Frequency effects of Chinese character processing in the brain: an event-related fMRI study

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Abstract

Knowing how the brain processes Chinese characters of different frequencies of occurrence may shed light on the extent to which orthographic variations of different languages can influence reading processes in the brain. In the present study, event-related fMRI was used to investigate frequency effects on Chinese character processing. Reading low-frequency characters invoked higher activation in several brain regions including the left premotor/inferior frontal gyrus, supplementary motor area, left anterior insula, left posterior inferior temporal gyrus, left superior parietal cortex, and lingual cortex, while reading high-frequency characters resulted in higher activation in the left supramarginal/angular gyrus and left precuneus. The activation pattern of reading infrequently encountered characters reflects a more demanding processing procedure of retrieving, formulating, and coordinating the phonological output. Access to the lexical route may benefit the reading of high-frequency characters. By uncovering the differential brain responses in reading Chinese characters of different occurrence frequencies, not only has a substantial overlap between functional neuroanatomy of reading Chinese and alphabetical languages been demonstrated, but also features permitting the separation of language-specific content from universal mechanisms.
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Introduction

During reading, lexically stored word knowledge must be accessed from visual input. The frequency of occurrence of words in the language has a robust influence on reading performance (Coltheart et al., 1993; Seidenberg and Mc-Clelland, 1989). The word frequency effects, coined as a behavioral term, imply that readers perform better or faster for words with a high frequency of occurrence (HF) than for low-frequency ones (LF) (Cattell, 1886). Repeated experience of a word can increase the efficiency with which a reader can identify its form and retrieve its semantic association and pronunciation (Monsell et al., 1989). Theoretical interpretations of these findings can be partially attributed to the fact that the frequency of occurrence in print commands the indexing of the internal lexicon and thereby influences lexical access. In studies of speech production, the word frequency effects have been demonstrated to take place in the phonological encoding stage, that is, during the computation of the phonetic form of the intended utterance (Jescheniak and Levelt, 1994; Levelt et al., 1999).

Neurophysiological correlates of frequency effect have been elucidated by electroencephalographic (EEG) and

magnetoencephalographic (MEG) measurements (Assadollahi and Pulvermuller, 2001; Embick et al., 2001; King and Kutas, 1998; Munte et al., 2001; Osterhout et al., 1997; Polich and Donchin, 1988; Pulvermuller, 1999; Rugg, 1990). The early negativity in event-related brain potentials is highly correlated with word frequency (Osterhout et al., 1997). Recognition is faster for common words than for uncommon ones and occurs during the first 350 ms of brain processing (King and Kutas, 1998). These EEG findings are corroborated by MEG observations (Embick et al., 2001; Koyama et al., 1998; Kuriki et al., 1998). Furthermore, the physical properties of words, for example, word length, have been shown to modulate the temporal scenario when processes differentiating between rare and common items become manifested in the neuromagnetic response of the human brain (Assadollahi and Pulvermuller, 2001).

Neuroimaging studies using positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) on alphabetical languages have also elucidated central representations of frequency effects (Chee et al., 2002; Fiebach et al., 2002; Fiez et al., 1999). In the PET study by Fiez et al. (1999), naming LF English words, particularly without spelling-to-sound correspondence, resulted in greater activity in the left inferior frontal gyrus (IFG), left superior temporal gyrus, supplemental motor area (SMA), and cerebellum (Fiez et al., 1999). The engagement of the left IFG is proposed to underscore the rule-based phonological computation (Fiez et al., 1999). In one recent event-related fMRI experiment, brain responses of lexical decisions to HF, LF, and pseudo-words were investigated (Fiebach et al., 2002). In compliance with the dual-route model of reading, frequency effects (LF vs. HF words) as indexed by a higher cortical activity were demonstrated in the left IFG, which encompasses the pars triangularis, pars opercularis, and anterior insula. The activation in these regions may echo the mental processes of grapheme-to-phoneme conversion (GPC). However, no difference between reading HF and LF words was found in another recent fMRI study (Chee et al., 2002), which is at odds with both existing behavioral data (Balota and Chumbley, 1985; Cattell, 1886; Coltheart et al., 1993; Monsell et al., 1989; Seidenberg, 1985) and neuroimaging reports (Fiebach et al., 2002; Fiez et al., 1999).

Reading printed words may target the posterior fusiform and lingual gyri for visual form processing while engaging the left posterior middle temporal, posterior temporoparietal, and anterior inferior temporal cortices for semantic processing (Fiez et al., 1999; Fiez and Petersen, 1998; Hagoort et al., 1999; Herbster et al., 1997; Paulesu et al., 2000; Price, 2000). In the model for alphabetical language as proposed by Pugh et al. (2000), neural circuitry for reading comprises the anterior circuit, mainly the left IFG, and two posterior circuits. The dorsal stream of the posterior circuit consists of the angular gyrus, the supramarginal gyrus, and the posterior part of the superior temporal gyrus, whereas the ventral stream includes the lateral extrastriate areas and left inferior occipital–temporal junction. The anterior circuit participates in speech gesture and articulation of printed words and in part service the orthography-to-phonology transformation (OPT). The posterior dorsal circuit pertains to the rule-based analysis of the relation between orthography and phonology; the ventral circuit constitutes a linguistically organized system for word identification (Price, 2000; Pugh et al., 2000). We have in our previous fMRI study reported that naming of Chinese logographs is characterized by left-lateralized neuronal networks for the processing of orthographic, phonological, and semantic attributes (Kuo et al., 2001). Despite sharing neural circuitry with reading of alphabetical languages, the orchestration of the middle frontal cortex, superior temporal cortex, superior parietal lobule (SPL), basal temporal area, and extrastriate cortices of the left hemisphere may manifest the particularity of the central representation of reading Chinese words (Kuo et al., 2001).

In English reading, there is a strong inverse correlation between word length and word frequency; any correlation of a measure with one of these variables implies an inverse correlation with the other if the two factors are not well controlled or matched (Osterhout et al., 1997; Pulvermuller, 1999). Such confusion can be avoided when using Chinese characters as the word stimuli for the study of word frequency effects, since each Chinese character has only one syllable. Moreover, the Chinese character is the basic unit of word composition and each logograph represents a unit of meaning rather than merely of sound. The GPC correspondences of alphabetical languages cannot be applied to Chinese. Although there are phonetic radicals in most Chinese characters (phonograms) to provide clues for the derivation of phonology, the computation is very distinct from that of alphabetical languages, as the phonological output of a Chinese character cannot be precisely derived from its radical.

Knowing how the brain processes Chinese characters of different occurrence frequencies may shed light on the extent to which orthographic variations in different languages influence reading processes in the brain. The present study utilized whole-brain 3-T fMRI to identify neural correlates of frequency effects on Chinese character reading. Subjects were asked to covertly name Chinese characters of distinct frequency levels since frequency effects of reading Chinese character have previously been demonstrated with naming tasks (Lee, 2000; Liu et al., 1996; Seidenberg, 1985). Different frequencies of occurrence of Chinese characters may elicit different patterns of brain organization for their processing. It is reasoned that reading LF characters may command more mental resources for their visuospatial analysis, phonological retrieval, and articulatory constellation whereas reading HF characters enjoys a more direct association with semantic attributes for efficient lexical identification.
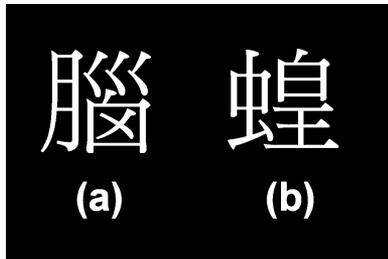
Fig. 1. Examples of high-frequency and low-frequency Chinese characters. (a) A high-frequency Chinese character ("brain" in English) with occurrence frequency more than 400 occurrences per 10 million. (b) A low-frequency Chinese character ("locust" in English) with occurrence frequency less than 50 occurrences per 10 million.

Material and methods

Subjects

Twenty right-handed university students were studied. Twelve of them (8 women, mean age 25 years, range 21 to 35 year) participated in the behavioral study while the rest (gender balanced, mean age 24 years, range 21 to 27 years) participated in the fMRI experiment. All volunteers were native Chinese speakers without any history of neurological disorders and had normal or corrected to normal vision. Handedness of the subjects 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.

Experimental paradigms

Behavioral study on the stimulus set

A behavioral measurement under similar task settings (see later, "fMRI paradigm") was performed to validate the frequency effects of the current set of stimuli (Fig. 1). Naming latencies were recorded by triggering from a voice-key as interfaced with a personal computer (PC). The accuracy of each response was registered. Subjects showed significant frequency effects in terms of naming latency (mean ± SD, 507 ± 54 ms for HF words; 614 ± 65 ms for LF words; $P < 0.001$, paired t test) and in response accuracy (0.94 ± 0.05 for HF words; 0.72 ± 0.09 for LF words; $P < 0.001$, paired t test).

fMRI paradigm

Subjects performed three sessions of covert naming of Chinese characters. In each session, there were 22 HF characters and equal number of LF characters randomly mixed for their presentation. The characters in the two groups were all phonograms and were matched for their regularity/consistency values, visual complexity, and other linguistic attributes, for example, proportions of nouns and verbs. All 132 characters (three sessions) used in this study were sampled from Sinica Corpus (Academic Sinica, 1997; http://rocling.iis.sinica.edu.tw/ROCLING/corpus98/index_cf.htm). It deserves a mentioning that the corresponding frequencies of occurrence between written and spoken forms of the stimuli used in this experiment are highly and positively correlated ($r = 0.732$; $P < 0.01$), as stemmed from the two corpuses of written (Sinica Corpus, Academic Sinica, Taiwan) and spoken formats (Mandarin Promotion Council, Ministry of Education, Taiwan). Frequency of occurrence was higher than 400 occurrences per 10 million for HF characters and less than 50 occurrences per 10 million for LF characters. Each character was displayed for 1000 ms at an average rate of every four MR acquisitions. The interstimulus interval varied from one to seven acquisitions. The character was replaced by a crosshair between trials. The crosshair, the location of which coincided with the character presentation, served as a fixation point to control for inadvertent eye movement throughout the experiment.

Recognition task

After MR image acquisition, subjects were requested to perform a recognition task in which 40 old characters, randomly sampled from the given 132 stimuli, and 40 new characters were intermixed and displayed, and the subjects were asked to judge if the presented character had been previously encountered. Since the mean hit rate of the subjects' performance to the sampled items was 80% (range 65% to 90%), the result confirmed that the subjects did follow the instructions and actively perform the requested reading task during the fMRI experiment.

For the character display during MR acquisition, the stimuli were presented with a PC using a custom-designed program and projected via a LCD projector (Toshiba TY-G3, Japan) outside the shielded room on a screen at the feet of the subject. Subjects saw the display via a homemade reflection mirror. The viewing distance was about 194 cm. Visual angle of each character subtended ~2.3° while that of the fixation crosshair (common baseline) subtended ~1° in both vertical and horizontal directions.

MRI procedure

Images were acquired using a 3.0-T MedSpec S300 system (Bruker, Kalsrube, Germany) with a quadrature head coil. Subjects' heads were immobilized with a vacuum-beam pad in the scanner. Global field homogeneity was optimized before data acquisition using both automatic and manual shimming. Functional data were acquired with a T2*-weighted gradient-echo EPI using BOLD contrast (TR/TE/θ = 2000 ms/50 ms/90°, slice thickness 5 mm, interslice interval 1 mm, FOV = 250 mm, 64 × 64 × 20 matrix, whole brain covered). For each slice, 181 images were acquired. The first 5 images were discarded from the analysis to eliminate nonequilibrium effects of magnetization. The behavioral task started after the first five acquisitions of images for equilibrium purpose. The anatomical image was

acquired using a high-resolution T1-weighted, 3D gradient-echo pulse sequence (MDEFT, modified driven equilibrium Fourier transform; TR/TE/TI = 88.1 ms/4.12 ms/650 ms, 128 × 128 × 128 matrix, FOV = 250 mm). Total duration of the experiment lasted for ~1.5 h.

Data processing and statistical analysis

Data were analyzed with statistical parametric mapping (SPM99 software from the Wellcome Department of Cognitive Neurology, London, UK), running under Matlab 6.0 (Mathworks, Sherbon, MA) on a Sun workstation. Scans were realigned, normalized, time corrected, and spatially smoothed with an 8-mm FWHM gaussian kernel. The resulting time series was high-pass filtered with a cut-off time window specific to each session to remove LF drifts in the BOLD signal (Holmes et al., 1997) and temporally smoothed with a hemodynamic response function (HRF). Estimated motion parameters were incorporated into the modeling as confounds.

The event-related time series was modeled using a general linear model with a HRF reference and its temporal derivative (Friston et al., 1998). The parameter estimates for the height of the canonical response for each covariate of interest were averaged for each study condition across all sessions and subjects. An F test for the contrast between all reading conditions relative to the baseline, yielding the overall representation of reading regardless of frequency levels, was conducted and thresholded at corrected $P < 0.05$ (Friston et al., 1998). A voxel-specific t test was performed to examine the contrast between LF and HF conditions. The t statistics were subsequently transformed to Z statistics to create a statistical parametric map {SPM(z)} for each contrast. Since regions of search were based on our previous work (Kuo et al., 2001), an uncorrected threshold of $P = 0.001$ ($Z = 3.09$) with a spatial constraint of $n \geq 20$ voxels was considered statistically significant for regionally specific effects (Henson et al., 1999). Z maxima were localized on the normalized T1 structural image (an SPM99 template) and labeled using the nomenclature of Talairach and Tournoux (1988) by means of the Talairach Daemon (Research Imaging Center, The University of Texas, Austin, TX). Event-related response estimates of maxima (time–activity plot) in regions identified by low-to-high and high-to-low contrasts were also presented.

Results

Neural correlates of reading Chinese characters

Fig. 2 shows that reading Chinese characters activated an extensive network involving both hemispheres with the left hemisphere predominating. Activation of bilateral temporooccipital cortices, bilateral lingual gyri, left anterior insula, bilateral precentral gyrus, bilateral inferior/middle frontal gyrus, medial superior frontal/anterior cingulate cortices, and left temporoparietal junction were observed. Parietal activation was seen in the right intraparietal sulcus, left precuneus, and left SPL.

Areas showing greater activity for low-frequency characters

Reading of LF characters, compared to HF characters, caused more engagement of the bilateral medial superior frontal gyri (i.e., SMA), left precentral (motor) gyrus, bilateral inferior/middle frontal gyri (more pronounced on the left), bilateral anterior insula (more pronounced on the left), left superior parietal cortex, left inferior temporooccipital cortex, and bilateral anterior lingual gyri (Table 1A and Fig. 3A). Response estimates in these regions are shown in Figs. 4a–g.

Areas showing greater activity for high-frequency characters

Reading HF characters led to stronger activation, compared to reading LF characters, in the left temporoparietal region and precuneus (Table 1B and Fig. 3B). Response estimates of the activated regions are shown in Figs. 4h–i.

Discussion

To our knowledge, this is the first fMRI imaging study addressing the frequency effects of Chinese reading. Other factors contributing to proficient reading, for example, regularity/consistency valence, are balanced between the HF and LF conditions in this study. There are reasons for exploiting a naming task instead of a lexical decision task in this imaging study. For a lexical decision task, it is necessary to make a motor response to every single item. The motor act is not directly related to reading but can be coregistered in the fMRI-BOLD responses. Notwithstanding, components inherent in task execution but not directly associated with lexicality per se may give rise to inadvertent weighting for different processing routes, which in turn will result in a different pattern of brain activation (Hagoort et al., 1999; Herbster et al., 1997; Price et al., 1996b; Rumsey et al., 1997).

Neuronal correlates for Chinese character reading

Component processes of reading as delineated from studies on alphabetical languages have been associated with different brain areas, for example, motoric execution of speech production will activate the primary motor cortex, the SMA, and the cerebellum; auditory stimulation from one's own vocalization can evoke bilateral activation in the auditory cortex in the superior temporal region; contributions of the left posterior temporal regions to phonological
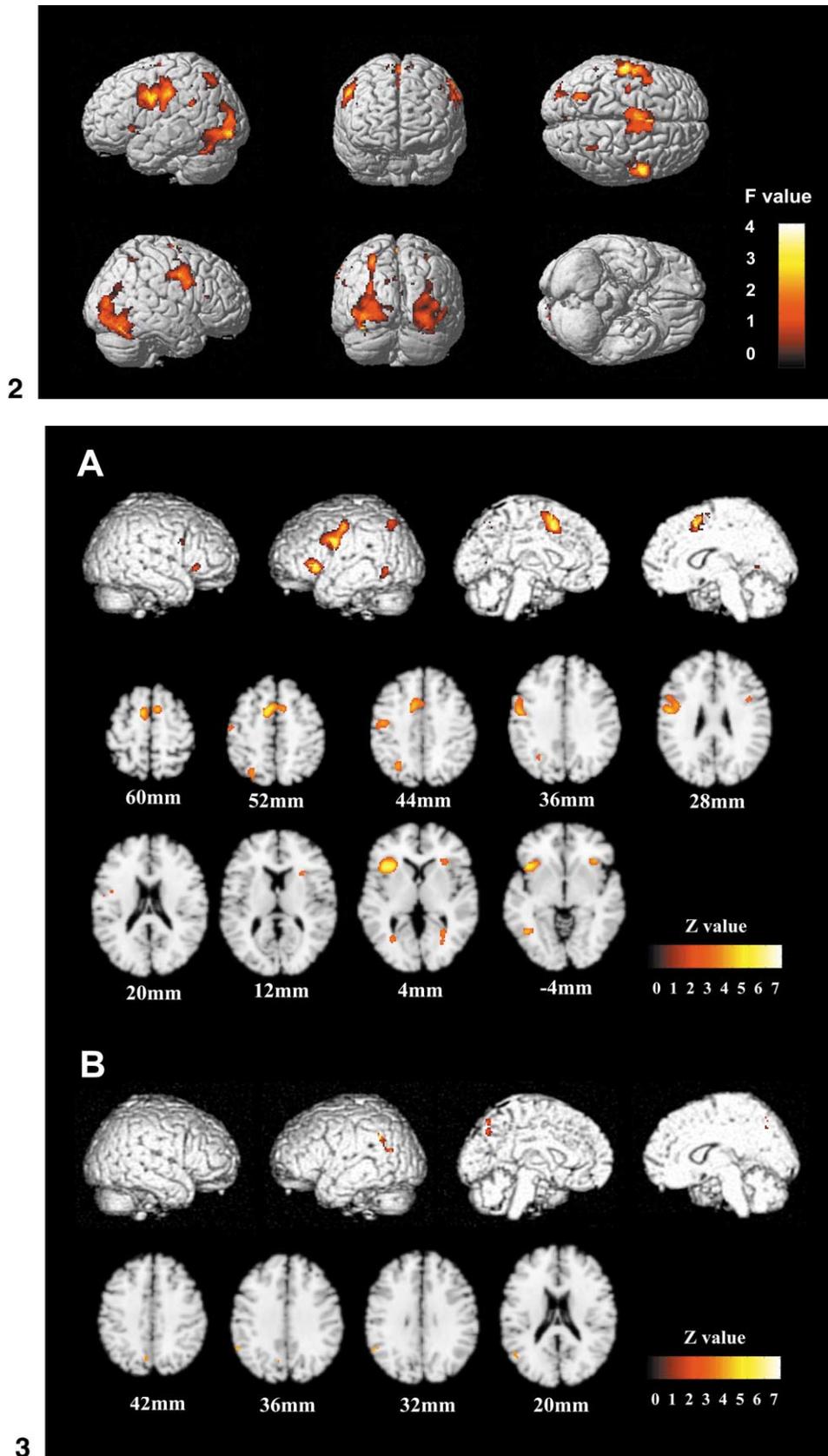
Fig. 2. Neuronal correlates of Chinese character reading. Images are the statistical parametric maps (*F* test; thresholded at corrected $P < 0.05$, $F > 1.91$) of brain activity during reading of Chinese characters of all frequency levels. The color bar denotes the *F* value.

Fig. 3. Differential brain responses in reading Chinese characters of different occurrence frequencies. (A) Statistical maps of reading low- versus high-frequency characters. (B) Statistical maps of reading high- versus low-frequency characters. Clusters survive an uncorrected $P < 0.001$ ($Z > 3.09$) with spatial extent $n \geqq 20$ voxels are considered statistically significant. The color bar denotes the *Z* value.
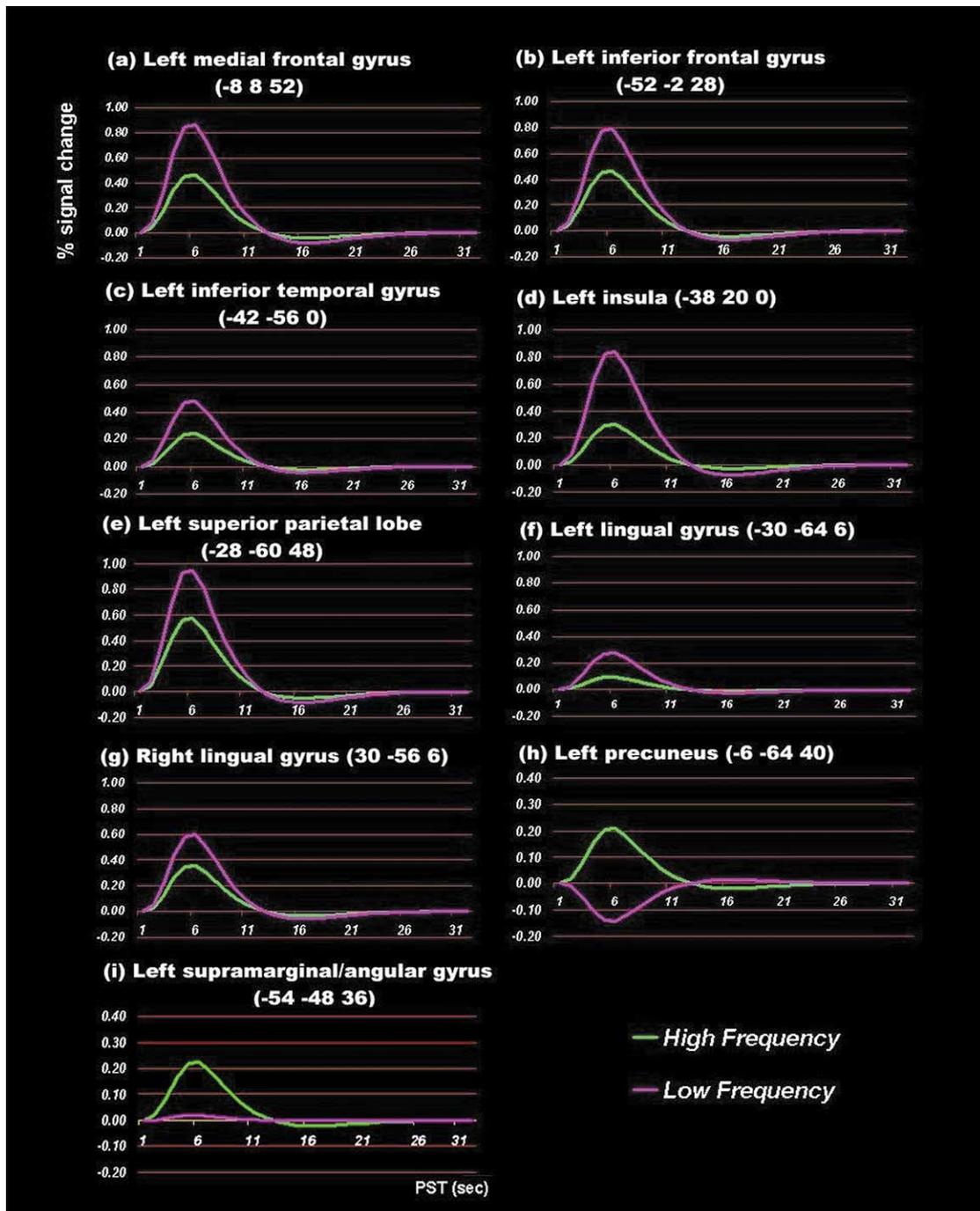
Fig. 4. Time–activity curves of the best-fitted hemodynamic response. Event-related response estimates of maxima in regions identified by the contrast of reading low- versus high-frequency characters (a–g) and high- versus low-frequency characters (h, i), respectively. Green line, reading high-frequency characters; purple line, reading low-frequency characters; PST, peristimulus time.

analysis are acoustically based; the left inferior frontal and anterior insular regions contribute to articulation-based phonological analysis; regions for semantic processing are near to the middle and superior temporal gyri; and the left occipital and occipitotemporal regions are important for visual word form analysis (Bookheimer, 2002; Brunswick et al., 1999; Cohen et al., 2000, 2002; Demonet et al., 1994; Fiez et al., 1996, 1999; Gabrieli et al., 1998; McGuire et al.,

1996; Poldrack et al., 1999; Poldrack et al., 2001; Price et al., 1996a; Turkeltaub et al., 2002; Zatorre et al., 1996). Reading Chinese single-character words activated a network encompassing a number of regions in the occipital, parietal, temporal, and frontal cortices (Fig. 2). Bilateral activation was noted in lateral extrastriate occipital, inferior/ middle frontal cortex, premotor, and supplementary motor/ cingulate motor regions while activation in the superior

Table 1
Brain regions showing significant difference between reading low-frequency and high-frequency characters

	Left hemisphere					Right hemisphere				
	BA	x	y	z	Z value	BA	x	y	z	Z value
				A. LF > HF						
Medial frontal G	6	−8	8	52	5.88					
Superior frontal G						6	10	10	52	5.11
Precentral G	4	−54	−12	48	3.52					
Inferior/middle frontal G	6	−52	−2	28	4.85					
	9	−44	4	28	4.14	9	42	8	24	3.73
						47	38	26	−4	4.22
Insula	13	−38	20	0	6.29	13	30	20	10	3.66
Superior parietal L	7	−28	−60	48	4.24					
Inferior temporal G	37	−42	−56	0	4.45					
Lingual G	19	−30	−64	6	3.65	19	30	−56	6	3.77
				B. HF > LF						
Supramarginal G	40	−54	−48	36	3.95					
Middle temporal G	39	−46	−62	22	3.31					
Precuneus	7	−6	−64	40	3.40					

Note. LF and HF refer to reading low-frequency and high-frequency characters, respectively. G, gyrus; L, lobule; BA, Brodmann's area. Z value is peak maxima. Clusters survived an uncorrected $P < 0.001$ ($Z > 3.09$) with spatial extent $n \geqq 20$ voxels are considered statistically significant.

parietal cortex, temporoparietal junction, and anterior insula/frontal operculum was left-lateralized (Fig. 2). The revealed neural network in general replicates our previous fMRI findings on Chinese reading (Kuo et al., 2001) and pinpointing the commonality of linguistic processing across different writing systems (Fiez and Petersen, 1998; Kuo et al., 2001; Price, 2000).

In accordance with previous fMRI reports of Chinese processing (Chee et al., 1999, 2000; Kuo et al., 2001; Tan et al., 2001a, 2001b), activations were observed in the inferior/middle frontal gyri (area 9; more prominent in the left hemisphere) and the left SPL (area 7) that have been relatively less reported in studies of alphabetical languages. The frontal activation spatially encompassed the precentral gyrus and the dorsal part of inferior/middle frontal gyrus (Fig. 2). The IFG is engaged when substantial phonological processing or articulatory rehearsal is required (Awh et al., 1996; Bookheimer, 2002; Chein and Fiez, 2001; Fiez et al., 1999; Fiez and Petersen, 1998; Gabrieli et al., 1998; Jonides et al., 1998; Paulesu et al., 1993; Poldrack et al., 1999; Price, 2000; Pugh et al., 2000; Smith and Jonides, 1998). The dorsal left middle/inferior frontal gyri (area 9) have been demonstrated to mediate spatial and verbal working memory (Courtney et al., 1998) and may subserve central executive function inherent for the coordination of cognitive resources (D'Esposito et al., 1995). It is in this context that the inferior/middle frontal gyri have been proposed to coordinate and integrate the intensive visuospatial analyses of Chinese logographs and phonological computation as well as semantic analysis. (cf. Chen et al., 2002; Kuo et al., 2001; Tan et al., 2001a, 2001b).

Recognizing a Chinese character requires the decomposition of character into smaller functional units, followed by a reconstruction for whole character recognition (Chen and

Allport, 1995; Fang and Xu, 1989). The SPL activation in the current study implies a "top-down" allocation of attention to global and local features of Chinese characters (Robertson et al., 1988) and indicates that recognition of Chinese characters may elaborate more perceptual and attentional mechanisms than that of alphabets in binding the features of spatial arrangement of the strokes and the stroke combinations in a square (Fu et al., 2002; Kuo et al., 2001). This idea is further corroborated by a brain imaging study of alphabetical word recognition with additional visual workload (Mayall et al., 2001). Changing the physical form of an English word, for example case mixing, will up-regulate only the expression of superior parietal area and leave other language areas intact during reading (Mayall et al., 2001).

Reading low-frequency characters

The overall reading process, in general, can be decomposed into component processes, including early visual processing, sublexical orthographic and/or phonological processing, lexical orthographic and/or phonological word-form selection, and semantic conceptual activation. In Chinese reading, the GPC should be replaced by OPT because of the lack of a tight spelling-to-sound correspondence in Chinese. OPT comprises a set of implicit rules, for example, phonetic radical, for the derivation of phonology. Our findings of heighten activity in the left IFG and anterior insula (preponderantly expressed in the left hemisphere albeit bilaterally activated; Fig. 3A and Table 1A) emphasize the phonological computation load (Fiebach et al., 2002) of OPT in reading LF Chinese characters. By contrasting LF words and pseudo-words, respectively, to HF words, greater activation was commonly noted in the left IFG (Fiebach et al., 2002). In the study by Fiez et al. (1999), reading LF

English words, particularly without spelling-to-sound correspondence, resulted in greater activity in the left IFG, left superior temporal gyrus, SMA, and cerebellum (Fiez et al., 1999). The authors interpreted the engagement of left IFG as a signature for the GPC computation. A growing body of fMRI evidence further indicates that there are functional subsegregates of the left IFG. These subregions respond differentially to phonological and semantic aspects of language processing (Bookheimer, 2002; Buckner et al., 1995; Demb et al., 1995; Fiebach et al., 2002; Fiez, 1997; Fiez et al., 1999; Fiez and Petersen, 1998; Gabrieli et al., 1998; Poldrack et al., 1999; Price, 2000; Wagner et al., 2000, 2001). Activations attributed to semantic processing most often are located anteriorly within the ventral inferior prefrontal cortex, whereas those of phonological processing are located posteriorly within the triangular and opercular portions of the IFG. The locus of peak fMRI activation in the left IFG in the contrast of LF versus HF (Fig. 3A and Table 1B) locates in the vicinity of the reported posterior subregion of IFG (Fiez, 1997; Fiez and Petersen, 1998; Fiebach et al., 2002).

We observed higher activity in the left SPL, inferior temporal region (area 37), and bilateral extrastriate areas (lingual gyrus, areas 19). The pattern indicates that naming LF Chinese characters engages neural substrates of ventral and dorsal streams for visuospatial analysis of both local and global features of the characters (Navon, 1977; Fink et al., 1996, 1997; Kuo et al., 2001; Hung and Tzeng, 1981). The left posterior inferior temporal gyrus is important for reading Chinese words (Kuo et al., 2001) and Japanese Kanji (Nakamura et al., 2000; Sakurai et al., 2000; Uchida et al., 1999). A stronger engagement of this region during reading of LF words may imply an active derivation of phonology via semantic mediation (Price, 2000) or word mapping via a linguistically organized word identification system (Pugh et al., 2000). As a contrast, in a recent PET study on an alphabetical language, reading LF words activated the superior temporal gyrus (BA 22) instead (Fiez et al., 1999). The discrepancy may reflect processing specificity for languages with different print forms. It is temping to suggest that reading LF Chinese characters may rely more on the ventral pathway while reading LF alphabets may rest more on the dorsal pathway of posterior circuits of reading, respectively (Price, 2000; Pugh et al., 2000). Our observations are in line with the theories asserting that the aforementioned activated regions service orthographic processing and lexical retrieval, interfacing between the perception and the long-term mental representation of words (Kuo et al., 2001; Moore and Price, 1999; Price, 2000; Wise et al., 2001).

Reading of LF words also causes higher activation in many regions, including the left anterior insula, left premotor, and SMA. These regions are integral to the motoric program for articulatory planning and speech coordination (Dronkers, 1996; Kuo et al., 2001; Wise et al., 1999). The modulation of activity in these regions contingent upon

levels of frequency is in line with the behavioral data which illustrate the word frequency effects on phonetic encoding during speech production (Indefrey and Levelt, 1999; Jescheniak and Levelt, 1994; Levelt et al., 1999).

Altogether, the constellation of neural substrates constitutes a distributed network that orchestrates the retrieval, formulation, and coordination of speech production and supports the idea that naming of LF Chinese characters may depend more on sublexical processes (Coltheart et al., 1993; Seidenberg, 1985; Zhou and Marslen-Wilson, 1999) and mandate more mental resources.

Reading high-frequency characters

While naming LF alphabetical characters may depend on sublexical processes, naming HF alphabetical characters may benefit from lexical processes (Coltheart et al., 1993; Seidenberg, 1985; Zhou and Marslen-Wilson, 1999). The lexical route maps directly the orthographic percepts onto stored word form representations while sublexical route translates grapheme input into phonological information (Coltheart et al., 1993, 2001). Lexical and sublexical routes function in parallel during reading (Paap and Noel, 1991) and lexical identification can invoke automatic retrieval of semantic attributes (Henderson, 1982; Monsell et al., 1989; Schvaneveldt et al., 1976).

The left supramarginal/angular gyri have been proposed to subserve in part the fine-grained, rule-based phonological processing (Paulesu et al., 1993, 2000, 2001; Pugh et al., 2000; Shaywitz et al., 2002) and the retrieval of word meaning (Brunswick et al., 1999; Price, 2000; Price et al., 1997). Although a possible role of this region in OPT-based phonological computation for Chinese reading cannot be ruled out, we reason that this GPC or OPT operation should be more expressed in the contrast of LF versus HF. In addition, both HF and LF characters used were all phonograms and the regularity/consistency valences were equal between the conditions. The proposed "assembling process," if any, via the dorsal pathway of posterior circuitry of reading, as proposed by Pugh and colleagues (Pugh et al., 2000; Shaywitz et al., 2002), might have been subtly balanced for both conditions as well. We speculate that a more plausible explanation for a higher activity of left supramarginal/angular/middle temporal regions in the contrast of HF versus LF characters is that reading HF Chinese characters may render the lexical route in successful mapping of the orthographic percepts onto visual word form representations (effectuated by the ventral pathway of posterior circuitry or reading) and subsequently the semantic access as manifested by the activation of this region (Coltheart et al., 2001; Fiebach et al., 2002).

The exact reason why the precuneus demonstrated relatively higher activity during reading HF words is unknown. The precuneus is a multimodal association area subserving episodic associative memory retrieval independent of presentation modality and imagery content of the presented

materials (Krause et al., 1999; Mellet et al., 1996). We can only speculate that imagery valence of the HF characters can be higher than low-frequency characters used in the experiment so that early visual processing might be invoked automatically, which in turn couples with semantic association and targets the precuneus in the context of retrieval (Fletcher et al., 1995).

Conclusions

Orthographic structures differ among different languages, and the orthographic variations in different languages or different word forms of even the same language can influence reading processes in the brain (Chen et al., 2002; Law et al., 1991; Nakamura et al., 2000; Sakurai et al., 2000). This study elucidates the central representation for frequency effects on Chinese reading in the brain. The activation pattern of reading infrequently encountered characters reflects a more demanding processing procedure of retrieving, formulating, and coordinating the phonological output. Access to the lexical route may benefit the reading of HF characters. By uncovering the differential brain responses in reading Chinese characters of different occurrence frequencies, not only has a substantial overlap between functional neuroanatomy of reading Chinese and alphabetical languages been demonstrated, but also features permitting the separation of language-specific content from universal mechanisms. Our study on frequency effects of Chinese reading invites further brain imaging work on consistency/regularity effects and the interaction of all these factors to further elucidate the central representations of OPT for Chinese reading.

Acknowledgments

References

Assadollahi, R., Pulvermuller, F., 2001. Neuromagnetic evidence for early access to cognitive representation. NeuroReport 12 (2), 207–213.

Awh, E., Jonides, J., Smith, E.E., Schumacher, E.H., Koeppe, R.A., Katz, S., 1996. Dissociation of storage and rehearsal in verbal working memory: evidence from positron emission tomography. Psychol. Sci. 7, 25–31.

Balota, D.A., Chumbley, J.I., 1985. The locus of word-frequency effects in the pronunciation task: lexical access and/or production? J. Mem. Cogn. 24, 89–106.

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

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.

Buckner, R.L., Raichle, M.E., Petersen, S.E., 1995. Dissociation of human prefrontal cortical areas across different speech production tasks and gender groups. J. Neurophysiol. 74 (5), 2163–2173.

Cattell, J.M., 1886. The time taken by cerebral operations. Mind 11, 220–242.

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.

Chee, M., Nicholas, H., Caplan, D., Lee, H.L., Goh, J., 2002. Frequency of concrete words modulates prefrontal activation during semantics judgments. NeuroImage 16, 259–268.

Chein, J.M., Fiez, J.A., 2001. Dissociation of verbal working memory system components using a delayed serial recall task. Cereb. Cortex 11 (11), 1003–1014.

Chen, Y.P., Allport, A., 1995. Attention and lexical decomposition in Chinese word recognition: conjunctions of from and position guide selective attention. Vis. Cogn. 2, 235–268.

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 from 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.

Coltheart, M., Rastle, K., Perry, C., Ziegler, J.C., 2001. DRC: a dual route cascaded model of visual word recognition and reading aloud. Psychol. Bull. 108 (1), 204–256.

Courtney, S.M., Petit, L., Maisog, J.M., Ungerleider, L.G., Haxby, J.V., 1998. An area specialized for spatial working memory in human frontal cortex. Science 279, 1347–1351.

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 (9), 5870–5878.

Demonet, J.F., Price, C.J., Wise, R., Frackowiak, R.S.J., 1994. A PET study of cognitive strategies in normal subjects during language tasks: influence of phonetic ambiguity and sequence processing on phoneme monitoring. Brain 117, 671–682.

D'Esposito, M., Detre, J.A., Alsop, D.C., Shin, R.K., Atlas, S., Grossman, M., 1995. The neural basis of the central executive system of working memory. Nature 378, 279–281.

Dronkers, N.F., 1996. A new brain region for coordinating speech articulation. Nature 384, 159–161.

Embick, D., Hackl, M., Schaeffer, J., Kelepir, M., Marantz, A., 2001. A magnetoencephalographic component whose latency reflects lexical frequency. Cogn. Brain Res. 10, 345–348.

Fang, S.P., Xu, P., 1989. Illusory conjunctions in the perception of Chinese character. J. Exp. Psychol. Hum. Perform. Percept. 15 (3), 434–447.

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

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

Fiez, J.A., Petersen, S.E., 1998. Neuroimaging studies of word reading. Proc. Nat. Acad. Sci. USA 95, 914–921.

Fiez, J.A., Raichle, M.E., Balota, D.A., Tallal, P., Petersen, S.E., 1996. PET activation of posterior temporal regions during auditory word presentation and verb generation. Cereb. Cortex 6 (1), 1–10.

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.

Fink, G.R., Halligan, P.W., Marshall, J.C., Frith, C.D., Frackowiak, R.S.J., Dolan, R.J., 1996. Where in the brain does visual attention select the forest and the trees? Nature 382, 626–628.

Fink, G.R., Halligan, P.W., Marshall, J.C., Frith, C.D., Frackowiak, R.S.J., Dolan, R.J., 1997. Neural mechanisms involved in the processing of global and local aspects of hierarchically organized visual stimuli. Brain 120, 1779–1791.

Fletcher, P.C., Frith, C.D., Baker, S.C., Shallice, T., Frackowiak, R.S., Dolan, R., 1995. The mind's eye—precuneus acttivation in memory-related imagery. NeuroImage 2 (3), 195–200.

Friston, K.J., Fletcher, P., Josephs, O., Holmes, A., Rugg, M.D., Turner, R., 1998. Event-related fMRI: characterizing differential responses. NeuroImage 7 (1), 30–40.

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. Nat. Acad. Sci. USA 95, 906–913.

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

Henderson, L., 1982. Orthography and Word Recognition in Reading. Academic Press, London.

Henson, R.N., Rugg, M.D., Shallice, T., Josephs, O., Dolan, R., 1999. Recollection and familiarity in recognition memory: an event-related functional magnetic imaging study. J. Neurosci. 19 (10), 3962–3972.

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.

Holmes, A.P., Josephs, O., Buchel, C., Friston, K., 1997. Statistical modeling of low frequency confounds in fMRI. NeuroImage 5, s480.

Hung, D.L., Tzeng, O.J.L., 1981. Orthographic variations and visual information processing. Psychol. Bull. 90 (3), 377–414.

Indefrey, P., Levelt, W.J.M., 1999. The neural correlates of language production, in: Tulving, E (Ed.), The New Cognitive Neurosciences. MIT Press, Cambridge (MA), pp. 845–865.

Jescheniak, J.D., Levelt, W.J.M., 1994. Word frequency effect in speech production: retrieval of syntantic information and of phonological form. J. Exp. Psychol. Learn. Mem. Cogn. 20, 824–843.

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 (13), 5026–5034.

King, J.W., Kutas, M., 1998. Neural plasticity in the dynamics of human visual word recognition. Neurosci. Lett. 244, 61–64.

Koyama, S., Kakigi, R., Hoshiyama, M., Kitamura, Y., 1998. Reading of Japanese Kanji (morphograms) and Kana (syllabograms): a magnetoencephalographic study. Neuropsychologia 36 (1), 83–98.

Krause, B.J., Schmidt, D., Mottaghy, F.M., Taylor, J., Halsband, H., Herzog, H., Tellman, L., Muller-Gartner, H.-W., 1999. Episodic retrieval activates the precuneus irrespective of the imagery content of word pair associates: a PET study. Brain 122, 255–263.

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 (18), 3997–4001.

Kuriki, S., Hirata, Y., Fujimaki, N., Kobayashi, T., 1998. Magnetoencephalographic study on the cerebral neural activities related to the processing of visually presented characters. Cogn. Brain Res. 4, 185–199.

Law, I., Kannao, I., Fujita, H., S., M., Lassen, N., Uemura, K. 1991. Left supramarginal/angular gyri activation during of syllabograms in the Japanese language. J. Neuroling. 6, 243–251.

Lee, C.-Y., 2000. The mechanisms for Chinese orthography-to-phonology transformations: an integrated research of behavioral measures and functional magnetic resonance imaging studies. Unpublished Ph.D. dissertation, National Chung-Cheng University, Chia-Yi, Taiwan.

Levelt, W.J.M., Roelofs, A., Meyer, A.S., 1999. A theory of lexical access in speech production. Behav. Brain Sci. 22, 1–38.

Liu, I.M., Wu, J.T., Chou, T.L., 1996. Encoding operation and transcoding as the major loci of the frequency effect. Cognition 59 (2), 149–168.

Mayall, K., Humphreys, G.W., Mechelli, A., Olson, A., Price, C.J., 2001. The effects of case mixing on word recognition: evidence from a PET study. J. Cogn. Neurosci. 13 (6), 844–853.

McGuire, P.K., Silbersweig, D.A., Frith, C.D., 1996. Functional neuro-anatomy of verbal self-monitoring. Brain 119 (3), 907–917.

Mellet, E., Tzourio, N., Crivello, F., Joliot, M., Denis, M., Mazoyer, B., 1996. Functional anatomy of spatial mental imagery generated from verbal instructions. J. Neurosci. 16 (20), 6504–6512.

Monsell, S., Doyle, M.C., Haggard, P.N., 1989. Effect of frequency on visual word recognition tasks: where are they? J. Exp. Psychol. Gen. 118 (1), 43–71.

Moore, C.J., Price, C.J., 1999. There distinct ventral occipitotemporal regions for reading and object naming. NeuroImage 10, 181–192.

Munte, T.F., Wieringa, B.M., Weyerts, H., Szentkuti, A., Matzke, M., Johannes, S., 2001. Differences in brain potentials to open and closed class words: class and frequency effects. Neuropsychologia 39, 91–102.

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.

Navon, D., 1977. Forest before trees: the precedence of global features in visual perception. Cogn. Psychol. 9, 353–383.

Oldfield, R.C., 1971. The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologia 9, 97–113.

Osterhout, L., Bersick, M., McKinnon, R., 1997. Brain potentials elicited by words: word length and frequency predict the latency of an early negativity. Biol. Psychol. 46, 143–168.

Paap, K.R., Noel, R.W., 1991. Dual route models of print to sound: still a good horse race. Psychol. Res. 53, 13–24.

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.

Paulesu, E., Demonet, J.F., Fazio, F., McCrory, E., Chanoine, V., Brunswick, N., Cappa, S.F., Cossu, G., Habib, M., Frith, C.D., Frith, U., 2001. Dyslexia: cultural diversity and biological unity. Science 291, 2165–2167.

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.

Poldrack, R.A., Temple, E., Protopapas, A., Nagarajan, S., Tallal, P., Merzenich, M., Gabrieli, J.D., 2001. Relations between the neural bases of dynamic auditory processing and phonological processing: evidence from fMRI. J. Cogn. Neurosci. 13 (5), 687–697.

Polich, J., Donchin, E., 1988. P300 and the word frequency effect. Electroencephalogr. Clin. Neurophysiol. 70, 33–45.

Price, C.J., 2000. The anatomy of language: contributions from functional neuroimaging. J. Anat. 197, 335–359.

Price, C.J., Wise, R.J.S., Warburtone, E., Moore, C.J., Patterson, K., Howard, D., 1996a. Hearing and saying: the functional neuroanatomy of auditory word processing. Brain 119, 919–931.

Price, C.J., Wise, R.J.S., Frackowiak, R.S.J., 1996b. 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., Mencl, W.E., Shaywitz, B.A., Shaywitz, S.E., Fulbright, R.K., Constable, R.T., Skudlarski, P., Marchione, K.E., Jenner, A.R., Fletcher, J.M., Liberman, A.M., Shankweiler, D.P., Katz, L., Lacadie, C., Gore, J.C., 2000. The angular gyrus in developmental dyslexia: task-specific differences in functional connectivity within posterior cortex. Psychol. Sci. 11 (1), 51–56.

Pulvermuller, F., 1999. Words in the brain's language. Behav. Brain Sci. 22, 253–279.

Robertson, L.C., Lamb, M.R., Knight, R.T., 1988. Effects of lesions of temporal-parietal junction on perceptual and attentional processing in humans. J. Neurosci. 8, 3757–3769.

Rugg, M.D., 1990. Event-related brain potentials dissociate repetition effects of high- and low-frequency words. Mem. Cogn. 17, 367–379.

Rumsey, J.M., Horwitz, B., Donohue, B.C., Nace, K., Maisog, J.M., Andreason, P., 1997. Phonological and orthographic components of word recognition: a PET-rCBF study. Brain 120, 739–759.

Sakurai, Y., Momose, T., Iwata, M., Sudo, Y., Ohtomo, K., Kanazawa, I., 2000. Different cortical activity in reading Kanji words, Kana words and Kans nonwords. Cogn. Brain Res. 9, 111–115.

Schvaneveldt, R.W., Meyer, D.E., Becker, C.A., 1976. Lexicality ambiguity, semantic context and visual word recognition. J. Exp. Psychol. Hum. Perform. Percept. 2, 243–256.

Seidenberg, M.S., 1985. The time course of phonological code activation in two writing systems. Cognition 19, 1–30.

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. Psych. 52 (2), 101–110.

Smith, E.E., Jonides, J., 1998. Neuroimaging analyses of human working memory. Proc. Natl. Acad. Sci. USA 95, 12061–12068.

Talairach, J., Tournoux, P., 1988. Co-planar Stereotactic Atlas of the Human Brain. Thieme, New York.

Tan, L.H., Feng, C.M., T., F.P., 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.

Turkeltaub, P.E., Eden, G.F., Jones, K.M., Zeffiro, T.A., 2002. Meta-analysis of the functional neuroanatomy of single-word reading: method and validation. NeuroImage 16, 765–780.

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 (2), 208–215.

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 (12), 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 (2), 329–338.

Wise, R.J.S., Greene, J., Buchel, C., Scott, S.K., 1999. Brain regions involved in articulation. Lancet 353, 1057–1061.

Wise, R.J.S., Scott, S.K., Blank, S.C., Mummery, C.J., Murphy, K., Warburton, E.A., 2001. Seperate neural subsystems within 'Wernicke's area.' Brain 124, 83–95.

Zatorre, R.J., Meyer, E., Gjedde, A., Evans, A.C., 1996. PET studies of phonetic processing of speech: review, replication, and reanalysis. Cereb. Cortex 6 (1), 21–30.

Zhou, X., Marslen-Wilson, W., 1999. The nature of sublexical processing in reading Chinese characters. J. Exp. Psychol. Learn. Mem. Cogn. 25 (4), 819–837.