

Orthographic and phonological processing of Chinese characters: an fMRI study

Wen-Jui Kuo,^{a,b,c,i} Tzu-Chen Yeh,^{b,d,i} Jun-Ren Lee,^{a,b,e,i} Li-Fen Chen,^{b,c,i}
Po-Lei Lee,^{b,i} Shyan-Shiou Chen,^{b,i} Low-Tone Ho,^{b,i} Daisy L. Hung,^{a,c,g,i}
Ovid J.-L. Tzeng,^{a,g,h,i} and Jen-Chuen Hsieh^{b,d,f,g,i,*}

^aCognitive Neuropsychology Laboratory, National Yang-Ming University, Taipei, Taiwan

^bLaboratory of Integrated Brain Research, Department of Medical Research and Education, Taipei Veterans General Hospital, Taipei, Taiwan

^cCenter for Neuroscience, National Yang-Ming University, Taipei, Taiwan

^dFaculty of Medicine, School of Medicine, National Yang-Ming University, Taipei, Taiwan

^eInstitute of Cognitive Neuroscience, National Central University, Taiwan

^fInstitute of Health Informatics and Decision Making, School of Medicine, National Yang-Ming University, Taipei, Taiwan

^gInstitute of Neuroscience, School of Life Science, National Yang-Ming University, Taipei, Taiwan

^hInstitute of Linguistics, Academia Sinica, Taiwan

ⁱBrain Research Center–National Yang-Ming University, University System of Taiwan, Taiwan

Received 3 September 2003; revised 3 December 2003; accepted 3 December 2003

The present study used functional magnetic resonance imaging (fMRI) to investigate the neural mechanisms underlying the orthographic and phonological processing of Chinese characters. Four tasks were devised, including one homophone judgment and three physical judgments of characters, pseudo-characters, and Korean-like nonsense figures. While the left occipitotemporal region, left dorsal processing stream, and right middle frontal gyrus constitute a network for orthographic processing, the left premotor gyrus, left middle/inferior frontal gyrus, supplementary motor area (SMA), and the left temporoparietal region work in concert for phonological processing. The ventral part of the left inferior frontal cortex responds specifically to the character stimuli, suggesting a general lexical processing role for this region for linguistic material. The stronger activation of the dorsal visual stream by Chinese homophone judgment pinpoints a tight coupling between phonological representation of Chinese characters and corresponding orthographic percepts. The concomitant engagement of sets of regions for different levels of Chinese orthographic and phonological processing is consistent with the notion of distributed parallel processing.

© 2004 Elsevier Inc. All rights reserved.

Keywords: fMRI; Inferior frontal cortex; Reading; Orthographic processing; Phonological processing; Chinese; Character

Introduction

A growing enthusiasm has emerged to exploit functional brain imaging and mapping to investigate the central representations of

Chinese reading due to its architectural and linguistic uniqueness. Cross-linguistic comparisons cannot only shed light on the fundamental understanding of central mechanisms of language processing, but also the neuroplasticity that accompanies the development of reading skills under different language contexts (Kuo et al., 2001). Most brain imaging studies on reading Chinese have not only reported a commonality of neural substrates shared with those activated in reading of alphabetic scripts but have also discussed particularity of the Chinese character processing in terms of brain dynamics and additional brain regions involved (Chee et al., 1999, 2000; Chen et al., 2002; Fu et al., 2002; Kuo et al., 2001, 2003; Tan et al., 2000, 2001a,b). Chinese characters have many distinct features that alphabetical words lack (Hung and Tzeng, 1981; Wang, 1973). Yet, the logographic nature of Chinese characters may engender a contention that there exists a closer relationship between shape and meaning for Chinese characters than alphabetical words (Chen and Juola, 1982; Leck et al., 1995), which in turn leads to a conjecture that reading Chinese characters would preferentially engage the ventral processing stream. Such reasoning is mainly based on brain imaging studies on Japanese kana (syllabary) and Kanji (Chinese character) reading. These studies on Japanese reading proposed that reading of kana depends on the dorsal stream from the occipital to the inferior parietal area while processing Kanji relies on the ventral stream from the occipital to the temporal cortex, in which the left mid-fusiform gyrus/occipitotemporal junction (OTJ) is of particular interest (Law et al., 1991; Nakamura et al., 2000, 2002; Sakurai et al., 2000; Tokunaga et al., 1999; Uchida et al., 1999). This region has been dubbed the “visual word form area” in previous neuropsychological reports (Binder and Mohr, 1992; Warrington and Shallice, 1980).

The dichotomous view has been challenged by imaging studies on alphabetical words, for example, in French (Cohen et al., 2000, 2002; Dehaene et al., 2001, 2002). In these studies, irrespective of stimulation to the left or right visual field (Cohen et al., 2000,

* Corresponding author. Laboratory of Integrated Brain Research, Department of Medical Research and Education, Taipei Veterans General Hospital, No. 201, Sect. 2, Shih-Pai Road, Taipei 112, Taiwan. Fax: +886-2-28745182.

E-mail address: jchsieh@vghtpe.gov.tw (J.-C. Hsieh).

Available online on ScienceDirect (www.sciencedirect.com).

2002), case variation (Dehaene et al., 2001), or semantic content of the stimuli (Dehaene et al., 2002), the OTJ demonstrated preferential activation to words and pseudo-words rather than to unpronounceable letter strings and nonlinguistic stimuli. Therefore, the OTJ may have a crucial role in extracting the orthographic knowledge of the words, namely, the invariant structural representation of the visual words as an ordered sequence of abstract letter identities at a level higher than their physical or perceptual attributes (Polk and Farah, 2002). In our recent fMRI studies on Chinese reading, we observed that the OTJ not only demonstrated a preferential response to Chinese words in comparison with nonsense figures (Kuo et al., 2001), but also expressed a subtle linguistic property, that is, frequency effects, with higher activation for reading low-frequency characters than for reading high-frequency characters (Kuo et al., 2003). Corroborated by the aforementioned studies of alphabetical words, our findings support the role of OTJ in the derivation of orthographic representation for reading, regardless of the surface structure of the words.

Both orthographic and phonological computations can be mandatory for lexical access (Booth et al., 1999; Plaut et al., 1996; Seidenberg and McClelland, 1989; Spinks et al., 2000; Van Orden, 1987; Van Orden et al., 1988). The neuronal correlates underpinning these two processes for alphabetical words have been thoroughly studied by tasks with different demands, with stimuli varying along the continuum of orthographic legality/regularity (conformity with the spelling rules of the language), that is, words, pseudo-words, consonant letter strings, and false fonts (Brunswick et al., 1999; Cohen et al., 2002; Dehaene et al., 2002; Fiez et al., 1999; Hagoort et al., 1999; Herberster et al., 1997; Mechelli et al., 2000, 2003; Paulesu et al., 2000; Petersen et al., 1990; Polk and Farah, 2002; Price et al., 1996; Pugh et al., 1996). However, few imaging studies have discussed the processing variations along the dimension of orthographic legality of Chinese characters. Unlike the linear arrangement of alphabetical words, each Chinese character consists of strokes or stroke patterns, that is, radicals, constituting various components of characters. All Chinese characters fit into a square-shaped space. More than 80% of Chinese characters are phonograms consisting of a phonetic part and a radical part cueing possible pronunciations and meanings, respectively (Zhou, 1978). The radical is found in a conventional position in characters and plays important roles in character recognition (Feldman and Siok, 1999; Taft and Zhu, 1997). Such structural properties can substantially affect the search efficiency when Chinese characters are used as stimuli (Yeh and Li, 2002) and indicates that the structural information contained in characters is processed at an early stage. This information is inherent in the orthography of Chinese characters. Another distinct feature of Chinese characters is the immense number of homophones with different physical attributes (Fig. 1). All these features promise a high degree of freedom in manipulating the stimuli to profoundly and specifically investigate the effect of orthographic legality in Chinese reading.

The present study seeks to use fMRI to study the neural mechanisms of orthographic and phonological processes of Chinese reading by using orthographic legality as a probe. Chinese pseudo-characters were exploited to address sub-lexical processing. Four tasks with various cognitive demands coupled with different levels of orthographic legality were implemented: a homophone judgment and three physical judgment tasks. Homophone judgment mandates early visual processing, pre-lexical orthographic and phonological engagement, and lexical ortho-

TASK	"Yes" trial	"No" trial
Homophone judgment	職 + 質	勃 + 稻
Character form judgment	鮮 + 鮮	躁 + 塵
Pseudocharacter form judgment	劃 + 劃	端 + 殼
Figure form judgment	잘 + 잘	것 + 데
Fixation	+	

Fig. 1. Examples of the four activation tasks. Stimulus pairs in the middle and right columns are the examples of "yes-trial" and "no-trial" of the four tasks, respectively.

graphic/phonological word-form selection in correspondence to the stimulus characters. Physical judgment commands visual processing and subsequent comparison. Physical judgment tasks composed three categories of stimuli, namely, real characters, pseudo-characters, and nonsense figures. Pseudo-characters consisted of radicals and constituents, following the orthographic architecture of Chinese character, so that they resembled real characters but were without meaning. Nonsense figures were modified from Korean characters to equate the overall distribution of the strokes in a fixed space like Chinese characters. Although task demands of the three physical judgment tasks were similar, the linguistic characteristics of the stimuli differed, for example, semantics and orthographic legality. Behavioral studies have confirmed that linguistic processing can be highly automatic and implicit (MacLeod, 1991; Van Orden, 1987), which in turn can drive language-related brain areas even in a non-linguistic feature detection task (Brunswick et al., 1999; Price et al., 1996; Turkeltaub et al., 2003). This implies that central processing actually reaches beyond the functional demands of the task, and the design promises a possibility to penetrate the subtle brain dynamics of Chinese reading. We reasoned that homophone judgment would cause higher activation in the premotor cortex, left inferior frontal gyrus, supplementary motor area, and left temporoparietal cortex (Demonet et al., 1992; McDermott et al., 2003; Poldrack et al., 1999; Price et al., 1997; Pugh et al., 1996; Xu et al., 2001). Different levels of orthographic analysis, as probed by different stimulus categories, could be deciphered to improve our understanding of the neuronal mechanisms underlying reading in Chinese.

Materials and methods

Subjects

Ten right-handed university students (four males and six females; 20 to 25 years of age) participated in this study. All were native Chinese speakers and naive to Korean, with no history of neurological disorders, and had normal or corrected-

to-normal vision. Handedness was verified using the Edinburgh Inventory (Oldfield, 1971). Written consent was obtained from all participants with the protocol approved by the Institutional Ethics and Radiation Safety Committees of Taipei Veterans General Hospital.

Tasks

Four tasks, comprising one homophone judgment and three physical comparisons (character, pseudo-character, and nonsense figure), were devised and interleaved with a fixation condition designated as a common baseline in a blocked fMRI paradigm. In the homophone judgment task (HJ), subjects determined whether the two displayed characters were homophones. The characters in each presented pair of characters did not share the same or similar physical form. In the character form judgment task (CJ), subjects had to determine whether the two characters were physically identical. In pseudo-character form judgment task (PJ), subjects determined whether the paired pseudo-characters were of the same physical form. In the figure form judgment task (FJ), subjects had to determine whether the paired figure forms were the same. For the common baseline, subjects fixated at a centrally located crosshair without any response requirement. The four tasks were blocked in a random order and interleaved with the fixation condition in each session of the experiment. Two runs of the experiment were conducted without repetition of any stimulus, with subjects prompted by the computer at the beginning of each task/condition. The “yes” and “no” response trials of each task were balanced in number. Subject’s performances (reaction time and accuracy) for each task were simultaneously registered using a PC interfaced with a two-key optic fiber response pad during the fMRI experiment. The subject pressed the left key with his/her right index finger for the “yes” response and pressed the right key with the right middle finger for the “no” response, respectively. All subjects participated in a short training session with a different stimulus set before scanning.

Stimuli

The stimuli for the four tasks consisted of characters, pseudo-characters, and Korean-like nonsense figures. The occurrence frequencies of the Chinese characters used were no less than 100 per million. Pseudo-characters were invented, in conformity with Chinese orthography, by combining different sub-lexical parts of real Chinese characters. Korean-like nonsense figures were modified from Korean characters (Fig. 1). The figures were made up of strokes similar to those found in Chinese characters and confined to a fixed space like that used by Chinese characters. In the HJ and CJ, real characters were used. There was no repetition of any stimulus pair in the HJ, CJ, and PJ. Number of strokes for the stimuli given for HJ, CJ, and PJ were 12 ± 3 , 13 ± 3 , and 11 ± 2 (mean \pm SD), respectively, and there was no statistical difference among them.

Stimulus presentation was controlled by a PC using an in-house program and stimuli were projected via a LCD projector onto a screen at the feet of the subject. Subject saw the display via a homemade reflection mirror with a viewing distance of approximately 194 cm. Each stimulus pair was juxtaposed horizontally with a crosshair at the center of the screen. The visual angle of single characters/figures subtended approximately 2.3° while that of the accompanying fixation crosshair subtended approximately

1° in both vertical and horizontal directions. The center-to-center distance of stimuli in each pair subtended approximately 3.5° . Each stimulus pair was displayed for 1000 ms, followed by a blank screen for 1400 ms before the next trial began.

MRI procedure

Scanning was performed using a 3.0 T Bruker MedSpec S300 system (Bruker, Kalsruhe, Germany). Subjects’ heads were immobilized with a vacuum-beam pad in the scanner. A T2*-weighted gradient-echo echo planar imaging (EPI) sequence was used for fMRI scans, with slice thickness = 5 mm, interslice gap = 1 mm, in-plane resolution = 3.9×3.9 mm, and TR/TE/ê = 2400/50 ms/90°. The field-of-view was 250×250 mm and the acquisition matrix was 64×64 . Twenty-four axial slices were acquired to cover the whole brain. Optimization of global field homogeneity was performed by automatic and manual shimming. For each slice, 141 images were acquired in one run. The first five volumes of each run were discarded for signal equilibrium. Each block was composed of 17 volume scans (approximately 40.8 s). Each subject’s anatomical image was acquired using a high-resolution ($1.95 \times 1.95 \times 1.95$ mm), T1-weighted, 3D gradient-echo pulse sequence (MDEFT, Modified Driven Equilibrium Fourier Transform; TR/TE/TI = 88.1/4.12/650 ms). The total duration of the experiment was about 1 h.

Behavioral data analysis

Reaction time (latency) and accuracy (error rate) were analyzed with a two-way ANOVA model with post hoc examination (Least Significant Difference, LSD), treating task (homophone, character, pseudo-character, and figure) and response type (“yes” and “no” responses) as repeated variables.

Imaging data analysis

Data were analyzed using statistical parametric mapping (SPM99 from the Wellcome Department of Cognitive Neurology, London), running under Matlab 6.0 (Mathworks, Sherbon, MA, USA) on a Sun workstation. The first five images were discarded from the analysis to eliminate non-equilibrium effects of magnetization. Scans were realigned, time corrected, normalized, and spatially smoothed with an 8-mm FWHM Gaussian kernel. The resulting time-series was high-pass filtered with a cut-off time window of 168 s to remove low frequency drifts in the BOLD signal and temporally smoothed with hemodynamic response function (HRF).

The main effect (HJ, CJ, PJ, and FJ) was studied by contrasting each task with the fixation condition. Hierarchical subtractions between the tasks were done to examine differential engagements of central phonological and orthographic processing. Regions of interest were selected from our previous studies, and the significance level threshold was set at $P < 0.001$ (uncorrected) with spatial extent larger than 20 voxels (Kuo et al., 2001, 2003). To affirm that the voxels activated were due to increased activity by the probed task instead of decreased activity in the reference task (i.e., lower BOLD responses as compared to the fixation condition), the deactivation contrasts (reference task vs. fixation condition) were exploited for an exclusive masking procedure. Masking contrast P values were set at 0.001 (uncorrected).

Results

Behavioral data

The reaction time (mean \pm SD) was 736.8 ± 27 , 749.3 ± 25 , 673.4 ± 34 , and 932 ± 38 ms for FJ, PJ, CJ, and HJ, respectively. Results of a two-way ANOVA showed a main effect of task for reaction time [$F(3, 27) = 34.615$, $P < 0.05$]. Post hoc analysis by LSD indicated that HJ significantly consumed more time than the other three form judgment tasks. Reaction times of FJ and PJ were similar and were both significantly longer than that of CJ. No effect was observed for response type [$F(1, 9) = 0.199$, $P = 0.67$] nor was there any interaction between task and response type [$F(3, 27) = 0.262$, $P = 0.852$].

The error rate (mean \pm SD) was 0.12 ± 0.05 , 0.03 ± 0.03 , 0.03 ± 0.02 , and 0.07 ± 0.06 for FJ, PJ, CJ, and HJ, respectively.

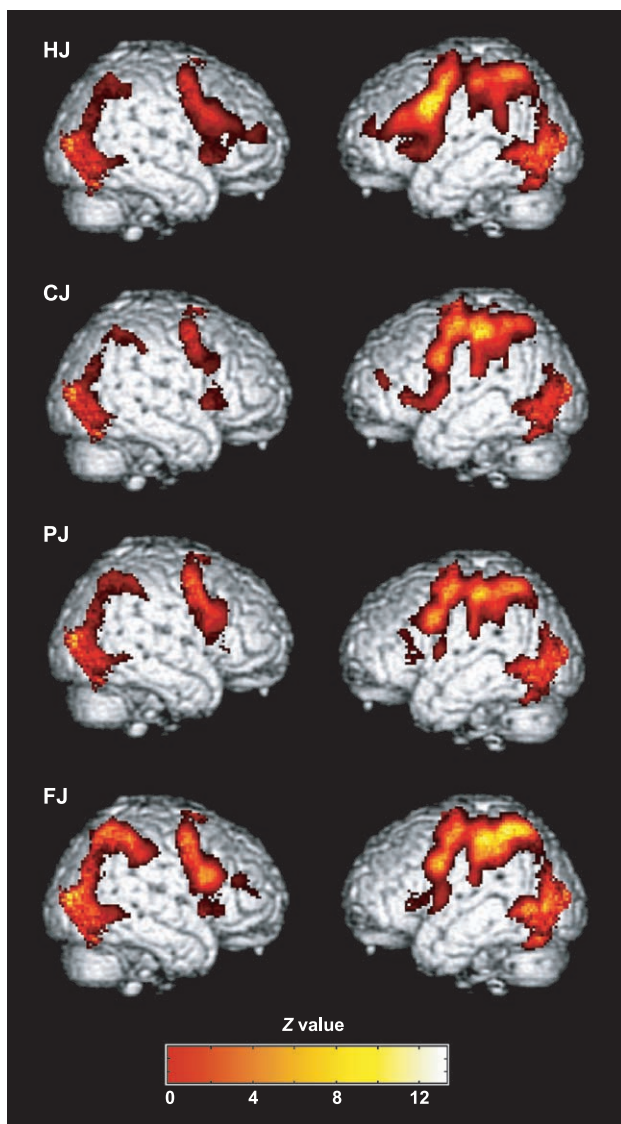


Fig. 2. Brain activation maps for the four tasks as indexed to fixation. Images are the statistical parametric maps of brain activities during the four tasks relative to fixation condition, thresholded at uncorrected $P < 0.001$ ($Z > 3.09$) with spatial extent $n \geq 20$ voxels. The color bar denotes the Z value.

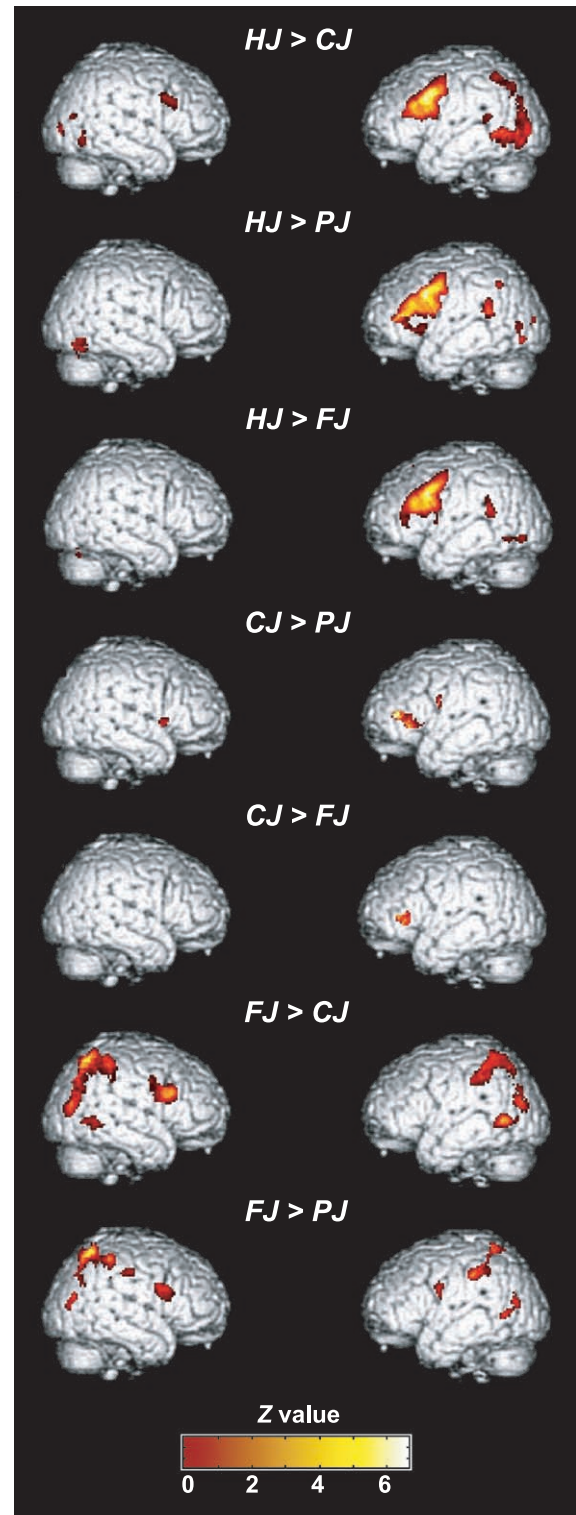


Fig. 3. Brain activation maps for the contrasts between the four tasks. Images are the statistical maps of effect-specific contrasts constructed from the four tasks. Clusters survive an uncorrected $P < 0.001$ ($Z > 3.09$) with spatial extent $n \geq 20$ voxels are considered statistically significant. The color bar denotes the Z value.

Two-way ANOVA also revealed a main effect of task for error rate [$F(3, 27) = 9.892$, $P < 0.05$]. Post hoc analysis by LSD revealed that subjects committed more errors during FJ than any other

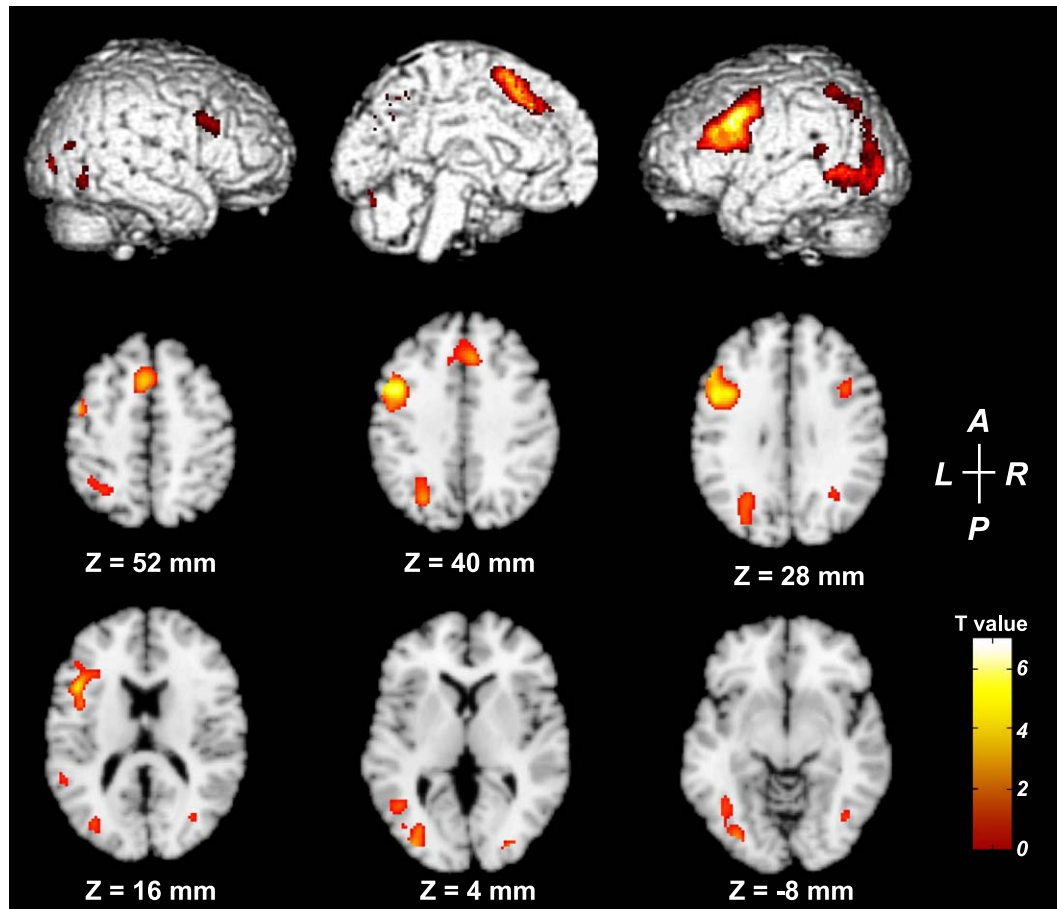


Fig. 4. Brain activation maps for the contrast of homophone judgment vs. character form judgment. Clusters survive an uncorrected $P < 0.001$ ($Z > 3.09$) with spatial extent $n \geq 20$ voxels are considered statistically significant. The color bar denotes the Z value.

judgment task. There was no difference among HJ, CJ and PJ. The effect of response type [$F(1, 9) = 3.273$, $P = 0.104$] and its interaction with task [$F(3, 27) = 0.876$, $P = 0.466$] were not significant. Both reaction times and error rates were similar on “yes” and “no” trials across the four tasks.

Imaging data

Main effects of the four judgment tasks versus fixation

The four judgment tasks activated neuronal networks of substantial similarity (Fig. 2). Frontal activation was found bilaterally in the medial superior frontal gyri, middle frontal gyri, inferior frontal gyri and insula. HJ yielded the most extensive activation in the left inferior frontal cortex. Parietal activation was noted in the left post-central gyrus, bilateral superior parietal gyri, bilateral inferior parietal gyri, and precuneus. Occipital activation was observed bilaterally in the middle occipital gyri, fusiform gyri, lingual gyri and cuneus; the thalamus and cerebellum were also activated. HJ additionally activated the left temporal-parietal cortex.

Effects revealed by comparisons among the four tasks

HJ vs. CJ, PJ, and FJ. HJ, when compared with CJ, PJ and FJ, respectively, resulted in higher activation of many regions, with

activation preponderant in the left hemisphere (Table 1 and Fig. 3). The regions commonly activated in the three contrasts were the medial superior frontal gyrus, left middle frontal gyrus, left inferior frontal gyrus, and left temporal-parietal cortex. The left dorsal stream, from the occipital to the parietal cortex, was prominent only in the HJ vs. CJ. Bilateral extrastriate activation was also more significant in this contrast than the other two contrasts. One intriguing finding was that the activation in the left inferior frontal gyrus extended more rostrally and ventrally in the contrasts with PJ and FJ, but not with CJ.

CJ vs. PJ and FJ. The left inferior frontal gyrus, mostly the ventral part, was activated in the contrasts with PJ and FJ (Table 1 and Fig. 3).

PJ vs. CJ and FJ. The right middle frontal gyrus showed higher activity in the contrast with CJ. No difference was seen between PJ and FJ (Table 1).

FJ vs. CJ and PJ. These two contrasts had similar patterns, but the activation was more expressed in the contrast with CJ. Relative to the character condition, FJ seemed to engage the right middle frontal gyrus, bilateral dorsal streams (including superior and inferior parietal lobules), and extrastriate cortices bilaterally (adjacent to middle temporal gyri). In contrast with pseudo-character condition, activation was observed in the middle frontal

Table 1
Brain regions showing significant differences between the four tasks

Contrasts	Left hemisphere					Right hemisphere				
	Area	x	y	z	Z value	Area	x	y	z	Z value
<i>HJ > CJ</i>										
Precentral G	6	-48	0	46	5.33					
Medial frontal G						6	8	28	36	4.84
Superior frontal G	6	-4	14	52	6.03					
Middle frontal G	9	-44	10	34	6.83	9	42	14	26	4.07
	46	-50	24	26	5.63					
Inferior frontal G	45	-46	18	18	6.75					
Insula	13	-42	6	18	5.29					
Superior parietal L	7	-24	-62	44	4.94					
Inferior parietal L	40	-38	-46	52	3.58					
Superior temporal G	22	-54	-42	14	3.61					
Middle occipital G	18	-34	-84	4	5.17	19	32	-84	6	4.75
	37	-42	-62	2	4.91					
Inferior occipital G	18	-32	-78	-2	4.78					
Fusiform G	37	-36	-54	-8	3.76					
<i>HJ > PJ</i>										
Precentral G	6	-46	2	44	5.75					
Superior frontal G	6	-4	14	56	6.38					
Middle frontal G	9	-40	14	30	7.13					
Middle frontal G	45	-48	26	22	5.87					
Inferior frontal G	9	-46	16	22	5.94					
	44	-46	4	22	5.55					
	47	-48	16	2	4.48					
Inferior parietal L	40	-42	-54	42	3.76					
Superior temporal G	22	-56	-44	16	5.03					
Middle occipital G	19	-34	-72	8	3.57	37	36	-62	-10	4.58
Inferior occipital G	18	-30	-78	-4	3.76					
Declive							28	-70	-14	3.69
<i>HJ > FJ</i>										
Medial frontal G	6	-2	30	36	4.27					
Superior frontal G	6	-4	14	54	7.42					
Middle frontal G	46	-50	26	26	7.16					
	9	-42	12	34	7.02					
Inferior frontal G	44	-42	4	8	3.46					
	46	-50	32	8	3.78					
	47	-42	32	2	3.33					
Cingulate G	32	-10	32	28	4.08					
Superior temporal G	22	-64	-44	22	3.91					
Inferior occipital G	19	-36	-76	-10	4.15					
Fusiform G	37	-38	-62	-10	3.49					
Declive							28	-70	-18	3.99
<i>CJ > PJ</i>										
Inferior frontal G	9	-54	2	22	3.77					
	47	-42	26	2	4.55					
<i>CJ > FJ</i>										
Inferior frontal G	47	-44	28	2	4.1					
<i>PJ > CJ</i>										
Middle frontal G						9	44	6	22	3.69
<i>FJ > CJ</i>										
Middle frontal G						46	48	18	22	5.49
Inferior frontal G						9	46	6	22	4.9
Superior parietal L	7	-24	-62	48	4.63	7	32	-62	48	6.96
		-32	-48	60	4.26		34	-50	62	4.26
Inferior parietal L	40	-38	-38	42	5.39	40	40	-36	44	4.95

Table 1 (continued)

Contrasts	Left hemisphere					Right hemisphere				
	Area	x	y	z	Z value	Area	x	y	z	Z value
<i>FJ > CJ</i>										
Middle temporal G	19	−36	−74	20	4.51					
	37	−46	−58	4	6.14	37	48	−48	−2	3.9
Middle occipital G						19	42	−74	16	5.41
<i>FJ > PJ</i>										
Precentral G						4	58	−16	38	4.03
Inferior frontal G	9	−52	2	24	4.88	9	54	12	22	4.41
Precuneus						7	26	−48	40	3.92
Superior parietal L	7	−26	−48	66	4.4	7	32	−62	48	4.99
							30	−54	60	4.65
Inferior parietal L	40	−50	−30	38	4.35	40	42	−34	36	3.94
							32	−48	44	3.62
Middle temporal G						19	42	−76	10	3.42
	37	−50	−60	6	4.08					
	39	−38	−66	20	3.86					

Note. HJ, homophone judgment; CJ, character form judgment; PJ, pseudo-character form judgment; FJ, figure form judgment; G, gyrus; L, lobule; BA, Brodmann area.

gyri, superior and inferior parietal lobules, and bilateral extrastriate cortices (adjacent to middle temporal gyri; see Table 1 and Fig. 3).

Discussion

This present study sought to investigate the neural mechanisms of orthographic and phonological processing of Chinese characters. HJ has the longest response latency among the four tasks. Response latencies of PJ and FJ were similar to each other and longer than that for CJ. FJ showed the highest error rate among the four tasks. The behavioral spectra reflect the different cognitive demands involved in the four tasks. While orthographic and phonological processes are indispensable for HJ, they are not explicitly demanded for physical comparison in other judgment tasks. A quicker response latency for CJ than the other two types of physical judgment also suggests that familiarity and automatic semantic access may implicitly facilitate central processing (Petersen et al., 1988; Price et al., 1996). These behavioral and cognitive profiles are mirrored in the fMRI activation dynamics.

fMRI main effects of the four judgment tasks as contrasted with the fixation

As indexed to fixation condition, the four tasks showed a common activation pattern involving the occipital, parietal, and frontal lobes (Fig. 2). Engagement of the left post-central gyrus, medial superior frontal gyrus (SMA, spatially extended to cingulate cortex), thalamus, and cerebellum was mostly due to subjects' voluntary movement of right index and middle fingers in response to the tasks. The right frontal activation and confluent activation of parietal and occipital cortices reflected the profound visual analysis inherent in the four tasks. Such visuomotor program patterns are typical in imaging studies of visuomotor control-integration and its interaction with attention and goal-directed action (Hamzei et al., 2002; Rushworth et al., 2001a).

The left temporoparietal cortex and left inferior frontal gyrus were activated most significantly in HJ, positing the critical role of these two substrates in the computation of phonological information (Fig. 2). This is in agreement with previous brain imaging studies using phonological tasks (Demonet et al., 1992; McDermott et al., 2003; Poldrack et al., 1999; Price et al., 1997; Pugh et al., 1996; Siok et al., 2003; Tan et al., 2001b; Xu et al., 2001, 2002) and verbal working memory tasks (Awh et al., 1996; Jonides et al., 1998; Paulesu et al., 1993; Smith and Jonides, 1998) to probe phonological representations. Since cognitive components of orthographic and phonological processing are necessary for the HJ, the corresponding neural correlates can be better studied by the contrasts of the HJ vs. different physical judgments in which no such component is explicitly required.

Explicit processing of Chinese characters

Orthographic processing is a dynamic process to extract the invariant, abstract structural representation from the surface structures of written words (Coltheart et al., 1993; Plaut et al., 1996). It is deemed an antecedent stage for word recognition, providing information for the subsequent processing, for example, phonology transformation. In the comparisons of HJ vs. the three physical judgments, the major differences lie in the posterior part of the brain (Fig. 3). There was pronounced activation of the left occipitotemporal region, left dorsal processing stream, and right middle frontal gyrus in the contrast of HJ vs. CJ, while little extrastriate activation survived in the contrasts of HJ vs. PJ and FJ. The activation pattern profiles a graded mental exertion through CJ, PJ and FJ as indexed to HJ, which in turn supports the idea that these regions constitute a distributed network for orthographic computation of the characters. In addition, the variations of activity in different levels of contrast comparisons are commensurate with the reaction time differences seen in the three physical judgments.

The contrast of HJ vs. CJ yields the best description of neural mechanisms for the orthographic processing of Chinese character,

since both conditions used real characters. In addition to the regions in the left frontal and temporal cortices known for phonological processing, the right middle frontal gyrus, left OTJ and left dorsal stream from occipital to parietal cortex are activated and considered parts of the overall network for dynamical orthographic processing (Fig. 4). The left OTJ has a recognized role in extracting orthographic legality from written scripts (Cohen et al., 2000, 2002; Dehaene et al., 2001, 2002; Polk and Farah, 2002). The right middle frontal gyrus can be engaged under the context of visual working memory and attentional load (Corbetta and Shulman, 2002) while performing HJ. Recruitment of the left dorsal occipitoparietal stream is consistent with our previous observations (Kuo et al., 2001, 2003) and is corroborated by studies relating activation of the left superior parietal cortex to attention switching and response switching (Rushworth et al., 2001a, 2001b; Weissman et al., 2002). Such activation implies a “top-down” modulation on the perceptual integration of global and local information for Chinese character processing (Kuo et al., 2001, 2003).

Phonological processing transforms the abstract structural representation in orthographic processing to its abstract phonological form and maps onto its phonology. Articulatory rehearsal is used to keep phonological information for further comparison. The left temporoparietal region is noteworthy in its expression in the contrasts of HJ vs. physical judgments (Figs. 3, 4). It has been suggested that this region participates in the orthography–phonology transformation (OPT) during Chinese reading (Kuo et al., 2001, 2003) and services rule-based OPT (Pugh et al., 2000; Shaywitz et al., 2002) or acoustically based phonological analysis (Fiez and Petersen, 1998; Salmelin et al., 1994, 1996). The absence of activation in this region in two recent fMRI studies on Chinese reading (Siok et al., 2003; Tan et al., 2001b), where homophone judgment tasks were also exploited, can be partially ascribed to technical factors, for example, 3T-MRI vs. 2T-MRI with sensitivity difference (Krasnow et al., 2003) and statistical strategies (a priori hypotheses with an uncorrected approach vs. omnibus significance testing with a corrected approach).

The region most prominently activated in the contrasts of HJ vs. physical judgments is the left middle/inferior frontal cortex. This confluent activation concurs with activation of the left premotor cortex and SMA, and indicates a motoric representation/articulatory rehearsal for phonological processing (Awh et al., 1996; Bookheimer et al., 1995; Gabrieli et al., 1998; Jonides et al., 1998; McDermott et al., 2003; Paulesu et al., 1993; Poldrack et al., 1999; Siok et al., 2003; Tan et al., 2001b). The concomitant activation of the left middle/inferior frontal (including the ventral part) and the left temporoparietal regions suggest that these two regions work in concert with each other for the controlled retrieval of phonological representations (Gold and Buckner, 2002).

One salient feature worthy of mention is the prominent activation of the left dorsal processing stream in the subtraction of HJ vs. CJ (Fig. 4). The dorsal visual stream has not been previously reported to be particularly active in alphabetical studies using similar phonological and physical judgment tasks (Gabrieli et al., 1998; Gold and Buckner, 2002; McDermott et al., 2003; Pugh et al., 1996; Xu et al., 2001, 2002). The stronger engagement of the dorsal visual stream by Chinese homophone judgment suggests a tight coupling between phonological representation and orthographic percept. This is particularly true since Chinese characters

must be read as unitary wholes, a process which requires fine-grain visuospatial analysis (Kuo et al., 2001, 2003). The idea that a logographic system mandates elaborative visuospatial processing is corroborated by behavioral studies (Hung and Tzeng, 1981; Tzeng and Wang, 1983). Specific processing requirements of individual languages may forge the organization of the language systems of the brain (Biederman and Tsao, 1979; Fang et al., 1981; Hung and Tzeng, 1981; Yeh and Li, 2002).

Implicit processing of Chinese characters

Central processing can reach beyond the functional demands of the task. Behavioral studies have confirmed that linguistic processing can be highly automatic and implicit (MacLeod, 1991; Van Orden, 1987), which in turn can target language-related brain areas even in a non-linguistic feature detection task (Brunswick et al., 1999; Price et al., 1996; Turkeltaub et al., 2003). CJ vs. both PJ and FJ, respectively, show common activation in the ventral part of left inferior frontal cortex, akin to the contrasts of HJ vs. PJ and FJ, respectively (Fig. 3). It is plausible that implicit or automatic semantic access, common to HJ and CJ, may engage this subregion of the inferior frontal area. This view gains strong support from the absence of activation of this region in the contrast of HJ vs. CJ. In conformity with a body of imaging studies on language and memory, our finding supports the theory of a functional segregation in the left inferior frontal cortex: the rostroventral part is more associated with semantic processing while the posterior dorsal part is related more to phonological processing (Bookheimer, 2002; Demb et al., 1995; Fiez and Petersen, 1998; Gabrieli et al., 1998; Kuo et al., 2003; Poldrack et al., 1999; Price, 2000; Wagner et al., 2000, 2001).

It has been argued that this ventral part of the left inferior frontal gyrus may rather subservise a general lexical processing, since its expression is dependent on lexical status of the stimulus rather than task demand (Gold and Buckner, 2002; McDermott et al., 2003). Gold and Buckner (2002) reported that this region was engaged not only in semantic processing but also in phonological processing and proposed that the left inferior frontal area participates in controlled processing across multiple information domains, collaborating with dissociable posterior regions upon the kind of information retrieved. It activates with the left temporal cortex during the controlled retrieval of semantics and with the left posterior frontal and inferior parietal cortex during the controlled retrieval of phonology (Gold and Buckner, 2002). It is possible that in the absence of explicit requirements for semantic computation, automatic or implicit semantic processing only activates the left inferior frontal cortex without overt expression of the left middle temporal area in the present study (Petersen et al., 1988, 1990).

Responses of the occipitotemporal junction/left mid-fusiform area in the current study

HJ elicited the highest response in the occipitotemporal junction/left mid-fusiform area (the peak *t* value was 16, 10, 12, and 14, and the signal change magnitude in terms of percentage as indexed to the control was 1.26, 0.81, 1.00, and 0.95 for HJ, CJ, PJ, and FJ, respectively), suggesting a differential cognitive load on this area based on the tasks rather than the stimulus categories. Since this area is functionally segregated and anatomically part of the ventral stream important for object

perception and recognition (Ungerleider and Haxby, 1994), the engagement of the OTJ by the four tasks (referenced to fixation condition) is expected (Fig. 2). Evidence that the OTJ also participates in the extraction of orthographic regularities for retrieving phonology of Chinese characters, similar to alphabetical language processing (Cohen et al., 2000, 2002; Polk and Farah, 2002), is substantiated by its activation in the subtraction of HJ vs. CJ (Fig. 4). It is possible that the OTJ, as a polymodal region, also subserves in part the visuospatial analysis in which form discrimination or form processing is one cognitive component for FJ that drives this region for computation (Price and Devlin, 2003).

Processing of pseudo-characters and Korean-like figures

Along the orthographic legality dimension of the current paradigm, no region was observed to behave parametrically across the three physical judgments. This is in line with Tagamets et al. (2000) where the authors manipulated linguistic properties of the material under the same task demand context (i.e., one-back matching task) finding no differential activation patterns for words, pseudo-words, letter-strings, or false-fonts (Tagamets et al., 2000). These findings are at odds with other imaging studies using feature detection tasks of a non-linguistic nature (Brunswick et al., 1999; Price et al., 1996; Turkeltaub et al., 2003), in which subjects automatically processed orthographically familiar stimuli, for example, words and pseudo-words, beyond the task demand and manifested the engagement of language-related brain areas. FJ acquired the right middle frontal and bilateral occipitoparietal cortices for processing, compared to CJ and PJ (Fig. 3). When PJ was contrasted with CJ, only the right middle frontal cortex was activated (figure not shown). This pattern may reflect the greater visuospatial effort required for coding unfamiliar items in both FJ and PJ, as reflected by the reaction time. FJ additionally taxes the frontoparietal networks and dorsal-ventral streams for finer visual analysis of unfamiliar and novel nonsense figures (Corbetta and Shulman, 2002; Newman et al., 2003). The lead-in effects of the stimulus categories, character-like vs. nonsense figure, may exert their influences in the early stage and change the downstream processes.

Conclusions

Characters, pseudo-characters, and figures have different linguistic properties. Using Chinese linguistic material as stimulus probes, the present study has investigated the central mechanisms at the representational level of orthographic and phonological processing for homophones, characters, pseudo-characters, and nonsense Korean-like figures. While the left occipitotemporal region, left dorsal processing stream, and right middle frontal gyrus constitute a network for orthographic processing, the regions of the left premotor gyrus, left middle/inferior frontal gyrus, medial frontal cortex, and the left temporoparietal region work in concert for phonological processing of Chinese. Our data support the theory that the left ventral inferior frontal cortex collaborates with the left temporoparietal cortex for controlled retrieval of phonology. The engagement of sets of regions for different levels of Chinese orthographic and phonological processing is consistent with the notion of distributed parallel processing. Our knowledge of characters arises from concurrent

interaction between orthographic, phonological, and semantic processing. The intricacy of how the task demand and the linguistic characteristics of Chinese interact with each other invites further investigation.

Acknowledgments

This study was supported by grants from the Taipei Veterans General Hospital (90400, 90443, 91361, 91380, 923721, 92348), National Science Council (902314B075124, 902314B075115, 912314B075069, 922314B075095), and Ministry of Education (89BFA221401 and 89BFA221406) of Taiwan. Special thanks to Dr. Hui-Cheng Cheng and the VGH-HT Imaging Center for technical support and Mr. Chi-Cher Chou for MRI operation and assistance.

References

- Awh, E., Jonides, J., Smith, E.E., Schumacher, E.H., Koeppel, R.A., Katz, S., 1996. Dissociation of storage and rehearsal in verbal working memory: evidence from PET. *Psychol. Sci.* 7, 25–31.
- Biederman, I., Tsao, Y.C., 1979. On processing Chinese ideographs and English words: some implications from Stroop-test results. *Cognit. Psychol.* 11, 125–132.
- Binder, J.R., Mohr, J.P., 1992. The topography of callosal reading pathways. A case control analysis. *Brain* 115, 1807–1826.
- Bookheimer, S.Y., 2002. Functional MRI of language: new approaches to understanding the cortical organization of semantic processing. *Annu. Rev. Neurosci.* 25, 151–188.
- Bookheimer, S.Y., Zeffiro, T.A., Blaxton, T., Gaillard, W., Theodore, W., 1995. Regional cerebral blood flow during object naming and word naming. *Hum. Brain Mapp.* 3, 93–106.
- Booth, J.R., Perfetti, C.A., MacWhinney, B., 1999. Quick, automatic, and general activation of orthographic and phonological representations in young readers. *Dev. Psychol.* 35, 3–19.
- Brunswick, N., McCrory, E., Price, C.J., Frith, C.D., Frith, U., 1999. Explicit and implicit processing of words and pseudowords by adult developmental dyslexics: a search for Wernicke's Wortschatz? *Brain* 122, 1901–1917.
- Chee, M.W., Tan, E., Thiel, T., 1999. Mandarin and English single word processing studies with functional magnetic resonance imaging. *J. Neurosci.* 19, 3050–3056.
- Chee, M.W., Weekes, B., Lee, K.M., Soon, C.S., Schreiber, A., Hoon, J.J., Chee, M., 2000. Overlap and dissociation of semantic processing of Chinese characters, English words, and pictures: evidence from fMRI. *NeuroImage* 12, 392–403.
- Chen, H.C., Juola, J.F., 1982. Dimensions of lexical coding in Chinese and English. *Mem. Cognit.* 10, 216–224.
- Chen, Y., Fu, S., Iversen, S.D., Smith, S.M., Matthews, P.M., 2002. Testing for dual brain processing routes in reading: a direct contrast of Chinese character and pinyin reading using fMRI. *J. Cogn. Neurosci.* 14, 1088–1098.
- Cohen, L., Dehaene, S., Naccache, L., Lehericy, S., Dehaene Lambertz, G., Henaff, M., Michel, F., 2000. The visual word form area: spatial and temporal characterization of an initial stage of reading in normal subjects and posterior split brain patients. *Brain* 123, 291–307.
- Cohen, L., Lehericy, S., Chochon, F., Lemer, C., Rivaud, S., Dehaene, S., 2002. Language specific tuning of visual cortex? Functional properties of the visual word form area. *Brain* 125, 1054–1069.
- Coltheart, M., Curtis, B., Atkins, P., Haller, M., 1993. Models of reading aloud: dual-route and parallel-distributed-processing approaches. *Psychol. Rev.* 100, 589–608.

- Corbetta, M., Shulman, G.L., 2002. Control of goal-directed and stimulus-driven attention in the brain. *Nat. Rev. Neurosci.* 3, 201–215.
- Dehaene, S., Le Clec'h, G., Poline, J.B., Le Bihan, D., Cohen, L., 2001. Cerebral mechanisms of word masking and unconscious repetition priming. *Nat. Neurosci.* 4, 752–758.
- Dehaene, S., Le Clec'h, G., Poline, J.B., Le Bihan, D., Cohen, L., 2002. The visual word form area: a prelexical representation of visual words in the fusiform gyrus. *NeuroReport* 13, 321–325.
- Demb, J.B., Desmond, J.E., Wagner, A.D., Vaidya, C.J., Glover, G.H., Gabrieli, J.D., 1995. Semantic encoding and retrieval in the left inferior prefrontal cortex: a functional MRI study of task difficulty and process specificity. *J. Neurosci.* 15, 5870–5878.
- Demonet, J.F., Chollet, F., Ramsay, S., Cardebat, D., Nespoulous, J.L., Wise, R., Rascol, A., Frackowiak, R.S.J., 1992. The anatomy of phonological and semantic processing in normal subjects. *Brain* 115, 1753–1768.
- Fang, S.P., Tzeng, O.J.L., Alva, E., 1981. Intra- versus inter-language Stroop interference effect in bilingual subjects. *Mem. Cognit.* 9, 609–617.
- Feldman, L.B., Siok, W.W.T., 1999. Semantic radicals contribute to the visual identification of Chinese characters. *J. Mem. Lang.* 40, 559–576.
- Fiez, J.A., Petersen, S.E., 1998. Neuroimaging studies of word reading. *Proc. Natl. Acad. Sci. U. S. A.* 95, 914–921.
- Fiez, J.A., Balota, D.A., Raichel, M.E., Petersen, S.E., 1999. Effects of lexicality, frequency, and spelling-to-sound consistency on the functional anatomy of reading. *Neuron* 24, 205–218.
- Fu, S., Chen, Y., Smith, S.M., Iversen, S.D., Matthews, P.M., 2002. Effects of word form on brain processing of written Chinese. *NeuroImage* 17, 1538–1548.
- Gabrieli, J., Poldrack, R., Desmond, J., 1998. The role of left prefrontal cortex in language and memory. *Proc. Natl. Acad. Sci. U. S. A.* 95, 906–913.
- Gold, B.T., Buckner, R.L., 2002. Common prefrontal regions coactivate with dissociable posterior regions during controlled semantic and phonological tasks. *Neuron* 35, 803–812.
- Hagoort, P., Indefrey, P., Brown, C., Herzog, H., Steinmetz, H., Seitz, R.J., 1999. The neural circuitry involved in the reading of German words and pseudowords: a PET Study. *J. Cogn. Neurosci.* 11, 383–398.
- Hamzei, F., Dettmers, C., Rijntjes, M., Glauche, V., Kiebel, S., Weber, B., Weiller, C., 2002. Visuomotor control within a distributed parieto-frontal network. *Exp. Brain Res.* 146, 273–281.
- Herbster, A.N., Mintun, M.A., Nebes, J.T., 1997. Regional cerebral blood flow during word and nonword reading. *Hum. Brain Mapp.* 5, 84–92.
- Hung, D.L., Tzeng, O.J.L., 1981. Orthographic variations and visual information processing. *Psychol. Bull.* 90, 377–414.
- Jonides, J., Schumacher, E.H., Smith, E.E., Koeppe, R.A., Awh, E., Reuter-Lorenz, P.A., Marshuetz, C., Willis, C.R., 1998. The role of parietal cortex in verbal working memory. *J. Neurosci.* 18, 5026–5034.
- Krasnow, B., Tamm, L., Greicius, M.D., Yang, T.T., Glover, G.H., Reiss, A.L., Menon, V., 2003. Comparison of fMRI activation at 3 and 1.5 T during perceptual, cognitive, and affective processing. *NeuroImage* 18, 813–826.
- Kuo, W.J., Yeh, T.C., Duann, J.R., Wu, Y.T., Ho, L.T., Hung, D.L., Tzeng, O.J.L., Hsieh, J.C., 2001. A left-lateralized network for reading Chinese words: a 3T fMRI study. *NeuroReport* 12, 3997–4001.
- Kuo, W.J., Yeh, T.C., Lee, C.Y., Wu, Y.T., Chou, C.C., Ho, L.T., Hung, D.L., Tzeng, O.J.L., Hsieh, J.C., 2003. Frequency effects of Chinese character processing in the brain: an event-related fMRI study. *NeuroImage* 18, 720–730.
- Law, I., Kanna, I., Fujita, H.S.M., Lassen, N., Uemura, K., 1991. Left supramarginal/angular gyri activation during of syllabograms in the Japanese language. *J. Neurolinguist.* 6, 243–251.
- Leck, K.J., Weekes, B.S., Chen, M.J., 1995. Visual and phonological pathways to the lexicon: evidence from Chinese readers. *Mem. Cognit.* 23, 468–476.
- MacLeod, C.M., 1991. Half a century of research on the Stroop effect: an integrative review. *Psychol. Bull.* 109, 163–203.
- McDermott, K.B., Petersen, S.E., Watson, J.M., Ojemann, J.G., 2003. A procedure for identifying regions preferentially activated by attention to semantic and phonological relations using functional magnetic resonance imaging. *Neuropsychologia* 41, 293–303.
- Mechelli, A., Friston, K.J., Price, C.J., 2000. The effects of presentation rate during word and pseudoword reading: a comparison of PET and fMRI. *J. Cogn. Neurosci.* 12, 145–156.
- Mechelli, A., Gorno-Tempini, M.L., Price, C.J., 2003. Neuroimaging studies of word and pseudoword reading: consistencies, inconsistencies, and limitations. *J. Cogn. Neurosci.* 15, 260–271.
- Nakamura, K., Honda, M., Okada, T., Hanakawa, T., Toma, K., Fukuyama, H., Konishi, J., Shibasaki, H., 2000. Participation of the left posterior inferior temporal cortex in writing and mental recall of Kanji orthography. A functional MRI study. *Brain* 123, 954–967.
- Nakamura, K., Honda, M., Hirano, S., Oga, T., Sawamoto, N., Hanakawa, T., Inoue, H., Ito, J., Matsuda, T., Fukuyama, H., Shibasaki, H., 2002. Modulation of the visual word retrieval system in writing: a functional MRI study on the Japanese orthographies. *J. Cogn. Neurosci.* 14, 104–115.
- Newman, S.D., Carpenter, P.A., Varma, S., Just, M.A., 2003. Frontal and parietal participation in problem solving in the Tower of London: fMRI and computational modeling of planning and high-level perception. *Neuropsychologia* 41, 1668–1682.
- Oldfield, R.C., 1971. The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia* 9, 97–113.
- Paulesu, E., Frith, C.D., Frackowiak, R.S.J., 1993. The neural correlates of the verbal component of working memory. *Nature* 362, 342–345.
- Paulesu, E., McCrory, E., Fazio, F., Menoncello, L., Brunswick, N., Cappa, S.F., Cotelli, M., Cossu, G., Corte, F., Lorusso, M., Pesenti, S., Gallagher, A., Perani, D., Price, C.J., Frith, C.D., Frith, U., 2000. A cultural effect on brain function. *Nat. Neurosci.* 3, 91–96.
- Petersen, S.E., Fox, P.T., Posner, M.I., Mintun, M.A., Raichel, M.E., 1988. Positron emission tomography studies of the cortical anatomy of single word processing. *Nature* 331, 585–589.
- Petersen, C.J., Fox, P.T., Snyder, A.Z., Raichel, M.E., 1990. Activation of extrastriate and frontal cortical areas by words and word-like stimuli. *Science* 249, 1041–1044.
- Plaut, D.C., McClelland, J.L., Seidenberg, M.S., Patterson, K., 1996. Understanding normal and impaired word reading: computational principles in quasi-regular domains. *Psychol. Rev.* 103, 56–115.
- Poldrack, R., Wagner, A., Prull, M., Desmond, J., Glover, G., Gabrieli, J., 1999. Functional specialization for semantic and phonological processing in the left inferior prefrontal cortex. *NeuroImage* 10, 15–35.
- Polk, T.A., Farah, M.J., 2002. Functional MRI evidence for an abstract, not perceptual, word-form area. *J. Exp. Psychol.: Gen.* 131, 65–72.
- Price, C.J., 2000. The anatomy of language: contributions from functional neuroimaging. *J. Anat.* 197, 335–359.
- Price, C.J., Devlin, J.T., 2003. The myth of the visual word form area. *NeuroImage* 19, 473–481.
- Price, C.J., Wise, R.J.S., Frackowiak, R.S.J., 1996. Demonstrating the implicit processing of visually presented words and pseudowords. *Cereb. Cortex* 6, 62–70.
- Price, C.J., Moore, C.J., Humphreys, G.W., Wise, R.S.J., 1997. Segregating semantic from phonological processes during reading. *J. Cogn. Neurosci.* 9, 727–733.
- Pugh, K.R., Shaywitz, B.A., Shaywitz, S.E., Constable, R.T., Skudlarski, P., Fulbright, R.K., Bronen, R.A., Shankweiler, D.P., Katz, L., Fletcher, J.M., Gore, J.C., 1996. Cerebral organization of component processes in reading. *Brain* 119, 1221–1238.
- Pugh, K.R., Mencl, W.E., Jenner, A.R., Katz, L., Frost, S.J., Lee, J.R., Shaywitz, S.E., Shaywitz, B.A., 2000. Functional neuroimaging studies of reading and reading disability (developmental dyslexia). *Ment. Retard. Dev. Disabil. Res. Rev.* 6, 207–213.
- Rushworth, M.F., Paus, T., Sipila, P.K., 2001a. Attention systems and the organization of the human parietal cortex. *J. Neurosci.* 21, 5262–5271.
- Rushworth, M.F., Krams, M., Passingham, R.E., 2001b. The attentional role

- of the left parietal cortex: the distinct lateralization and localization of motor attention in the human brain. *J. Cogn. Neurosci.* 13, 698–710.
- Sakurai, Y., Momose, T., Iwata, M., Sudo, Y., Ohtomo, K., Kanazawa, I., 2000. Different cortical activity in reading of Kanji words, Kana words and Kana nonwords. *Brain Res. Cogn. Brain Res.* 9, 111–115.
- Salmelin, R., Hari, R., Lounasmaa, O.V., Sams, M., 1994. Dynamics of brain activation during picture naming. *Nature* 368, 463–465.
- Salmelin, R., Service, E., Kiesila, P., Uutela, K., Salonen, O., 1996. Impaired visual word processing in dyslexia revealed with magnetoencephalography. *Ann. Neurol.* 40, 157–162.
- Seidenberg, M.S., McClelland, J.L., 1989. The distributed development model of word recognition and naming. *Psychol. Rev.* 96, 523–568.
- Shaywitz, B.A., Shaywitz, S.E., Pugh, K. R., Mencl, W.E., Fulbright, R.K., Skudlarski, P., Constable, R.T., Marchione, K.E., Fletcher, J.M., Lyon, G.R., Gore, J.C., 2002. Disruption of posterior brain systems for reading in children with developmental dyslexia. *Biol. Psychiatry* 52, 101–110.
- Siok, W.W.T., Jin, Z., Fletcher, P., Tan, L.H., 2003. Distinct brain regions associated with syllable and phoneme. *Hum. Brain Mapp.* 18, 201–207.
- Smith, E.E., Jonides, J., 1998. Neuroimaging analyses of human working memory. *Proc. Natl. Acad. Sci. U. S. A.* 95, 12061–12068.
- Spinks, J.A., Liu, Y., Perfetti, C.A., Tan, L.H., 2000. Reading Chinese characters for meaning: the role of phonological information. *Cognition* 76, B1–B11.
- Taft, M., Zhu, X., 1997. Submorphemic processing in reading Chinese. *J. Exp. Psychol.: Learn. Mem. Cogn.* 23, 761–775.
- Tagamets, M.A., Novick, J.M., Chalmers, M.L., Friedman, R.B., 2000. A parametric approach to orthographic processing in the brain: an fMRI study. *J. Cogn. Neurosci.* 12, 281–297.
- Tan, L.H., Spinks, J.A., Gao, J.H., Liu, H.L., Perfetti, C.A., Xiong, J., Stofer, K.A., Pu, Y., Liu, Y., Fox, P.T., 2000. Brain activation in the processing of Chinese characters and words: a functional MRI study. *Hum. Brain Mapp.* 10, 16–27.
- Tan, L.H., Feng, C.M., Fox, P.T., Gao, J.H., 2001a. A fMRI study with written Chinese. *NeuroReport* 12, 83–88.
- Tan, L.H., Liu, H.L., Perfetti, C.A., Spinks, J.A., Fox, P.T., Gao, J.H., 2001b. The neural system underlying Chinese logograph reading. *NeuroImage* 13, 836–846.
- Tokunaga, H., Nishikawa, T., Ikejiri, Y., Nakagawa, Y., Yasuno, F., Hashikawa, K., Nishimura, T., Sugita, Y., Takeda, M., 1999. Different neural substrates for Kanji and Kana writing: a PET study. *NeuroReport* 10, 3315–3319.
- Turkeltaub, P.E., Gareau, L., Flowers, D.L., Zeffiro, T.A., Eden, G.F., 2003. Development of neural mechanisms for reading. *Nat. Neurosci.* 6, 767–773.
- Tzeng, O.J.L., Wang, W.S.Y., 1983. The first two R's. *Sci. Am.* 71, 238–243.
- Uchida, I., Kikyo, H., Nakajima, K., Konishi, S., Sekihara, K., Miyashita, Y., 1999. Activation of lateral extrastriate areas during orthographic processing of Japanese characters studied with fMRI. *NeuroImage* 9, 208–215.
- Ungerleider, L.G., Haxby, J.V., 1994. “What” and “where” in the human brain. *Curr. Opin. Neurobiol.* 4, 157–165.
- Van Orden, G.C., 1987. A ROWS is a ROSE: spelling, sound, and reading. *Mem. Cognit.* 15, 181–198.
- Van Orden, G.C., Johnston, J.C., Hale, B.L., 1988. Word identification in reading proceeds from spelling to sound to meaning. *J. Exp. Psychol.: Learn. Mem. Cogn.* 14, 371–386.
- Wagner, A.D., Koutstaal, W., Maril, A., Schacter, D.L., Buckner, R.L., 2000. Task-specific repetition priming in left inferior prefrontal cortex. *Cereb. Cortex* 10, 1176–1184.
- Wagner, A.D., Pare-Blagoev, E.J., Clark, J., Poldrack, R.A., 2001. Recovering meaning: left prefrontal cortex guides controlled semantic retrieval. *Neuron* 31, 329–338.
- Wang, W.S.Y., 1973. The Chinese language. *Sci. Am.* 228, 50–60.
- Warrington, E.K., Shallice, T., 1980. Word-form dyslexia. *Brain* 103, 99–112.
- Weissman, D.H., Mangun, G.R., Woldorff, M.G., 2002. A role for top-down attentional orienting during interference between global and local aspects of hierarchical stimuli. *NeuroImage* 17, 1266–1276.
- Xu, B., Grafman, J., Gaillard, W.D., Ishii, K., Vega-Bermudez, F., Pietrini, P., Reeves-Tyer, P., DiCamillo, P., Theodore, W., 2001. Conjoint and extended neural networks for the computation of speech codes: the neural basis of selective impairment in reading words and pseudowords. *Cereb. Cortex* 11, 267–277.
- Xu, B., Grafman, J., Gaillard, W.D., Spanaki, M., Ishii, K., Balsamo, L., Makale, M., Theodore, W.H., 2002. Neuroimaging reveals automatic speech coding during perception of written word meaning. *NeuroImage* 17, 859–870.
- Yeh, S.L., Li, J.L., 2002. Role of structure and component in judgments of visual similarity of Chinese characters. *J. Exp. Psychol.: Hum. Percept. Perform.* 28, 933–947.
- Zhou, Y.G., 1978. To what degree are the “phonetics” of present-day Chinese characters still phonetic? *Zhongguo Yuwen* 146, 172–177.