# Testing for Dual Brain Processing Routes in Reading: A Direct Contrast of Chinese Character and Pinyin Reading Using fMRI

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## Abstract

■ Chinese offers a unique tool for testing the effects of word form on language processing during reading. The processes of letter-mediated grapheme-to-phoneme translation and phonemic assembly (assembled phonology) critical for reading and spelling in any alphabetic orthography are largely absent when reading nonalphabetic Chinese characters. In contrast, script-to-sound translation based on the script as a whole (addressed phonology) is absent when reading the Chinese alphabetic sound symbols known as pinyin, for which the script-to-sound translation is based exclusively on assembled phonology. The present study aims to contrast patterns of brain activity associated with the different cognitive mechanisms needed for reading the two scripts. fMRI was used with a block design involving a phonological and lexical task in which subjects were asked to decide whether visually presented, paired Chinese characters or pinyin "sounded like" a word. Results demonstrate that reading Chinese characters and pinyin activate a common brain network including the inferior frontal, middle, and inferior temporal gyri, the inferior and superior parietal lobules, and the extrastriate areas. However, some regions show relatively greater activation for either pinyin or Chinese reading. Reading pinyin led to a greater activation in the inferior parietal cortex bilaterally, the precuneus, and the anterior middle temporal gyrus. In contrast, activation in the left fusiform gyrus, the bilateral cuneus, the posterior middle temporal, the right inferior frontal gyrus, and the bilateral superior frontal gyrus were greater for nonalphabetic Chinese reading. We conclude that both alphabetic and nonalphabetic scripts activate a common brain network for reading. Overall, there are no differences in terms of hemispheric specialization between alphabetic and nonalphabetic scripts. However, differences in language surface form appear to determine relative activation in other regions. Some of these regions (e.g., the inferior parietal cortex for pinyin and fusiform gyrus for Chinese characters) are candidate regions for specialized processes associated with reading via predominantly assembled (pinyin) or addressed (Chinese character) procedures. ■


## INTRODUCTION

An important question for studies of word recognition and reading is how surface form influences language processing in the brain. Chinese characters with no apparent letters, each a compact stroke pattern occupying the same amount of space, appear conspicuously different from alphabetic scripts. Early visual hemifield studies focusing largely on the visuospatial properties of Chinese characters suggested right hemisphere dominance in reading Chinese characters (Fang, 1997; Cheng & Yang, 1986; Naeser & Chan, 1980; Tzeng, Hung, Cotton, & Wang, 1979) in contrast to a left hemisphere dominance for reading alphabetic words like English (Price, 1998). However, subsequent studies indicated that this distinction only existed at lower level processing of nonlinguistic information (Hung & Tzeng, 1981). Recent fMRI studies also failed to reveal a simple distinction in terms of hemispheric specialization in reading different scripts (Tan et al., 2000; Chee, Caplan, et al., 1999; Chee, Tan, & Thiel, 1999).

Although reading both alphabetic and reading nonalphabetic scripts must use many common mechanisms for orthographic, phonological, and semantic processing, the key element of processing script-to-sound translation (which may occur even with silent reading of a written script) (Patterson & Coltheart, 1987) may be substantially different for alphabetic and nonalphabetic reading. The dual route model (Coltheart, 1981; Marshall & Newcombe, 1973) proposed that there are two procedures for this translation: an addressed procedure based on whole-script (with or without semantics) and an assembled procedure based on component grapheme-to-phoneme correspondences (Patterson & Coltheart, 1987). It was hypothesized that the differential impairment of these two reading mechanisms leads to clinically distinct types of dyslexia—deep and surface dyslexia (Coltheart, Patterson, & Marshall, 1987;

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Patterson, Coltheart, & Marshall, 1985 respectively). More recent theories have explained such phenomena in terms of differences in relative activity of nodes in a distributed network (Seidenberg & McClelland, 1989).

The development of functional brain imaging techniques such as fMRI now potentially permits a direct investigation of the neural basis of these two putative reading mechanisms (Small, Flores, & Noll, 1998). In a recent PET study (Paulesu et al., 2000) contrasting brain activity associated with reading a language with a highly transparent orthography (Italian) and one with a relatively opaque orthography (English), distinct brain activation patterns were demonstrated, for example. Compared to bilingual and cross-language studies, biscriptal studies using the same subjects and the same language offer potential advantages for addressing the problem of mapping orthography-to-phonology mapping. For example, biscriptal studies in the Japanese language between kanji (Chinese characters used in Japanese language) and kana (Japanese syllabic symbols) (Sakurai et al., 2000) has enhanced our understanding of language processing in reading different written scripts and dyslexia in Japanese (Sasanuma, 1985). However, the phonetic kana script in Japanese is used mainly for functional words, which limits interpretation of the kana–kanji comparisons.

The Chinese language may be better suited for this type of study. Since the early 1970s, the traditional Chinese characters have no longer been the only written form of Chinese speech. A set of 26 English letters and 13 letter groups (e.g., zh, ch, ang, etc.) was developed as sound symbols for Chinese characters, known in Chinese as pinyin (meaning ‘‘assembling sound’’). Pinyin is taught in schools all over China before children learn to read characters. Pinyin also facilitates input of Chinese into computer systems using alphabetic keyboards. It is worth pointing out, however, that pinyin is neither used generally as a written script nor mixed with Chinese characters in Chinese text as kanji and kana are in Japanese text. More

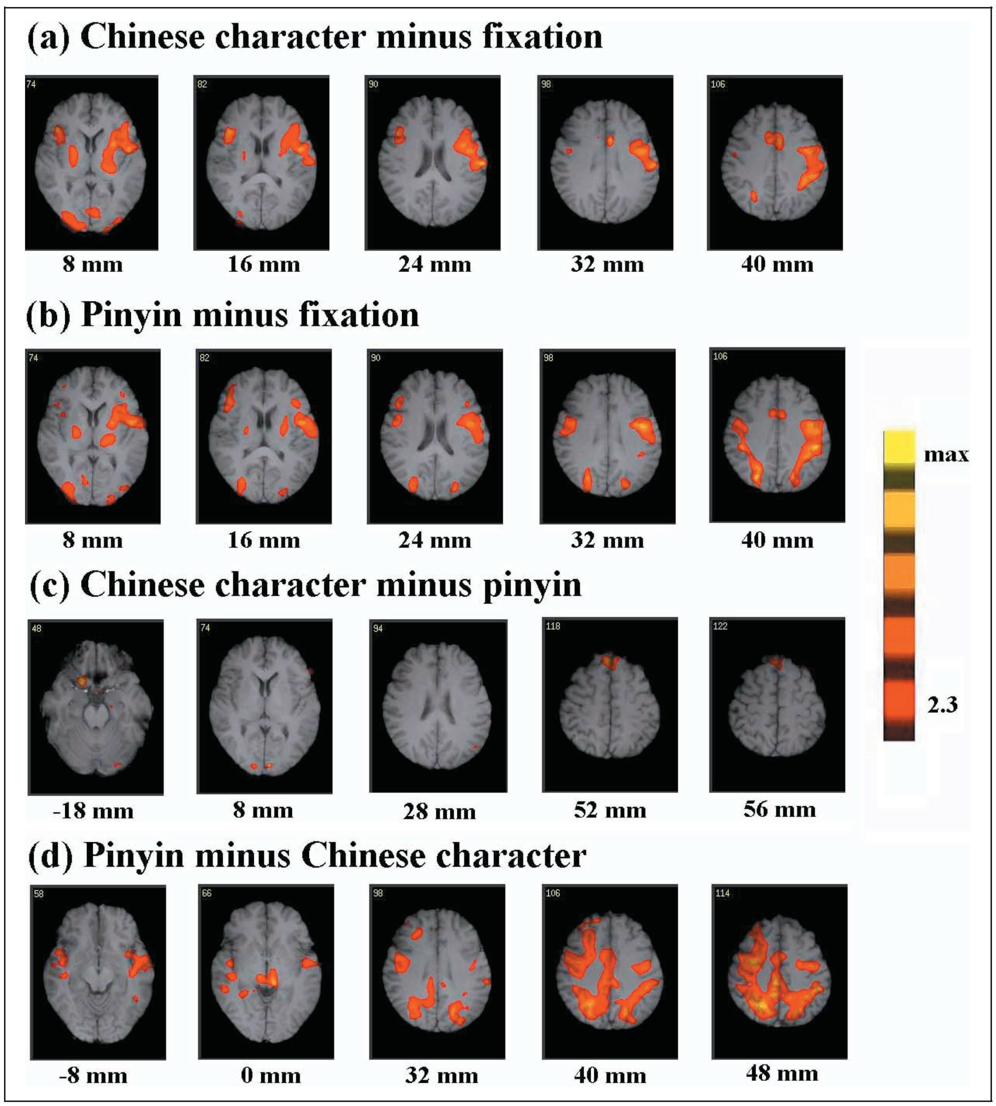


**Figure 1.** Patterns of brain activation from a random effects analysis of the group ($n$ = 9). Chinese character reading minus fixation (a), pinyin reading minus fixation (b), Chinese character reading minus pinyin reading (c), and pinyin reading minus Chinese character reading (d). All of the functional maps (in color) are overlaid on one subject's brain warped into a standard brain space. The left side of each slice is the right side of the brain.

**Table 1.** Group Random Effects Analysis of Brain Activations During Chinese Character or Pinyin Reading (Positive Activation Differences Only) Relative to Fixation

| | *Chinese Character* | | *Pinyin* | |
|---|---|---|---|---|
| *Brain Region* | *Z Score* | *Talairach Coordinates* | *Z Score* | *Talairach Coordinates* |
| *Frontal* | | | | |
| Left superior frontal gyrus | 3.49 | −4, 10, 48 | 3.62 | −3, 9, 52 |
| Right superior frontal gyrus | 2.86 | 6, 10, 52 | 3.55 | 4, 10, 52 |
| Left inferior frontal gyrus | 3.40 | −44, 4, 16 | 3.66 | −46, 3, 16 |
| | 3.26 | −40, 20, 10 | | |
| Right inferior frontal gyrus | 3.77 | 45, 25, 16 | 2.44 | 44, 28, 16 |
| Left inferior frontal gyrus | 3.50 | −40, 26, −9 | | |
| Left insula | 3.17 | −38, 16, −5 | 3.62 | −32, 16, −4 |
| Right insula | 2.39 | 39, 13, 5 | 2.40 | 40, 12, 0 |
| Left precentral gyrus | 3.81 | −47, 1, 18 | 4.24 | −42, 0, 27 |
| | 3.48 | −43, 0, 33 | 3.64 | −48, 2, 6 |
| Right precentral gyrus | | | 3.03 | 54, 2, 27 |
| Cingulate gyrus | 3.78 | −4, 14, 34 | 3.02 | −4, 12, 40 |
| | | | 3.03 | 8, 12, 41 |
| *Parietal* | | | | |
| Left postcentral gyrus | 3.81 | −60, −15, 24 | 3.63 | −37, −29, 50 |
| | 4.33 | −38, −32, 49 | | |
| Left superior parietal lobule | | | 4.22 | −17, −67, 52 |
| Right superior parietal lobule | 4.34 | 30, −55, 46 | 4.19 | 24, 66, 53 |
| Left inferior parietal lobule | 4.33 | −32, −46, 46 | 4.21 | −35, −46, 45 |
| Right inferior parietal lobule | | | 3.64 | 33, −53, 44 |
| *Occipital* | | | | |
| Left lingual gyrus | 3.78 | −14, −86, −11 | 2.44 | −17, −66, −5 |
| Right lingual gyrus | 2.90 | 12, −82, −8 | 3.05 | 19, −63, −5 |
| Left fusiform gyrus | 3.78 | −29, −92, −13 | 2.44 | −20, −63, −8 |
| Right fusiform gyrus | 4.34 | 26, −84, −12 | 3.02 | 20, −62, −9 |
| Left inferior occipital gyrus | 3.47 | −36, −90, −8 | 4.04 | 28, −84, −14 |
| Right inferior occipital gyrus | 3.45 | 41, −84, −14 | 3.59 | −38, −84, −14 |
| *Temporal* | | | | |
| Left middle occipital/temporal gyrus | 2.75 | −44, −49, −3 | 3.64 | −46, −52, −4 |
| Right middle occipital/temporal gyrus | | | 3.62 | 54, −62, −5 |
| Left inferior temporal/fusiform gyrus | 2.89 | −42, −54, −16 | | |
| Right inferior temporal/fusiform gyrus | 3.46 | 52, −63, −12 | 4.02 | 50, −66, −10 |
| | | | 4.37 | 52, −72, −12 |

**Table 1.** (*continued*)

| Brain Region | *Chinese Character* Z Score | *Chinese Character* Talairach Coordinates | *Pinyin* Z Score | *Pinyin* Talairach Coordinates |
|---|---|---|---|---|
| *Cerebellum* | | | | |
| Left cerebellar hemisphere | 4.31 | −31, −53, −32 | 3.63 | −20, −60, −26 |
| Right cerebellar hemisphere | 4.31 | 36, −62, −28 | 4.81 | 30, −70, −28 |
| | 4.08 | 36, −82, −21 | | |
| *Subcortical structures* | | | | |
| Left thalamus | 3.19 | −14, −19, 2 | 3.66 | −10, −20, −2 |
| Right thalamus | 3.53 | 23, −2, 4 | 3.06 | 18, −16, 2 |

important, one cannot decipher the meaning of a single word in pinyin script solely from its visual form, as homophones are common in Chinese. However, grapheme-to-phoneme correspondences are entirely regular, allowing pinyin to used for a unique assembly of word sound. By contrast, a simple assembly procedure based on similar grapheme-to-phoneme correspondences is impossible in reading Chinese characters (Perfetti & Zhang, 1995; Plaut, McClelland, Seidenberg, & Patterson, 1996; Chen, 1993; Chen & Allport, 1995; Chen, Allport, & Marshall, 1996), for which a more addressed phonology is necessary. The distinction is not absolute, as the pronunciation of a character can in some cases be suggested at the subcharacter level by a phonetic radical.

The present study aimed to contrast patterns of brain activation associated with reading using addressed versus assembled procedures in script-to-sound translation by exploiting the unique properties of Chinese characters and pinyin. In doing so, we hope to identify components of the neural network for language that contribute relatively specifically to the assembled and the addressed procedures critical for alphabetic and nonalphabetic reading, respectively. To isolate cognitive processing associated with script-to-sound translation, a phonological–lexical task was used in this study.

Subjects were shown either two real Chinese characters in a meaningless combination or paired pinyin symbol group and asked whether the pair ‘‘sounded like’’ a real two-character word. In order to make these decisions, a script-to-sound translation must be performed, which relies on a more addressed procedure for Chinese reading and an assembled procedure for pinyin reading. For example, although they together do not ‘‘look like’’ a two-character word, the two-characters, 杀 末 (which together ‘‘translate’’ as ‘‘kill–end’’), a nonsense combination of two characters in Chinese, sound (/sha/1/mo/4) exactly the same as the real two-character word 沙漠 (/sha/1/mo/4), meaning ‘‘dessert.’’ In order to minimize the contribution of script-to-sound translation at subcharacter rather than at a whole character level, the individual homophonic characters were selected to be either single-unit characters (e.g., 杀 and 末) that do not have phonetic components or the irregular compound characters 秤 in which the phonetic component 平 (/ping/2) does not indicate the correct pronunciation of the compound character 秤 (/cheng/4). Orthographic similarity between homophonic character and its base character also was controlled. Unlike homophones in English, which inevitably share the same letters, for example, ‘‘pair’’ and ‘‘pear,’’ homophonic Chinese characters selected in this study do not share any identical orthographic unit (杀末 for base word 沙漠 ‘‘dessert’’ and 淀颖 for base word 电影 ‘‘movie’’). By contrast, in pinyin a letter string cannot be recognized immediately as representing a word, as it is not conventionally used as a written script, but has meaning only through the assembled sound.

## RESULTS

### Behavioral Experiments

Although a Chinese reader finds reading real words in pinyin more difficult than in characters, the difficulty of deciding whether a character or pinyin pair ‘‘sounds like’’ a real word seems quite well matched. The task demand for reading the two types of stimuli were assessed by measurement of reaction time for the word–nonword decision for each. The mean reaction time ($n = 9$) for character (3800 ± 410 msec) and pinyin (4600 ± 520 msec) pairs were not significantly different (mean individual difference = 800 ± 605 msec, $p = .5$).

### Activation Patterns for Chinese Character and Pinyin Reading Relative to Fixation

The peak activation areas during Chinese character and pinyin reading relative to the baseline fixation task are shown in Figure 1a,b. Anatomical regions commonly activated by the native Chinese speakers are summarized in Table 1 along with their peak coordinates and *Z* scores.

Significant activations relative to viewing fixation controls were found in the occipital (bilateral inferior occipital, lingual, and fusiform gyri), temporal (right inferior and left middle temporal gyri), parietal (right superior and left inferior parietal lobules, right postcentral gyrus), and frontal (bilateral superior frontal gyrus, left inferior frontal gyrus, and left precentral gyrus) cortex for reading of both Chinese and pinyin scripts. Regions of activation apparently distinct for each of the two reading tasks also were found. For example, the left inferior temporal cortex in the fusiform gyrus was activated significantly only during Chinese reading. To test further for differences in activation patterns between the two reading tasks a direct contrast analysis was performed.

## Direct Contrast of Chinese Character versus Pinyin Reading

A random effects contrast of Chinese character with pinyin reading tasks identifies differences based on either the extent or the magnitude of activations between the two conditions (Figure 1c,d). Significant differences in contrasts of Chinese with pinyin and pinyin with Chinese, their coordinates, and *Z* scores are shown in Table 2. By this analysis, the brain regions showing greater activation during Chinese character

**Table 2.** Group Random Effects Analysis of Brain Activations in Contrasts of Chinese Character versus Pinyin or Pinyin versus Chinese Character Reading (Positive Activation Differences Only)

| | *Left Hemisphere* | | *Right Hemisphere* | |
|---|---|---|---|---|
| *Brain Region* | *Z Score* | *Talairach Coordinates* | *Z Score* | *Talairach Coordinates* |
| *Chinese character minus pinyin* | | | | |
| Superior frontal gyrus | 3.14 | −4, 44, 52 | 3.55 | 5, 44, 52 |
| Inferior frontal/orbital gyrus | | | 3.98 | 21, 17, −17 |
| Fusiform gyrus | 3.16 | −24, −90, −17 | | |
| Cuneus | 3.55 | −3, −90, 10 | 3.18 | 16, −91, 11 |
| Middle temporal gyrus | 3.16 | −44, −66, 28 | | |
| Cerebellum | 3.14 | −14, −87, −38 | 3.35 | 40, −55, −25 |
| Thalamus/putamen | 3.17 | −17, 9, −5 | 3.55 | 19, 15, −10 |
| *Pinyin minus Chinese character* | | | | |
| Middle frontal gyrus | 4.07 | −27, −5, 56 | 4.91 | 39, −1, 55 |
| Inferior frontal gyrus | | | 3.20 | 52, 4, 30 |
| Medial frontal gyrus | 3.18 | −2, 4, 56 | | |
| Paracentral gyrus | | | 4.07 | 8, −29, 49 |
| Insula | 3.20 | −36, 10, −10 | | |
| Postcentral gyrus | | | 4.48 | 32, −32, 65 |
| Superior parietal lobule | 4.05 | −20, −52, 62 | 3.61 | 25, −58, 58 |
| | | | 4.52 | 29, −60, 44 |
| Inferior parietal lobule | 4.06 | −39, −44, 54 | 4.06 | 35, −48, 54 |
| Precuneus | 4.02 | −16, −66, 36 | 4.06 | 30, −61, 41 |
| Superior temporal gyrus | 4.48 | −44, 9, −14 | 3.19 | 52, 12, −13 |
| Middle temporal gyrus | 3.60 | −63, −3, −9 | | |
| Cingulate gyrus | | | 3.20 | 8, 3, 44 |
| Thalamus | 4.95 | −7, −29, −1 | 3.66 | 11, −21, 0 |
| | 4.09 | −6, −16, 13 | 4.09 | 13, −18, 13 |

**Table 3.** The Relative Extent of Activations and for Chinese Character and Pinyin Reading Measured for Individual Subjects in Specific ROIs

| | *Chinese Character Minus Fixation* | | | *Pinyin Minus Fixation* | | |
|---|---|---|---|---|---|---|
| *Brain Region* | *Left* | *Right* | *AI* | *Left* | *Right* | *AI* |
| Inferior frontal gyrus (BA 44/45) | 80 (38) | 58 (27) | 0.23 (0.11) | 92 (32) | 59 (33) | 0.29 (0.16) |
| Supramarginal gyrus (BA 40) | 94 (46) | 34 (28) | 0.35 (0.59) | 130 (30) | 73 (34) | 0.30 (0.24) |
| Superior parietal lobule (BA 7) | 41 (30) | 53 (30) | −0.15 (0.26) | 92 (52) | 119 (42) | −0.18 (0.22) |
| Lateral extrastriate cortex (BA 18/19) | 135 (52) | 128 (41) | −0.04 (0.17) | 145 (39) | 132 (24) | 0.04 (0.12) |

Numbers of significant voxels in a cluster (with standard deviation in parentheses) or AI ratios are shown.

than during pinyin reading included the bilateral superior frontal gyri, the right inferior frontal/orbital gyrus, the left fusiform gyrus, the left middle temporal gyrus, and the bilateral cuneus. More brain regions showed greater relative activation with pinyin than Chinese reading, including the bilateral inferior parietal lobule, precuneus, and the superior temporal and left middle temporal gyri. While both contrasts identified significant differences in the middle temporal gyrus, the greater activation for Chinese characters was found substantially more posterior to that for pinyin reading.

### Region-of-Interest Analysis for Individual Subjects

A limitation of the direct contrast is that if there are significant interindividual variations in the positions of activation even locally, then the group analysis may not be sensitive to differences. Thus, as a further test for differences, the relative extents of activation in four regions-of-interest (ROIs)—the inferior frontal gyrus (BA 44/45), the supramarginal gyrus (BA 40), the superior parietal lobule (BA 7), and the lateral extrastriate cortex (BA 18/19)—were defined for each subject individually (Table 3). There was greater activation in the superior parietal lobule bilaterally for pinyin reading than for Chinese character reading, $F(1,8) = 15.64$, $p < .004$. There was no significant difference overall in relative hemispheric lateralization of activations between the two reading tasks, $F(1,8) = 1.13$, $p < .318$, but for both Chinese and pinyin, the extent of activation was larger on the left side in the supramarginal gyrus, $F(1,8) = 24.57$, $p < .001$ (Table 3).

## DISCUSSION

The results of the present study are broadly consistent with previous studies of both English (Petersen, Fox, Snyder, & Raichle, 1990; Petersen, Fox, Posner, Mintun, & Raichle, 1988) and Chinese (Tan et al., 2000; Chee, Caplan, et al., 1999). This work further confirms that brain activity for Chinese character reading does not show markedly difference hemispheric lateralization from reading an alphabetic language such as English or pinyin, despite the use of an orthography based on spatial relations between individual strokes. Common activations during both Chinese and pinyin reading were localized to several regions, including the inferior frontal and middle temporal gyri and extrastriate areas in occipital cortex (Table 1). However, the direct contrast between Chinese and pinyin also revealed patterns of activation relatively distinct for Chinese or pinyin reading (Table 2). We shall now discuss the possible functions of these regions in the cognitive processes of reading.

### Distinct Functional Localization for Primary Orthographic Processing

Previous work has implicated multiple occipital or posterior temporal regions specifically in aspects of orthographic processing. In a pioneering PET study, Petersen et al. (1988) suggested that the left medial extrastriate cortex is the visual word form area, as words and pseudowords elicited activation in this region, whereas letter strings or false fonts did not. Later work (Howard et al., 1992) suggested that the posterior left middle temporal gyrus or inferior temporal and fusiform gyrus performed this function (Bookheimer et al., 1997). More recently, it has been argued (Indefrey et al., 1997) that the activation in the left extrastriate area reported by Petersen et al. could be a response to the relatively increased visual complexity of word forms (see also Tagamets, Novick, Chalmers, & Friedman, 2000). In an fMRI study of Japanese (Uchida et al., 1999) using ''scrambled kanji'' as the false font for kanji, activation was shown in the left inferior occipital gyrus (BA 19) in the kanji versus scrambled kanji contrast. Earlier studies have shown that reading Chinese single- or two-character words for either a word (Chee, Tan, et al., 1999) or semantic generation tasks (Tan et al., 2000) gives significant activation in the left middle occipital gyrus (BA 18).

Our study showed significant activation in bilateral occipital areas including lingual, fusiform, and inferior occipital gyri for both Chinese character and pinyin reading versus fixation (Table 1), consistent with involvement of these regions in word form processing. Of particular interest, however, was that greater activation in the left fusiform gyrus and the cuneus bilaterally was shown in the direct contrast between Chinese character and pinyin reading. This suggests greater involvement of these areas in the orthographic processing of Chinese characters, which, unlike letter recognition in alphabetic reading, involve recognition of the recurring integral stroke patterns in two-dimensional space.

### Distinct Pathways for Phonological Processing Based on Language Surface Form

A primary goal of the present study was to distinguish regions likely to be involved in grapheme-to-phoneme processing that activated preferentially or selectively by either the assembled or addressed procedures for reading the Chinese or pinyin scripts, respectively. Previous work has suggested that tasks that may involve addressed procedures, such as the naming of letters, objects, and colors activate the left inferior temporal cortex (Price, 1998). Supramarginal gyrus activation has been demonstrated in tasks that could involve an assembled procedure, such as reading English words versus naming pictures (Moore & Price, 1999; Bookheimer et al., 1997; Vandenberghe, Price, Wise, Josephs, & Frackowiack, 1996), reading English pseudowords and real words, rhyming or syllable versus semantic judgments (Pugh et al., 1996), and reading kana versus kanji in Japanese (Law et al., 1991).

While in the more sensitive, ROI-based analysis pinyin was associated with a greater mean activation in the supramarginal gyrus than was Chinese character reading, in neither hemisphere did the differences reach significance (Table 3). In a direct, whole brain contrast, the cuneus and left fusiform gyrus showed greater activation during Chinese character relative to pinyin reading, but the precuneus, superior temporal gyrus and inferior parietal lobule showed greater activation with pinyin (Table 2). Differences also were found within the middle temporal gyrus. In the contrast of Chinese characters with pinyin, the more posterior part of the middle temporal gyrus was activated (Table 3), while the reverse contrast showed relative activation in the more anterior part of the middle temporal gyrus (Table 3). This evidence for functional differences between the anterior or posterior parts of the middle temporal gyrus that may contribute relatively specifically to addressed or assembled procedures, respectively, is of particular interest to us in view of recent work suggesting functional specialization of the superior temporal sulcus for complex sound and speech processing (Scott, Blank, Rosen, & Wise, 2000).

### Semantic Processing and Activation in the Frontal Cortex

Although the present experimental paradigm was designed to focus attention on phonological processing, the task had an implicit semantic element. Recent evidence suggests that the left inferior frontal gyrus is involved in both semantic (Demb et al., 1995) and phonological processing (Poldrack et al., 1999; Pugh et al., 1996). It is not possible to attribute the activations observed in our study specifically to one or the other. Previous work also has shown that reading Chinese characters (Tan et al., 2000; Chee, Caplan, et al., 1999; Chee, Tan, et al., 1999) gives rise to significant activation in left inferior frontal cortex (BA 47). Here this has been found as well for pinyin reading. However, our study indicates that distinct regions of inferior frontal gyrus (BA 47) are relatively more strongly activated with processing for the two different word surface forms. A more inferior and anterior activation in the left inferior frontal gyrus was shown for Chinese reading. It is intriguing to consider whether this could arise because of functional specialization in this region. For example, implicit semantic processing may be greater for the Chinese characters (as the individual characters are interpretable as words), possibly giving rise to greater activation in one subregion, while phonological processing may be engaged for a longer period over the task with assembled processing for pinyin, giving greater activation in a more superior and posterior subregion.

### Hemispheric Lateralization

A striking finding in the present study is that there is little overall hemispheric lateralization of the extent or magnitude of activations in the chosen ROIs. In contrast to the earlier English (Petersen et al., 1990) and Japanese (Uchida et al., 1999) studies, no left or right hemisphere dominance was found between the extents of activation in the lateral extrastriate cortex for either Chinese character or pinyin reading relative to the fixation control. The relative lack of left-sided lateralization compared with many previous language studies was also apparent in the inferior frontal gyrus.

There are a number of possible reasons for the low lateralization of activations in the present study. This task focuses on phonological processing and was designed to limit semantic components. Elements of general phonological processing may be relatively less lateralized (Binder et al., 1997). Recent studies of auditory language comprehension have emphasized that only language tasks that isolate lexico-semantic processing explicitly show strongly (left) lateralized activation (Scott et al., 2000). The present study also is relatively difficult in comparison with conventional lexical decision task and therefore may require a greater right hemispheric contribution to this processing (Caplan, 1989). An additional consideration is that increased BOLD contrast-to-noise at 3 T relative to 1.5 T (Gati, Menon, Ugurbil, & Rutt, 1997) may act to reduce apparent lateralization by increasing numbers of significantly activated pixels in the less dominant (right) hemisphere.

### Limitations to Interpretation

Although the experimental design provides a promising strategy for isolating brain regions responsible for processing assembled versus addressed procedures in grapheme-to-phoneme translation, we are aware of limitations to interpretation. First, in the present study, the pairs of stimuli in both Chinese and pinyin are meaningful only through sound but not through the visual form. However, individual characters in pairs of Chinese characters are meaningful while individual pinyin syllables are not. Hence, while the stimuli used in this study may help to isolate the script-to-sound translation in reading, there may be implicit semantic processing of individual Chinese characters, which must be ignored. Differences in activation patterns observed in the middle temporal and inferior frontal gyri, for example, therefore could be related to the differences in the semantic demands. Second, nonlinguistic elements of processing (e.g., eye movements) may differ between the tasks. The greater activation in the superior parietal lobule for pinyin could be accounted by relatively increased eye movements for scanning of the pinyin as pinyin provides a relatively unfamiliar form, especially when two syllables of a pinyin word presented as a single letter string. Further studies need to contrast Chinese characters and pinyin with their false fonts in order to know to what extent the different activation pattern observed in this study are related to nonlinguistic element of processing. Third, while the current study exploited unique features of Chinese to examine the addressed and assembled phonology, the distinction is not absolute. Reading the Chinese characters involves assembly of the sounds of the two characters into one sound. It also may involve some degree of subcharacter assembly, although we attempted to minimize this by choosing characters without regular phonetic radicals. The assembly procedure for pinyin may have special features, as it is not a usual written script, so direct generalization to other alphabetic languages must be done with caution.

### Testing a Dual Pathway Model for Reading

An oversimplified but useful hypothetical framework for interpretation of the present study contrasting Chinese character and pinyin reading is in terms of dual processing pathways for reading. Orthographic processing of both alphabetic and nonalphabetic scripts appears to involve extrastriate areas (BA 18) including the lingual, fusiform, and cuneus. However, the results presented here suggest that the left fusiform gyrus, bilateral cuneus, and an anterior portion of the left middle temporal gyrus may have a relatively specific role in the pattern-based, addressed process crucial to reading the nonalphabetic Chinese characters. In contrast, the letter-mediated grapheme-to-phoneme translation crucial to alphabetic reading and spelling used for pinyin reading relies more on activation of distinct regions including the precuneus, inferior parietal, and superior temporal cortex bilaterally, as well as a posterior segment of the left middle temporal gyrus. Elements of these pathways for Chinese language reading recapitulate aspects of processing in English, consistent with the notion that reading of English words can involve either pathway. The finding of both common and distinct elements for processing via predominantly addressed or assembled reading helps us to extend empirically the notion of dual pathways for learning into a broader framework, such as that proposed from connectionist models (Seidenberg & McClelland, 1989). Our work suggests that further study of Chinese reading could illuminate mechanisms of grapheme-to-phoneme translation, which has practical implications for understanding the genesis of both congenital and acquired dyslexia.

## METHODS

### Participants

Nine (six men and three women) native Mandarin speakers and skilled readers of Chinese who participated in this study with informed consent. Nine different, similar subjects were used for behavioral studies of reaction times for Chinese character or pinyin reading. All the participants were right-handed as assessed by the Edinburgh handedness inventory (Oldfield, 1971). None of them had any history of brain damage or any neurological or psychiatric disorder. The present study was approved by the Central Oxford Research Ethics Committee.

### Apparatus and Procedure

Experiments were performed on a 3.0-T MRI/MRS scanner at the Centre for Functional Magnetic Resonance Imaging of Brain, University of Oxford. Twenty-one separate slices covering the whole brain were collected with GE MBEST sequence, with a 3.0-sec repetition time (TR), an echo time (TE) of 30 msec, and a flip angle (FA) of 90°. Slice thickness was 6 mm with no interslice gap. A $64 \times 64$ matrix and $256 \times 256$ mm field of view (FOV) was used, yielding an effective voxel size of $4 \times 4 \times 6$ mm. The anatomical images were obtained in the transverse plane during the same scan session with 3-D Turbo FLASH sequence after the functional measurements. The parameters of anatomical scans were the following: TR = 25 msec, TE = 5 msec, inversion time = 500 msec, and FA = 15°. The resolution of structural images of the brain is $1 \times 1 \times 3$ mm.

### Materials and Design

*Stimuli*

Sets of 72 Chinese and 72 pinyin stimuli, each divided into 12 blocks of 6 stimuli each, were used in the

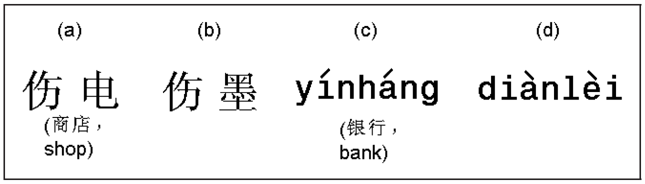


**Figure 2.** Examples of the Chinese characters and pinyins used in the present study: Chinese characters that sound like a word (a), Chinese characters that do not sound like a word (b), pinyins that sound like a word (c), and pinyins that do not sound like a word (d). The corresponding Chinese words and its meaning in English for sound-like-word stimuli are shown below the stimuli.

experiment. In each type of script, half of the stimuli were words and half were nonwords (see Figure 2 for examples of stimuli). For Chinese characters, the homophonic two-character words were formed by selecting first the real two-character words (e.g., 沙漠) from the frequency band of 16–140 per million in terms of two-character word known in Chinese as CI in ‘‘Modern Chinese Frequency Dictionary’’ (Anonymous, 1986). Individual characters in the two-character word (in brackets) were then replaced by their homophonic characters (e.g., 杀(沙)末(漠)) so that the two homophonic characters together were visually meaningless, but sounded like a real two-character word. The two-character nonwords in Chinese were formed by using characters appearing in the homophonic two-character words group but in a different combination so that the two characters together could neither sound nor look like a real word (e.g., 末海). The same two types of two-character words and nonwords using different word items were chosen from the same CI frequency band but presented in the standard pinyin format. All Chinese characters were presented in the printed simplified format used in China. Pinyin scripts were presented in the standard format with tone marked at the top of the vowel. Each two-character pinyin words and nonwords had either six or seven letters with no space between them. All of the two-character words in Chinese and in pinyin were concrete nouns with high imageability.

## Experimental Design

In order to train them with the procedures, all of the participants underwent a practice session for the task, using a different set of stimuli from those later used in the experiment. The practice session was completed outside the scanning room 10 min before entering the scanner. They were told that the stimuli presented during the task would be either pinyin or Chinese characters that the Chinese character pairs (like the pinyin) would not be meaningful until translated (correctly) into sound. In the single scanning session, each subject completed three consecutive stimulus contrasts: Chinese character versus fixation (CH), pinyin versus fixation (PY), and Chinese character versus pinyin (CH/PY). In both the Chinese character versus fixation and the pinyin versus fixation sessions, the 12-block stimulus sequence was ABABABABABAB, in which A represents a Chinese character or pinyin block, and B represents a fixation control block. In the Chinese character versus pinyin contrast, the sequence was ABBAABBAABBA, in which A stands for Chinese character and B stands for pinyin. Each block lasted 30 sec. In both Chinese character reading and pinyin reading blocks, each trial began with the same cross appearing at the center of the screen for 400 msec. The cross then disappeared and 200 msec later the Chinese characters or pinyin were presented for 3500 msec with 500-msec interstimulus interval. In fixation control blocks, a central fixation cross (‘‘+’’) was presented for 4000 msec with 200-msec interstimulus interval. Each block consisted of six trials. Within each stimulus block, half of the stimuli sounded like words and the other half did not. Pairs sounding like words and nonwords were presented randomly in each block and the sequence of presentation was different for different participants.

During each stimulus block, subjects were asked to judge whether or not the Chinese characters or pinyin sounded like real words and to respond by pressing a response button with their right index finger for a ‘‘yes’’ response and with their right middle finger for a ‘‘no’’ response. All subjects were able to perform the task with accuracy exceeding 90%. During the fixation control blocks, the participants were asked to fixate in the center of the screen and to respond by pressing the two buttons alternatively using index and middle finger of the right hand whenever a ‘‘+’’ appeared.

## Data Analysis

The first four scans in each session (during which magnetization steady state was being reached) were excluded from data analysis. Data analysis was carried out using FEAT, the FMRIB Easy Analysis Tool (www.fmrib.ox.ac.uk/fsl). 3-D motion correction was performed using AIR (Woods, Cherry, & Mazziotta, 1992), and spatial smoothing was performed using a Gaussian kernel of FWHM 10.0 mm. Afterwards, the functional images underwent global (volumetric) multiplicative mean intensity normalization and matched Gaussian/Butterworth band pass temporal filtering. $Z$ statistic (Gaussianized $T$ statistic) images adjusted for multiple comparisons were produced using the Student's $t$ test (between activated and nonactivated volumes) and thresholded by finding clusters determined by $Z > 3.1$ and a cluster significance threshold of $p = .01$ (Poline, Worsley, Evans, & Friston, 1997). Group activation images were generated by random effects analysis. These images were then overlaid onto the structural image, which was registered to standard stereotactic space (Talairach & Tournoux, 1988). The anatomical labels of brain activations were defined on the basis of local anatomy defined with reference to a standard atlas (Duvernoy, 1999) and using the Talairach Daemon (Lancaster et al., 2000). Voxel counting of ROIs defined neuroanatomically on each participant's anatomical image was performed for Chinese character versus fixation and pinyin versus fixation contrasts. Repeated measures analyses of variance were used to analyze these voxel counting results with condition (CH vs. PY) and hemisphere (left vs. right) as factors. The corresponding asymmetry index (AI) for ROI voxel counts was calculated from the relative numbers of significantly activated voxels with the following formula: AI = (total voxels [L − R])/(total voxels [L + R]), where L and R refer to the left and right hemispheres, respectively. Two-tailed *t* tests were performed between the AIs of Chinese character versus fixation and pinyin versus fixation.


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The data reported in this experiment have been deposited in The fMRI Data Center (http://www.fmridc.org). The accession number is 20-2002-112MY.


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