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The Neuroanatomical System Underlying Chinese Reading and Its Constraints on Second Language Learning

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Abstract This paper reviews our recent brain imaging studies that indicate that the left middle frontal gyrus plays a crucial role in explicit Chinese character recognition and reading. The left middle frontal gyrus seems to serve as a neural system for coordinating and integrating visuo-orthographic information with phonological and semantic elements in written Chinese, as seen in several paradigms including word generation, homophone decision, and semantic judgment (all relative to fixation baseline). This neural system is responsible for the orthography-to-phonology conversion as well as the orthography-to-semantics mapping. Neuroimaging research with Chinese-English bilinguals indicates that Chinese bilinguals apply the neural system for native language to the learning of English.

Key words Chinese reading; Dyslexia; fMRI; Neuroimaging; Second language learning

Written languages differ in whether they represent the spoken language's phonology (speech sound) or morphology (meaning). The two languages with a sharp contrast in design principle are morphosyllabic Chinese and alphabetic English. While English words map onto phonemes (minimal sound units as represented by letters) and abide by grapheme-phoneme correspondence rules, written Chinese uses the character as a basic writing unit whose phonology is defined at the monosyllabic level, with no parts of the character corresponding to phonological segments such as phonemes. Thus, the grapheme-to-phoneme conversion rules that exist in all alphabetic languages are impossible in Chinese. Visually, Chinese characters possess a number of intricate strokes that are packed into a square configuration; they map onto morphemes, often having their meaning suggested by visual configurations. Hence, a Chinese character has a more direct connection with its meaning than a written word in English does. The square-shaped graphic form of the character demands intensive visuo-spatial processing during character identification.

How does the human brain read Chinese? Does the surface form of written languages influence reading processes and cerebral organisation? This paper reviews recent functional magnetic resonance imaging (fMRI) studies with Chinese language that may advance our understanding of the universality and specificity of neuro-anatomical systems underlying reading across languages. I begin with a summary of our fMRI findings of Chinese character and word recognition; then I review our results showing that Chinese-English bilinguals resort to the neurocognitive system for the Chinese language to processing English words. In particular, we found that the left middle frontal cortex (at Brodmann area, i.e. BAs 9 and 46) is the "center" of Chinese reading.

Brain Circuits in Reading Chinese

The primary working principle of fMRI is that changes in neuronal activity associated with a cognitive (e.g. reading) task are accompanied by focal changes in blood oxygenation.[1] By measuring haemodynamic responses underlying neuronal events, researchers are able to localise brain activation with high spatial and temporal resolution.[2-5] In fMRI experiments, typically we used an experimental

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task that required either semantic or phonological processing of Chinese characters and a control task in which subjects maintained fixation on a crosshair. The experimental task, whether it is meaning- or phonology-related, would activate linguistic components of Chinese characters (i.e. orthography, phonology, and semantics), whereas the control task would not activate any linguistic information. Subtraction of the brain activation provoked by the crosshair baseline from the brain activation elicited by the experimental task could not fractionate fine-grained neural processes such as phonology or semantics, but it would lead to an identification of the neural circuits engaged by reading in their entirety.

Word Generation

We asked male, right-handed Chinese subjects to covertly generate a word that was semantically related to a viewed Chinese stimulus.[6] This task is similar to the verb generation task developed by Petersen, Fox, and their colleagues,[7] with the exception that we did not specify to our subjects that a verb must be generated. Three sorts of Chinese items were used: single characters of precise and dominant meanings, single characters of vague and several frequently used meanings, and 2-character Chinese words. The baseline condition was that the subject maintained their fixation on a crosshair. In a block design alternating experimental conditions (precise-meaning character, vague-meaning character, and two-character word) with the baseline, we found that the left middle frontal cortex at BAs 9 and 46 peaked for all the three types of Chinese stimuli, without dissociation. The left inferior prefrontal regions including Broca's area were also active, but the activations in these areas were much weaker compared to the middle frontal cortex. Inter-subjects consistency analysis[8] indicated that the left middle frontal cortex peaked for all the subjects we scanned.

To evaluate a previous proposal that the right cerebral hemisphere is more efficient in processing single Chinese characters than the left cerebral hemisphere, whereas there is a reverse tendency in processing two-character Chinese words,[9,10] we computed activation voxels in regions of interest (ROIs) that included frontal, temporal, parietal, and occipital cortices. Brain activity was strongly left-lateralized in frontal and temporal (BA 37) cortices and right-lateralized in visual systems (BAs 17-19), parietal lobe (BA 3), and cerebellum. However, the overall brain activation showed strong left lateralization both for vague- and precise-meaning characters as well as for two-character words, without dissociation in laterality patterns.

Semantic Judgement

We scanned another group of male, right-handed native Chinese readers by using a semantic judgement task.[11] The subject judged whether a pair of Chinese characters exposed synchronously were semantically related. We still used the crosshair as the baseline condition. All Chinese characters had semantically precise meanings, and the two characters exposed in each pair shared no visuo-orthographic similarity so that the subject had to make a decision based on characters' semantic attributes rather than on their visual properties. We found that peak activation was located in the left middle frontal cortex (BA 9). Minor activations were observed in bilateral inferior prefrontal gyri (BAs 45/47) and bilateral frontal pole (BA 10). The total activations in the frontal lobe were strongly left lateralized. In the parietal lobe, bilateral superior parietal lobules (BA 7) and inferior parietal gyri (BA 40) were significantly activated. In the occipital lobe, activation in left infero-middle gyrus (BA 18) was present. However, activations in the right side covering the cuneus, fusiform, and inferior occipital gyrus were stronger than activations in the left side, revealing right lateralization.

Homophone Decision

A homophone decision task was devised to further elucidate the neural network responsible for Chinese reading.[11] Subjects were required to decide whether two Chinese characters exposed synchronously were homophones. Compared to the fixation baseline, we observed a pattern of brain activation that was highly similar to that produced by the semantic judgement, as introduced above. Still, peak activation occurred in left middle frontal gyrus (BA 9). Bilateral infero-middle prefrontal cortex (BAs 44/45 and 47/10) and left medial prefrontal lobe (BA 11) was weakly activated. Activations in these areas were left lateralized. The bilateral superior parietal lobule (BA 7) participated in homophone judgements, and the activations in the occipital cortex were still right lateralized.

The above-mentioned fMRI studies have produced clear-cut results. Compared to fixation baseline, the distributed neural systems activated by semantic and phonological tasks largely overlapped. Many of the activated areas that contributed to reading Chinese have been implicated in previous work on alphabetic languages. For instance, a number of studies using alphabetic words demonstrated involvement of ventral occipito-temporal regions, such as the fusiform and lingual gyri,[12,13] the left inferior frontal lobe including BAs 44/45 and BA 47 and the neighbouring vicinity,[14-22] and the temporo-occipito-parietal junction

(BAs 39/19).[23-25] The presence of significant activations in these cerebral regions indicates their involvement in reading, regardless of the particular writing system.

However, our results also reveal an important difference in cortical organisations across languages. Both semantic and homophone tasks showed that peak activation in the processing of Chinese characters was located in the left middle frontal cortex (BAs 9 and 46), a region above Broca's area. Nevertheless, past investigations with English and other alphabetic languages, whether using similar[26-28] or different paradigms,[29,30] have not commonly implicated this middle prefrontal region in word recognition and reading. Even though this region is noted by several researchers, the reported activation in this area is much weaker for native English readers.[20,25,31,32]

We have hypothesized that the extremely strong activation of the left middle frontal gyrus in reading Chinese is associated with the unique square configuration of characters (Tan et al, 2001a). In the literature, the left middle frontal cortex is known to subserve visual-spatial processing of objects and verbal and spatial working memory by which the subject maintains a limited amount of verbal or spatial information in an active state for a brief period of time (0-60 sec).[33-35] Furthermore, this region may act as a central executive system of working memory that is responsible for coordination of cognitive resources.[36-38] In our fMRI studies, the subject needed to coordinate the semantic (or phonological) processing of the Chinese characters that was explicitly required by the experimental task and the intensive visuo-spatial processing that was demanded by the visual form of characters. In this case, the left middle frontal gyrus is recruited to integrate these two cognitive processes.

Our findings of the involvement of a set of right hemisphere cortical sites converge on the view that reading Chinese demands elaborated visual-spatial analysis. The right frontal pole (BA 10/11), frontal operculum (BA 47/45), dorsolateral frontal gyrus (BA 9/44), and the superior and inferior parietal lobules (BAs 7, 40/39) mediated semantic and homophonic judgements. These areas were not often implicated in most of the studies with alphabets as well (but see a recent PET study by MacLeod et al[39]). However, it is well known that these right prefrontal regions service episodic memory processes by which one retrieves the spatial relation of perceived objects.[40-43] In addition, the right BAs 7 and 40/39 are routinely activated in spatial working memory tasks.[33,34,44,45] Based on these previous studies, it is reasonable to assume that the right frontal and parietal regions are involved in perceiving the spatial locations of the character's strokes.

While activations in the occipital cortex were bilateral, the right side was dominant over the left side. As the right occipital cortex is relevant to the spatial recognition of visual symbols,[46] its strong activity seen in our studies can, again, be attributed to the visual properties of Chinese characters. The involvement of the bilateral visual cortex and the supero-inferior parietal lobe suggests the role of a dorsal pathway responsible for spatial localisation in reading Chinese. Through the dorsal pathway, visual processing that originates from the striate cortex reaches the posterior parietal cortex.[47]

To summarise, our results suggest that reading in Chinese is mediated by a distributed neural system. As in English word reading and recognition, the left inferior prefrontal cortex is active in processing Chinese characters. Peak activation associated with reading Chinese, however, is located in the left middle frontal region, a central executive cognitive system that subserves the coordination of cognitive resources. We have assumed that in reading Chinese, the left middle frontal cortex is recruited to coordinate and integrate the intensive visuo-spatial analysis demanded by characters' unique square configuration and the linguistic (semantic or phonological) analysis required by an experimental task using Chinese characters.

A Neural Basis for Phonological Processing of Written Chinese

To fractionate phonological processes and associated cortical regions, we ran several neuroimaging studies. In one, we devised a rhyme judgement task in which the subject decided whether a pair of synchronously exposed Chinese characters rhymed with each other[48] (see also Siok et al[49]). In the control scan, the subject decided whether a pair of Chinese characters had the same physical size ("font size judgement"). This task should control for activation due to the visual-orthographic and semantic processing of the linguistic stimuli in the experimental task.[25] The two Chinese characters exposed in each pair shared no visuo-orthographic similarity. Activations related to rhyme decision contrasted with font size decision peaked in the left middle frontal cortex at BAs 9 and 46. The left motor cortex and supplementary motor cortex and the left inferior parietal cortex (at BA 40) were also strongly active. Minor activations were seen in the left inferior prefrontal gyrus (BAs 44 and 45). These findings are important in suggesting that the left middle frontal cortex is responsible for the explicit phonological processing of Chinese characters.

Note that previous work with neuroimaging has consistently identified left superior and infero-posterior temporal gyri (BAs 22 and 37) and left posterior portion of inferior frontal cortex (BA 44) in phonological processing of alphabetic words by English monolinguals, with left superior temporal regions more specifically identified as being responsible for fine-grained phonemic analysis.[7,16,17,50-52] Our results with Chinese characters suggest a segregation of cortical representations of phonological information for Chinese and native English speakers. Phonological analysis in Chinese peaked in the left middle frontal cortex, implying the dependence of phonological processing on visuo-orthographic components of characters.

Our second set of the fMRI study has localised brain areas contributing to the reading aloud of Chinese characters[53] (see also He et al[54] and Liu et al[4]). We utilised whole-brain, event-related functional magnetic resonance imaging (ER-fMRI) to observe the transient brain response associated with Chinese reading. With this technique, we exposed a single Chinese character that was either regular or irregular on each trial. The subject was asked to name the viewed character. We used highly familiar Chinese characters in this study, because our previous cognitive studies found greater regularity effects for higher frequency characters than for lower frequency characters in some range of frequency.[55] Unlike our other fMRI studies that used a block design, in this ER-fMRI study, presentations of regular and irregular Chinese single characters were randomised. Thus, this design permitted us to ascertain the neural substrate relevant to automatic processing of sublexical phonological information. This study is also dissimilar to Tan et al (2003)[48] in that the subject read Chinese characters out rather than making a "silent" rhyme decision.

Converging with the studies of alphabetic languages, this study found regularity effects in left inferior frontal regions (BAs 44, 45/47), left (pre)-motor cortex including supplementary motor area, and left superior temporal lobe, suggesting their contribution to orthographic to phonological transformation that is presumably general across languages. The left inferior frontal and temporal cortices may be related to a general phonological analysis of stimuli in naming task, while the motor cortex is responsible for phonological output at the articulatory stage. The greater activations observed in these areas for irregular words arose from the competition of phonological codes and/or articulatory gestures at the phonetic component level and at the whole word level.

The regularity effect was also seen in left middle frontal cortex at BA 9, indicating its participation in orthography-to-phonology transformation. This lends support to our proposal that the left BA 9 is crucial for Chinese reading. Another interesting area showing the regularity effect is the right superior temporal cortex that is known to be relevant to perception and analysis of pitch and tone. We assume that its activity here is associated with tonal representations and processing of Chinese characters. The regularity effect observed in this area indicated the involvement of a general phonological analysis subsystem to which the tonal information is attached.

We also found a regularity effect in the anterior cingulate cortex, a brain area that plays a prominent role in the executive control of cognition and the online monitoring and evaluating of performance by detecting cognitive states such as response competition.[56,57] Greater activation in this area for irregular characters than for regular ones should stem from the activation of the phonological code of phonetic components in an irregular word, which competes with the activation of the phonological code of the whole word. Further, it may be also relevant to the competition between articulatory gestures of the word and its phonetic component. As an evaluation module, the anterior cingulate cortex detects such kinds of competition.

The right superior frontal and parietal regions (BAs 8/6, 7) and the bilateral cuneus (BAs 19/18) in the visual system mediated the reading of irregular, but not regular, characters. Previous research indicates that these areas participate in allocation of attention resources and analysis of visuo-spatial information of objects. Their involvement in the processing of irregular characters implies that evaluation of the appropriateness of the phonological code of phonetic components is associated with a further analysis of orthographic units.

Thus, our ER-fMRI study has generated important findings for elucidating the process underlying the reading of words; in particular, Chinese characters. The regularity effect detected with high frequency Chinese stimuli provides strong neural evidence for our eye movement results.[55] Consistent with the assumptions of the cognitive model of reading Chinese,[58] our ER-fMRI results indicate that during the reading aloud of a familiar Chinese character, its phonological information is processed obligatorily at sub-character componential level. The reading aloud of a Chinese character hypothetically involves four sub-processes: (1) general phonological processing, which activates phonological information predominantly by left infero-middle frontal and bilateral temporal cortices; (2) tonal analysis, which is mediated by right superior temporal gyri and is characterised by the nature of Chinese; (3) articulatory production, which is serviced by the left motor cortex; and (4) evaluation of phonological codes and production gestures, which is subserved by the anterior cingulate cortex. Through the evaluation sub-process, the consistency of phonetic components' and whole words' phonological codes was decided. When there is a discrepancy between activated phonological representations or articulatory gestures, such as in irregular characters, competition occurs, which leads to additional analysis of visual-orthographic and phonological information of printed characters. Right superior frontal and parietal gyri and bilateral cuneus are recruited for this further checking of orthography to phonology mappings.

Brain Mechanisms for Chinese Dyslexia

Neuroimaging data have shown that developmental dyslexia (defined as severe reading disability that is unaccountable by deficiency in intelligence or educational opportunities) in alphabetic languages is characterised by reduced activation of brain areas mediating phonological processing (left mid-superior temporal gyri) and subserving orthography-phonology integration (BA 37 and the angular gyrus).[59-63] These results lend support to a widely-accepted cognitive theory which assumes that dyslexia is a language-based disorder caused by phonological deficits.[64]

We performed brain scans to investigate biological abnormality of impaired Chinese reading.[65] In a lexical decision task, eleven-year old children were required to judge whether or not a viewed stimulus was a real Chinese character. In a homophone decision task, the same group of children was asked to judge whether or not a pair of characters were homophones. The character decision paradigm provides insight into the processing of visuo-orthographic and semantic constituents and their interconnections. The homophone decision task, when contrasted with the control task, allows us to assess cortical areas for explicit phonological processing of characters by reading-impaired children and their controls.

Important differences in brain activity were seen between normal and impaired readers. When making lexical decisions, reading-impaired Chinese children showed much weaker brain activation than controls in bilateral middle prefrontal gyri (BA 9), bilateral inferior prefrontal gyri (BA 44), and left fusiform gyrus (BAs 19/37). Conversely, impaired readers showed stronger activation than normal readers in right extrastriate near BA 18. In the homophone decision task, direct comparisons of the BOLD activity of the two groups of readers indicated that cortical activation was stronger in the left middle frontal gyrus (BA 9) for normal readers than for reading impaired children. In the left inferior prefrontal cortex at BA 45, however, impaired readers had stronger brain activation than normal readers.

In this study, strong brain activations in the left middle frontal cortex were observed in both lexical decision and homophone judgement tasks, indicating that these cortical regions play a central role in semantic and phonological processing of characters in Chinese children. This finding agrees with our previous fMRI studies with normal Chinese adult readers. More important is that impaired Chinese reading provoked weaker BOLD activity in the left middle frontal cortex when compared with normal reading, implicating a failure of left middle frontal brain systems to function properly during impaired Chinese reading. As the right extrastriate cortex is engaged in visual processing of Chinese characters,[6,11,66] its overactivation in impaired reading reveals that Chinese poor readers struggle even in visual analysis of printed materials. This proposal that Chinese poor readers make more effortful processing of viewed characters than controls is buttressed by stronger BOLD activity in left inferior frontal cortex at BA 45 (during homophone judgement), as activation in that brain region is known to be relevant to a general task difficulty effect.[29] Thus, Chinese reading impairment is characterised by two deficits: one relating to orthography-to-semantics mapping as revealed in character decision, and the other concerning orthography-to-phonology mapping as demonstrated in homophone decision. In conclusion, the biological origin of Chinese reading disability is different from the biological origin of alphabetic reading disability.

Neurocognitive Networks for Second Language Learning by Chinese Students

How do children and adults learn to read in a second language (L2)? Does learners' native language (L1) influence their L2 learning? In the past two decades, these questions of bilingual literacy have provoked considerable research interest of linguists, cognitive psychologists, and neuroscientists.[67-70]

To discover how the linguistic information of L1 and L2 is organised in the neural and cognitive systems and whether bilinguals apply their L1 system to L2 reading, we carried out two studies with bilinguals who learnt Chinese as L1 and English as L2.[48] In Study 1, we used the Stroop paradigm and measured bilingual subjects' reaction time and response accuracy in naming the ink colour of viewed English colour words ("red, blue, green, yellow") and their pseudohomophones ("wred, bloo, grene, yeloe"). Past research with English monolinguals has indicated that naming the ink colour of incongruent colour words (e.g., *red* written in green) took longer than naming the ink colour of neutral word controls (e.g., *time* written in green).[71] Further, naming the ink colour of incongruent pseudohomophones of colour words (e.g., *bloo* written in red) also took longer than naming the ink colour of their visual controls (e.g., *blur*).[72] The interference effect from pseudohomophones suggested that English monolinguals use the grapheme-to-phoneme correspondence rules to compute phonological codes of pseudohomophones, through which (colour words') meanings were accessed.

We tested Chinese-English bilinguals who started to learn English as L2 from age 10 (grade 4) and were senior English majors in Beijing Normal University and Beijing Foreign Study University at the time we conducted this study. While there was an interference effect from incongruent colour words, incongruent pseudohomophones did not impede colour naming compared to their visual controls, revealing that our bilingual subjects who were among best English speakers in China did not efficiently apply the grapheme-to-phoneme correspondence rules to reading English letter strings. The nature of the Chinese writing system that logographs do not call for phonemic computation is supposed to be responsible for the indolence of the grapheme-to-phoneme conversion route.

In a second study,[48] we used fMRI to discover the brain areas contributing to the phonological processing of English words by native Chinese readers. Similar to the rhyme judgement task that we devised in fractionating brain regions associated with Chinese characters' phonological processes (introduced above), we asked Chinese-English bilingual subjects to decide whether a pair of synchronously exposed English words rhymed with each other. In the control scan, the subject decided whether a pair of English words had the same physical size ("font size judgement"). The two English words exposed in each pair (e.g., hay/weigh) were visually dissimilar so that the subject had to make a decision based on stimuli's phonological attributes rather than on their visual properties. We scanned 12 right-handed male bilinguals who started to learn English in China after age 12 and who were Ph.D. students of the University of Texas Health Science Center at San Antonio at the time of testing. Our assessment of their English proficiency indicated that they were fluent L2 users.

Activations related to English rhyme decision (contrasted with font size decision) were remarkably similar to the activations elicited by Chinese rhyme decision. Peak activations occurred in the left middle frontal cortex at BAs 9 and 46. The left motor cortex and supplementary motor cortex were also strongly active. Other important activated areas included precuneus (at BA 7) and cuneus in the left hemisphere. Minor activations were seen in the left inferior prefrontal gyrus (BAs 45 and 47).

As introduced in the preceding section, past imaging research with English (and other alphabetic languages) has consistently identified left superior and posterior inferior temporal gyri and left posterior portion of inferior frontal cortex in phonological processing of English monolinguals. One might expect that, as English words are linearly constructed and follow the grapheme-to-phoneme correspondence rules that require elaborated phonemic processing, the left temporal gyrus would be active when our bilingual subjects processed English. Our failure to show activation in these regions, along with our demonstration of the peak activity of the left middle frontal cortex, suggested the processing of L1 phonology (where Chinese characters are pronounced monosyllabically and do not call for phonemic parsing) carries over to L2 processing. The peak activity of the left middle frontal cortex in Chinese-English bilinguals' processing of English has also been seen in our fMRI studies of word generation and syntactic analysis.[73,74]

The aforementioned discoveries provide strong cognitive and neuroscientific evidence for the role of native language in L2 learning. Moreover, these findings provide a scientific foundation for reforming English teaching and learning methods in Mainland China. Chinese students (in China) cannot efficiently resort to the grapheme-to-phoneme conversion rules in reading English, even after they had learnt English as L2 for more than 10 years (and even after they had lived in the United States for several years). Note that a great deal of empirical evidence has indicated that the ability to use the grapheme-to-phoneme conversion rules (and to analyse spoken language into small sound units such as phonemes) is crucial for acquiring English reading ability.[75] Remedial instruction plans that focus on the grapheme-to-phoneme conversion and phonemic awareness are being developed for Chinese students who learn English as L2. Cognitive studies have indicated that Chinese students' L2 reading ability can be improved after sufficient and appropriate training.[76]

Conclusions

In summary, strong fMRI evidence has indicated that the visual identification of Chinese characters is characterised by peak activity of the left middle frontal regions. These cortical regions are not crucial for the phonological and orthographic processing of alphabetic languages by native speakers. Further, our behavioral and brain-imaging data reveal that Chinese students who had learnt English as L2 for more than ten years still could not efficiently use the grapheme-to-phoneme conversion rules, the rules that are crucial for the development of the ability to read in English. This implies that the processing of L1 phonology carries over to L2 processing. Our fMRI findings are important for advancing our understanding of the neuro-anatomical bases for Chinese reading and L2 literacy. Moreover, our findings have great clinical implications for a pre-surgical identification of cerebral dominance for language, in order to prevent a post-surgical neurologic deficit (such as loss of language).

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