregarding tone) (Tan and Perfetti, 1998). Thus, homophones abound. It is quite easy to find Chinese characters that are pronounced identically but look very different. In our study, the two characters exposed in each pair shared no visual similarity.

pair of Chinese characters exposed synchronously were semantically related. In the homophone task, subjects were required to decide whether a pair of Chinese characters exposed synchronously were homophones. For both tasks, we monitored the subjects' performance. To control for the effects of word familiarity on cognitive and neuronal activities (Fiez *et al.*, 1999; Pugh *et al.*, 1997), the stimuli used in our experiment were matched across frequencies of occurrences. Moreover, the two Chinese characters exposed in each pair shared no visuo-orthographic similarity so that the subject had to make a decision based on characters' semantic or phonological attributes rather than based on their visual properties. Figure 1 shows examples of experimental stimuli used in our study.

In this study, the experimental tasks alternated with a control task in which the subject maintained fixation on a crosshair. Functional brain activation was measured during each block, using fMRI. Comparisons of

each of the two experimental tasks with the baseline allowed us to identify the holistic neural network active during reading Chinese.

METHODS

Subjects

Six male volunteers participated in this 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 40 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 which 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.

Materials and Behavioral Performance

Forty-four pairs of semantically related Chinese characters and 44 pairs of homophones were used in this study. For the semantically related pairings, we asked 20 informants who were not participants of this study to assess their semantic relatedness in terms of a 7-point rating scale, ranging from 1 (not related at all) to 7 (very closely related). We added 50 pairs of semantically unrelated characters to serve as fillers in this rating scale. The ratings for the 44 semantically associated pairs ranged from 5.50 to 7.00, with an average of 6.0 (SD = 0.58). Homophones are pervasive in Chinese. However, Chinese is a tonal language that uses four distinctive tones (in Mandarin), and a complete specification of a Chinese syllable (pronunciation) involves both its segmental (consonants plus vowels) and suprasegmental tonal information (Spinks *et al.*, 2000). To avoid any possible effects from tone variation, the 44 pairs of homophones used in this study satisfied the constraint that they shared both segments as well as tones.

All Chinese characters used were common characters with a frequency of occurrence no fewer than 25 per million according to the Modern Chinese Frequency Dictionary (1986). To control for possible influences of familiarity and orthographic variation

(Weekes *et al.*, 1998), character frequency and visual complexity (as measured by the number of strokes in the character) were matched across the homophonic pairs and the semantic pairs.

The stimuli were shown through a LED projector system. The two experimental tasks were the semantic decision task, in which subjects judged whether the two characters they viewed were semantically related, and the homophone decision task, in which subjects decided whether the two characters were homophones. In each trial, a pair of characters were exposed synchronously for 500 ms, one above and one below a fixation crosshair. After the presentation of the two characters, a fixation crosshair was exposed for 1000 ms. Subjects were asked to perform the experimental task as quickly and accurately as possible. They indicated a positive response by pressing the key corresponding to the index finger of their right (dominant) hand and a negative response by pressing the key corresponding to the index finger of their left (nondominant) hand. A block design was adopted in this study. Semantically related characters (or homophonic characters) were randomized within 24 s blocks comprised of 11 pairs of semantically related characters (or 11 pairs of homophones) and 5 pairs of unrelated characters that served as fillers. In the control scan, the subject maintained fixation on a crosshair. Blocks of 16 pairs of Chinese stimuli (24 s) were separated by 20 s of fixation. The experiment was conducted in a single run, which consisted of four blocks of semantic decision, four blocks of homophone decision, and eight blocks of crosshair fixation. Presentation of the semantic pairs and homophone pairs was counterbalanced for each subject and randomized across subjects.

Apparatus and Procedure

The fMRI experiment was performed using a 1.9 T GE/Elscint Prestige whole-body 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 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 = 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 373 \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, 176 images were acquired with a total scan

time of 352 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 ($1 \times 1 \times 1$ 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 3-D 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; Lancaster *et al.*, 1999).

Functional images were grouped into semantic decision, homophone decision, and fixation groups. Images from the first 8 s 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 (semantic judgment and homophone judgment) with those acquired during the control state (fixation), using a students' 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 six subjects with a *t* value of 2.4 ($P < 0.01$) 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 3-D electronic brain atlas (Lancaster *et al.*, 1997).

Laterality was evaluated from the functional maps. Activated voxels in regions of interest (ROIs) were used to calculate an asymmetry index (AI) ($\text{AI} = \frac{\text{sum} [\text{voxels} (\text{L} - \text{R})]}{\text{sum} [\text{voxels} (\text{L} + \text{R})]}$; Binder *et al.*, 1995; Chee *et al.*, 1999a; Desmond *et al.*, 1995). The values of AI range from -1 to $+1$, with a negative value indicating right hemispheric dominance and a positive value indicating left hemispheric dominance.

RESULTS

Behavioral Data

Average response accuracies and reaction times across subjects were 84%/767 ms and 88%/762 ms for semantic and homophone judgments, respectively. The differences were statistically nonsignificant, with both *F* values less than one. Thus, the two experimental tasks used in this study were regarded as equally difficult (Gabrieli *et al.*, 1998).

Activation data

Semantic judgment versus fixation. The fMRI images averaged across subjects for the semantic decision vs fixation comparison are shown in Fig. 2. Significant areas of activation in the frontal lobe, as summarized in Table 1, encompassed left middle frontal gyrus (BA 9), bilateral inferior and middle prefrontal gyri (BAs 45/47/11), bilateral frontal pole (BA 10), and precentral (motor) gyri (BAs 6 and 4). Peak activation was located in the left middle frontal cortex (BA 9) with an activation volume of 782 (voxels). To quantify an asymmetry index of functional activation ($\text{AI} = \frac{\text{sum} [\text{voxels} (\text{L} - \text{R})]}{\text{sum} [\text{voxels} (\text{L} + \text{R})]}$), we selected the middle and inferior frontal areas as regions of interest (ROIs). AI was 0.62, indicating a strong left lateralization.

Activations in the parietal lobe were bilateralized. Both left and right superior parietal lobules (BA 7) and inferior or postcentral parietal gyri (BA 40) were significantly activated. In the occipital lobe, activation in left infero-middle gyrus (BA 18) was present. However, activations in the right cortex covering the cuneus, fusiform, and inferior gyrus were stronger than activations in the left cortex, revealing right lateralization ($\text{AI} = -0.57$). Activations in the temporal lobe were localized to the right superior and middle gyri (BA 38). In addition, the left and right sublobar caudate, as well as cerebellum, were involved.

Homophone judgment versus fixation. The comparison of homophone decision with fixation produced a pattern of brain activation similar to that produced by the comparison of semantic decision and fixation (Fig. 3 and Table 2). Peak activation occurred in left middle frontal gyrus (BA 9). Bilateral inferomiddle prefrontal cortex (BAs 44/45 and 47/10) and left medial prefrontal lobe (BA 11) were active. Activations in these areas were left lateralized, $\text{AI} = 0.34$. Bilateral precentral (motor) gyri (BA 4/6) were also active. In the parietal cortex, the bilateral superior parietal lobule (BA 7), left postcentral gyrus (BA 3) and right precuneus (BA 39) were involved. In the occipitotemporal regions, significant activations occurred in the left and right cuneus (BA 17/18), the extrastriate cortex covering left inferior gyrus (BA 18), the right fusiform gyrus and lingual gyrus (BAs 18 and 19). The left sublobar and right sublobar caudate, as well as cerebellum, were also activated.

Brain regions active during the homophone decision task but not the meaning decision task relative to fixation were bilateral middle temporal lobes (BAs 21 and 22). Thus, the activation from the occipital cortex extended rostrally to the bilateral temporal gyrus.

DISCUSSION

We have shown that reading logographic Chinese is characterized by extensive brain activation. Compared

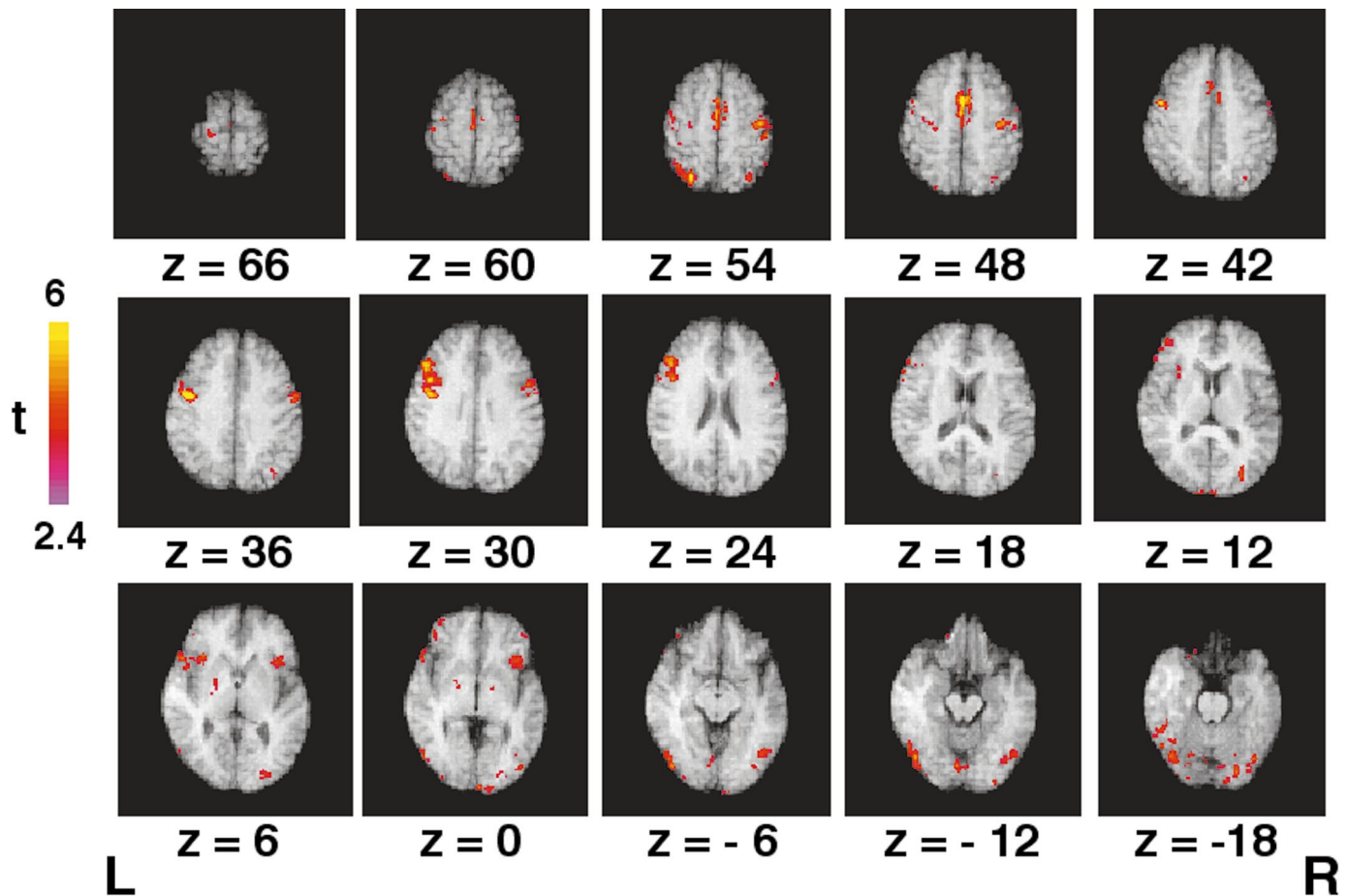


FIG. 2. Functional maps. Averaged brain activations involved in the semantic decision task compared to fixation. Normalized activation brain maps averaged across six subjects demonstrate the statistically significant activations ($P < 0.01$). All of the functional maps (in color) are overlaid on the 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.

to fixation baseline, the distributed neural networks activated by semantic and homophone decisions largely overlapped. Many of the activated areas that contributed to reading Chinese have been implicated in previous work on alphabetic languages. For instance, a number of studies using alphabetic words demonstrated involvement of ventral occipitotemporal regions, such as the fusiform and lingual gyri (Petersen *et al.*, 1990; Pugh *et al.*, 1997), the left inferior frontal lobe including BAs 44/45 and BA 47 and the neighboring vicinity (Cappa *et al.*, 1998; Demb *et al.*, 1995; Demonet *et al.*, 1992; Fiez *et al.*, 1999; Illes *et al.*, 1999; Mummery *et al.*, 1999; Paulesu *et al.*, 1993; Petersen *et al.*, 1988; Poldrack *et al.*, 1999; Ricci *et al.*, 1999; Vandenberghe *et al.*, 1996; Zatorre *et al.*, 1992), and the temporo-occipitoparietal junction (BA 39/19) (Hodge and Patterson, 1997; Mummery *et al.*, 1998; Price *et al.*, 1997). Cerebellum was also engaged in English word reading, as reported by Petersen *et al.* (1988), Herbster *et al.* (1997), and Rumsey *et al.* (1997), among

others. This supports our hypothesis that the function of the cerebellum goes beyond motor coordination (Gao *et al.*, 1996; Liu *et al.*, 1999). The presence of significant activations in these cerebral and cerebellar regions indicates that some brain areas are involved in reading, regardless of the particular language.

However, our results also reveal an important difference in cortical organizations across languages. As can be seen in Figs. 2 and 3, both semantic and homophone decisions showed that peak activation in the processing of logographs was located in the left lateral middle frontal cortex (BA 9), a region above Broca's area. This finding is in line with our previous result from word generation of Chinese characters (Tan *et al.*, 2000) and is also corroborated by the activation result of some of the subjects in the Chinese reading studies by Chee *et al.* (1999a, 2000). Nevertheless, past investigations with English and other alphabetic languages, whether using similar (Buckner *et al.*, 1995; Klein *et al.*, 1995; Petersen *et al.*, 1988; Thompson-Schill *et al.*, 1999) or

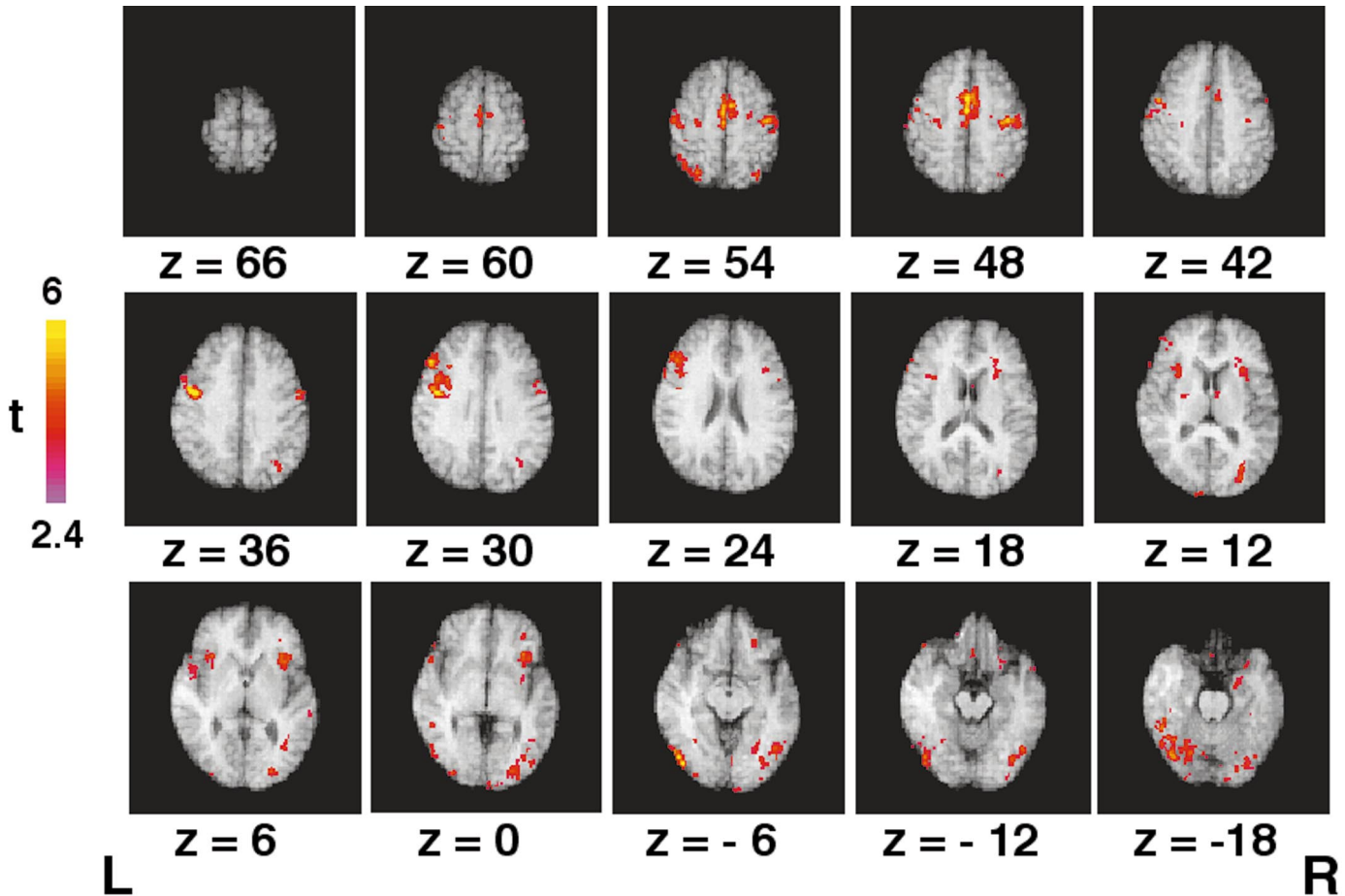


FIG. 3. Functional maps. Averaged brain activations involved in the homophone decision task compared to fixation. Normalized activation brain maps averaged across six subjects demonstrate the statistically significant activations ($P < 0.01$). All of the functional maps (in color) are overlaid on the corresponding T₁ 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.

different paradigms (Gabrieli *et al.*, 1998; Kim *et al.*, 1997), have not commonly implicated this middorsal prefrontal region in word recognition and reading. Even though this region is noted by several researchers, the reported activation in this area is much weaker for native English readers (Poldrack *et al.*, 1999; Price *et al.*, 1997; Warburton *et al.*, 1996; Wise *et al.*, 1991).

We believe that the extremely strong activation of the left middle frontal gyrus in reading Chinese is associated with the unique square configuration of logographs. Unlike English words that have a linear structure, Chinese logographs comprise a number of strokes that are packed into a square shape according to stroke assembly rules. This requires fine-grained analyses of the visual-spatial locations of the strokes and subcharacter components. Recent data from functional imaging studies suggest that the left middorsal lateral frontal cortex (at BAs 9 and 46) mediates spatial and verbal working memory by which the subject maintains a limited amount of spatial and verbal in-

formation in an active state for a brief period of time (0–60 s) (Courtney *et al.*, 1998; McCarthy *et al.*, 1994; Owen *et al.*, 1996; Paulesu *et al.*, 1993). More specifically, this region may act as a central executive system of working memory that is responsible for coordination of cognitive resources (D'Esposito *et al.*, 1995). In our present study, although working memory processes may not be engaged in character decision (Perfetti and Zhang, 1995), the subject indeed needed to coordinate the semantic (or phonological) processing of the Chinese logographs that was explicitly required by the experimental task and the intensive visuospatial processing that was demanded by the visual form of logographs. In this case, the left middle frontal gyrus may be recruited to integrate these two cognitive processes.

Our findings of the heavy involvement of a set of right hemisphere cortical sites converge on the view that reading Chinese logographs demands intensive visual-spatial analysis. The right frontal pole (BA10/11), frontal operculum (BA 47/45), dorsolateral frontal

TABLE 1

Stereotactic Coordinates, *t* Values, and Corresponding Brodmann Areas (BAs) for Regions Activated Significantly
(*Meaning Judgment minus Fixation*)

Regions activated	BA	Coordinates			Volume (voxels)	<i>t</i>	<i>P</i>
		X	Y	Z			
Frontal							
Left middle frontal gyrus	9	-45	13	30	782	3.72	0.0002
Left inferior/middle frontal gyrus	45	-43	21	6	221	3.03	0.0018
	45	-57	18	21	37	2.77	0.0037
	11	-16	42	-17	78	3.04	0.0017
	11	-20	27	-19	18	2.99	0.002
	10	-40	44	-2	30	2.89	0.0026
	10	-36	56	1	15	2.78	0.0035
Left precentral gyrus	6	-29	-16	55	44	2.79	0.0035
	4	-46	-9	53	46	2.78	0.0036
	4	-35	-13	47	19	2.83	0.0032
Right inferior/middle frontal gyrus	47	38	19	2	168	3.07	0.0016
	9/44	51	9	29	101	2.89	0.0026
	10	45	44	0	10	2.62	0.0055
Right precentral/medial gyrus	6	0	-1	50	588	3.54	0.0004
	6	55	-1	35	104	3.00	0.002
	4	40	-17	52	260	3.37	0.0006
	4	51	-4	46	11	2.70	0.0044
Temporal							
Right superior/middle gyrus	38	27	14	-37	27	2.77	0.0037
	38	41	5	-35	16	2.74	0.004
Parietal							
Left superior parietal lobule	7	-30	-64	54	181	3.24	0.001
Left postcentral gyrus	3	-40	-21	59	22	2.78	0.0036
	40	-37	-33	56	10	2.87	0.0028
Right superior parietal lobule	7	31	-67	46	79	2.77	0.0037
Right inferior parietal lobule	40	44	-48	52	29	2.72	0.0043
Occipital							
Left middle/inferior gyrus	18	-11	-95	12	18	2.88	0.0028
	18	-34	-87	0	16	2.68	0.0046
Right cuneus	17	8	-97	-1	82	2.91	0.0025
Right inferior occipital gyrus	19	39	-78	-3	30	2.81	0.0034
Right fusiform gyrus	18	28	-91	-13	12	3.13	0.0013
Other areas							
Left sublobar caudate		-21	-3	4	57	2.77	0.0037
Right sublobar caudate		15	-5	2	13	2.81	0.0033
Cerebellum							
Left declive		-44	-59	-20	975	3.45	0.0005
Right uvula		17	-72	-23	1502	3.12	0.0010
Right cerebellar tonsil		44	-47	-31	54	2.84	0.0031
Right anterior cerebellum		19	-38	-28	17	2.77	0.0037
Right tuber		50	-59	-29	14	2.95	0.0022

Note. The *t* values presented in this table are the mean *t* values of a cluster.

gyrus (BA 9/44), and the superior and inferior parietal lobules (BAs 7, 40/39) mediated semantic and homophonic judgments. These areas were not implicated in most of the studies with alphabets as well (reviewed by Price, 1997, and Fiez and Petersen, 1998; but see a recent PET study by MacLeod *et al.*, 1998). However, it is well known that these right prefrontal regions service episodic memory processes by which one retrieves the spatial relation of perceived objects (Kapur *et al.*, 1995; Lepage *et al.*, 2000; Haxby *et al.*, 1996; Nyberg *et*

al., 1996; Schacter *et al.*, 1995; Squire and Zola, 1998; Tulving *et al.*, 1994). In addition, the right BAs 7 and 40/39 are routinely activated in spatial working memory tasks (Courtney *et al.*, 1998; Haxby *et al.*, 1995; Heinze *et al.*, 1994; Jonides *et al.*, 1993; McCarthy *et al.*, 1994; Smith and Jonides, 1998). Based on these previous studies, it is reasonable to assume that the right frontal and parietal regions are involved in perceiving the spatial locations of the strokes and the processes of stroke combinations.

TABLE 2

Stereotactic Coordinates, *t* Values, and Corresponding Brodmann Areas (BAs) for Regions Activated Significantly (*Homophone Judgment minus Fixation*)

Regions activated	BA	Coordinates			Volume (voxels)	<i>t</i>	<i>P</i>
		X	Y	Z			
Frontal							
Left middle frontal gyrus	9	-43	13	27	952	3.42	0.0006
	9	-32	24	30	11	2.99	0.0020
Left inferior frontal gyrus	10	-41	44	12	22	2.60	0.0058
	45	-58	19	21	38	2.98	0.0021
	47	-47	34	-11	16	2.94	0.0023
Left medial frontal gyrus	47	-50	31	-1	12	2.77	0.0037
	11	-17	41	-19	12	2.77	0.0037
Left precentral gyrus	4	-29	-16	50	80	2.81	0.0033
	4	-47	-14	53	178	2.91	0.0025
Right inferior/middle frontal gyrus	45	33	20	7	400	3.08	0.0016
	9/44	50	9	29	22	2.85	0.0030
	47	27	15	-16	71	2.74	0.0040
	47	23	33	-7	24	2.68	0.0047
	11	36	37	-14	10	2.61	0.0056
Right medial/middle frontal gyrus	6	1	-3	51	777	3.49	0.0004
	6	23	-10	55	24	2.78	0.0036
Right precentral gyrus	4	40	-17	51	307	3.39	0.0006
	6	54	-1	35	90	2.90	0.0026
Temporal							
Left middle temporal gyrus	21	-52	-42	0	19	2.81	0.0033
Right superior/middle gyrus	22	61	-31	7	10	2.61	0.0056
	38	27	15	-36	35	2.77	0.0037
	38	36	8	-38	24	2.80	0.0034
	38	54	11	-14	15	2.73	0.0041
Parietal							
Left superior parietal lobule	7	-32	-61	54	124	2.98	0.0020
Left postcentral gyrus	3	-37	-32	57	17	3.00	0.0019
Right superior parietal lobule	7	30	-66	52	35	2.94	0.0023
Right precuneus (PCu)	39	34	-66	34	66	2.81	0.0033
Occipital							
Left inferior gyrus	18	-33	-87	-1	51	3.07	0.0016
Left cuneus	18	-12	-97	13	21	2.84	0.0030
Right cuneus	17	6	-98	-2	46	2.79	0.0035
Right fusiform gyrus	18	31	-88	-13	10	2.57	0.0063
	19	26	-59	-7	35	2.76	0.0038
Right lingual gyrus	19	3	-72	-5	18	2.55	0.0066
Other areas							
Left sublobar caudate		-26	-5	12	16	2.67	0.0048
Right sublobar caudate		4	1	14	38	2.72	0.0043
Right sublobar claustrum		33	0	1	13	2.61	0.0056
Cerebellum							
Left declive		-6	-66	-18	2915	3.17	0.0012
Right cerebellar tonsil		42	-46	-33	49	2.67	0.0048

Note. The *t* values presented in this table are the mean *t* values of a cluster.

While activations in the occipital cortex were bilateral, the right side was dominant over the left side (AI was -0.57 in the semantic task vs fixation comparison and -0.204 in the homophone task vs fixation comparison). As the right occipital cortex is associated with the spatial recognition of visual symbols (e.g., Clark *et al.*, 1996; Shen *et al.*, 1999), its strong activity seen in this experiment can, again, be attributed to the visual properties of Chinese characters. The involvement of the bilateral visual cortex and the superior and inferior

parietal lobe suggests the role of a dorsal pathway responsible for spatial localization in reading Chinese characters. Through the dorsal pathway, visual processing that originates from the striate cortex reaches the posterior parietal cortex (Ungerleider and Mishkin, 1982).

To summarize, our results suggest that reading logographic Chinese is serviced by a distributed neural system. As in English word reading and recognition, the left inferior prefrontal cortex is active in processing

Chinese characters. Peak activation associated with reading Chinese, however, is located in the left middle lateral frontal region, an area that mediates the coordination of cognitive resources. We hypothesize that in reading Chinese logographs, the left middle frontal cortex is recruited to coordinate and integrate the intensive visuospatial analysis demanded by logographs' unique square configuration and the semantic (or phonological) analysis required by the present experimental tasks. Our finding of the involvement of the right prefrontal and parietal areas lends strong support to the assumption that the visual-spatial attributes of Chinese script require a fine-grained analysis during reading and recognition.

CONCLUSIONS

We have demonstrated that, when normal Chinese adults read logographic characters, a distributed network of brain areas was activated. Compared to fixation baseline, peak activations provoked by semantic as well as homophony decisions were found in the left middle frontal gyrus (BA 9). The left inferior frontal cortex also mediated the processing of Chinese logographs. There were more right hemispheric regions (e.g., BAs 47/45, 7, 40/39, and the right visual system) involved in reading Chinese compared with reading English. This can be explained by the fact that the Chinese logographs' square shape requires a particular analysis of spatial information of various strokes which make up the logographic character. Our explanation agrees with the notion that some languages have special processing requirements (Neville *et al.*, 1998; Paulesu *et al.*, 2000). We infer that the left middle frontal area (BA 9) coordinates and integrates semantic (phonological) and visuospatial analyses of Chinese logographs. In a nutshell, our experiment has implicated brain regions common to both logographic and alphabetic languages as well as brain regions specialized in processing and representing logographic Chinese.

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