Reading in two writing systems: Accommodation and assimilation of the brain's reading network*

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Bilingual reading can require more than knowing two languages. Learners must acquire also the writing conventions of their second language, which can differ in its deep mapping principles (writing system) and its visual configurations (script). We review ERP (event-related potential) and fMRI studies of both Chinese–English bilingualism and Chinese second language learning that bear on the system accommodation hypothesis: the neural networks acquired for one system must be modified to accommodate the demands of a new system. ERP bilingual studies demonstrate temporal indicators of the brain's experience with L1 and L2 and with the frequency of encounters of words in L2. ERP learning studies show that early visual processing differences between L1 and L2 diminish during a second term of study. fMRI studies of learning converge in finding that learners recruit bilateral occipital-temporal and also middle frontal areas when reading Chinese, similar to the pattern of native speakers and different from alphabetic reading. The evidence suggests an asymmetry: alphabetic readers have a neural network that accommodates the demands of Chinese by recruiting neural structures less needed for alphabetic reading. Chinese readers have a neural network that partly assimilates English into the Chinese system, especially in the visual stages of word identification.

How does the brain come to support the acquisition of a new writing system? Not just a new orthography, as when a speaker of Italian or Finnish learns to speak and read English, but a new writing system, a way of encoding the spoken language that is different in its deep design features? The case of Chinese and English provides just this situation, and that is what we examine in this paper. We will review research that suggests how an alphabetically experienced brain responds to the learning of Chinese and how a bilingual Chinese reader responds to English.

We pose the question in terms of an exaggerated contrast that helps focus the question: When a reader acquires some ability to read in a new writing system, does the brain network for writing system 1 (WS1) ASSIMILATE the properties of the second writing system 2 (WS2)? Or does the network change to ACCOMMODATE the features of the new system?

We begin with a brief review of some writing concepts that are critical in addressing this question. There is ample confusion in the use of three related terms – writing system, orthography, and script – and we need to be clear on which of them is involved when we speak of assimilation and accommodation.

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Writing systems, orthographies, and scripts

WRITING SYSTEMS reflect design principles, not appearances. However, appearances are the first aspect of writing that one notices, and differences in appearances might be relevant for how the brain handles variability in writing. Arabic looks very different from both English and Russian, and all three look different from Hindi, Hebrew, Tamil, Khmer, Chinese, Japanese Kana, and Korean, which all look different from each other. Although from a Roman alphabet point of view, these last three might look rather similar, they in fact represent three different writing systems: Chinese is morpho-syllabic, Japanese Kana are syllabic, and Korean is alphabetic. Thus, a critical point is that appearances are about THE SCRIPT – the visual forms of the writing – and writing systems are about design principles – the basic unit size for the mapping of graphic units to language units. The superficial nature of script variation is reinforced by noticing that even within English, countless variations for the Roman alphabet have been developed, accelerated by the multiplicity of computer fonts.

A third writing category is ORTHOGRAPHY, the implementation of a writing system design in a specific language. Thus, written English is not a distinct writing system but it has a distinctive orthography, differing from Italian, Korean and other orthographies within the alphabetic writing system. Within the alphabetic writing

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system, orthographies vary in the transparency of mappings between letters and phonemes; Italian and Finnish are very transparent; English is relatively nontransparent; Danish is in-between. (See Perfetti and Dunlap, in press, for how this matters for reading.)

With this three-way distinction among writing systems, orthographies, and scripts, we can move to a specific examination of two writing systems, comparing Chinese and alphabetic English. The latter, whatever its imperfections in implementing the alphabetic principle, is alphabetic because it generally maps grapheme units to phonemes.

Alphabetic–Chinese comparative reading research

Although it is typical to refer to written Chinese as a logographic system (because a single character can be a whole word), it is more accurate to characterize it either as morpho-syllabic (the morpheme is usually a spoken syllable) or, following DeFrancis (1989), morpho-phonological: A character corresponds to a spoken syllable that is usually a morpheme, and often a word. Given its mapping to morphemes and words, Chinese has often been viewed as a system that takes the reader directly to meaning, with phonology not playing an important role. However, the fact that the meaning units are spoken syllables allows the possibility that spoken language units are involved. Furthermore, Chinese compound characters contain components that can provide information about meaning (semantic radicals) and pronunciation (phonetic radicals).

For comparative purposes, the most important fact about a character is that it maps onto a syllable, never a phoneme. Whereas the *b* in *bike* maps to the initial segment (/b/) of the spoken word, a phonetic radical does not map to any segment of the syllable-morpheme represented by the character. Instead, it maps to a whole syllable that may (or may not) be the syllable-morpheme represented by the character. Thus, the critical departure from alphabetic writing is that Chinese writing does not reflect the segmental structure fundamental to alphabetic systems (Mattingly, 1987; Leong, 1997).

This analysis of Chinese writing leads to an important conclusion about reading: Phonological assembly – the activation of phonemes by graphemes and their "assembly" into syllables and words – is not possible for a single Chinese character. This is because the Chinese graphic units (including those components inside characters) correspond to whole syllables. (Syllable-level phonological assembly is possible for two- and three-character words and there is some evidence that this is how two-character words are identified; Tan and Perfetti, 1999.)

Not allowing phonological assembly, however, is not the same as not allowing phonology. Like alphabetic readers, Chinese readers engage phonology when they read, from the sentence level (Hung, Tzeng and Tzeng, 1992; Zhang and Perfetti, 1993), where phonology supports memory and comprehension, down to the single character level (Perfetti and Zhang, 1991, 1995; Chua, 1999; Xu, Pollatsek and Potter, 1999). At the character level, the evidence is consistent with the IDENTIFICATION-WITH-PHONOLOGY hypothesis (Perfetti and Zhang, 1995; Tan and Perfetti, 1997; Perfetti and Tan, 1998, 1999): phonology as a CONSTITUENT of word identification, rather than either a pre-lexical mediator or a post-lexical by-product. This characterization applies to alphabetic writing (Perfetti, Liu and Tan, 2005) as well at the whole-word phonology level.

On the lexical constituency model (Perfetti et al., 2005), which builds on the identification-with-phonology hypothesis, phonology is activated at the moment of orthographic recognition – the point at which the identification system distinguishes a given graphic representation from other (similar and partly activated) representations. Phonological activation is part of a psychological moment of identification that is observable across writing systems. The difference among writing systems is that in an alphabetic system, the graphic units that initiate phonology correspond to phonemes, whereas in Chinese, these units correspond to a syllable.

The lexical constituency model (Perfetti and Tan, 1998; Perfetti et al., 2005) is an expression of these ideas that includes computational assumptions about identifying characters. The model has implications for how the brain's reading network might respond to variations in writing systems. It assumes that orthographic, phonological, and semantic constituents specify word identity. It further assumes that form–form relationships are available rapidly so that phonological information will be quickly retrieved given a graphic input. The most important feature of the model's application to Chinese is that it captures an asynchrony between orthographic and phonological processing that is absent in alphabetic reading. In reading an alphabetic word, the individual graphemes can activate phonemes, and the process of word identification can proceed with the assembly of these phonemes toward a match with a word representation. (Identification also can proceed along a direct path to the stored representation, the addressed route of dual route models; Coltheart et al., 2001.)

The fact that Chinese does not allow an assembled route for a single character is a writing system factor that is expressed in behavioral data. In particular, Chinese shows an asynchrony in the time course of graphic and phonological priming (Perfetti and Tan, 1998). Phonological priming, a reduction in naming time when a character is preceded by a graphically non-overlapping homophone, was found to begin when facilitation by graphic priming turns to inhibition. When a prime preceded the target by 43 ms (43 ms SOA), the graphic prime was facilitative and there was no phonological or semantic priming; at 57 ms SOA, phonological priming appeared and graphic facilitation turned to inhibition. In alphabetic reading, this pattern has not been observed. Instead, in comparable time windows, one observes graphic facilitation followed quickly by phonological facilitation (e.g., Perfetti and Bell, 1991). Perfetti et al. (2005) interpret these differences this way: reading alphabetic writing involves a cascaded process of phonology, in which phonological processes can begin prior to the completion of orthographic processes (Coltheart et al., 1993). Reading Chinese involves a threshold process of phonology, in which phonology awaits the completion of orthographic processes

Additional differences between Chinese and alphabetic reading result partly from the basic difference in how the writing systems map spoken language – graph to phoneme in one case and graph to syllable in the other. Another factor is that Chinese contains many homophones, an average of 11 per single-syllable word not counting tone (and about 4 counting tone; Beijing Language and Culture University, 1986), making the use of phonology to mediate access to meaning difficult. Only a process that uses the character in meaning access can be reliably successful. That fact, coupled with the evidence that character-level phonology is always activated in reading Chinese, implies the following: the character's orthographic form has connections to both meaning and phonology (syllable-level). In reading an alphabetic word, the corresponding connections are also functional. The difference is that the Chinese reader may need to retain the orthography (the character) rather than relying on phonology while meaning is retrieved. This possible difference may have an effect on how the brain reads the two different systems.

Thus, the picture is one that shows a Universal Phonological Principle in reading (Perfetti, Zhang and Berent, 1992) that derives from the dependence of reading on the spoken language. However, the simple picture of a universal phonology at this level does not mean that there is a universal implementation of phonology, either as observed in behavior, which we have just shown may be different, or in the brain. We turn now to the brain part of this picture.

Comparative cognitive neuroscience research

In this section, we review some of what has been learned about the neural substrate for alphabetic reading as a point of departure to examine recent research on Chinese.

The alphabetic reading network

From the more than 150 published neuroimaging papers on visual word recognition (e.g., Bolger, Perfetti and Schneider, 2005) some consensus has emerged concerning how the brain reads alphabetic writing. Several meta-analyses (Fiez and Petersen, 1998; Price, 2000; Turkeltaub, Eden, Jones and Zeffiro, 2002; Jobard, Crivello & Tzourio-Mazoyer, 2003; Mechelli, Gorno-Tempini and Price, 2003; Bolger et al., 2005) point to a neural network whose components share responsibility for orthographic, phonological, and semantic processes of word reading.

The reading network includes posterior visual regions (occipital areas and the left mid-fusiform gyrus) for orthographic processes, temporal/parietal and anterior areas (superior temporal sulcus and inferior frontal sulcus/insula) for phonology, and both posterior (anterior fusiform) and anterior regions (inferior frontal gyrus) for meaning. (Bolger et al., 2005 provide more precise localizations of these regions.) Other meta-analyses provide converging functional regions, although their precise functional anatomy remains a partly open question. The precision of localization seems particularly high for the left fusiform region or "visual word form area" (VWFA), according to several meta-analyses (Cohen et al., 2000; Bolger et al., 2005).

An interesting question concerns the shaping of this visual word form area, which has an important role in identifying words and word-like letter strings, even if it is equally good at other perceptual tasks (Price and Devlin, 2003). If there are no brain structures specifically evolved for reading, then this most distinctive of all reading areas, responsible for the initial processing of printed word forms, must have its basic capacities of visual perception shaped by experience with word forms (McCandliss, Cohen and Dehaene, 2003). Pugh and colleagues have called the left fusiform area the reading skill area, because it seems to be less active for dyslexics (Pugh et al., 2001) and because it shows the effects of orthographic-phonological training (Sandak et al., 2004).

Further differentiation of the alphabetic reading network to five or six components is required for more precise functional descriptions (Pugh et al., 1996). However, to provide a point of departure for Chinese, the coarse-grain three-part network – occipital-temporal areas that include the left fusiform gyrus, temporal-parietal areas, and the inferior frontal gyrus – is sufficient.

The universality of the alphabetic network

The network identified for alphabetic reading has wide applicability to both alphabetic and non-alphabetic writing systems. However, even comparisons within alphabetic systems suggest differences (Paulesu et al., 2001). Imaging studies in Asian languages, including Japanese (Sakurai et al., 2000; Nakada, Fugii and Kwe, 2001; Nakamura et al., 2005) and Korean (Lee, 2004; Yoon et al., 2005a; Yoon, Cho & Park, 2005b), as well as Chinese (Chee, Tan and Thiel 1999; Chee et al., 2000), now provide richer alphabetic and nonalphabetic comparisons.

The first studies of Chinese showed a convergence with alphabetic research in key respects. Chee et al. (1999) found generally similar patterns of activation in Chinese and English, including the left fusiform gyrus. Tan et al. (2000) also reported overlap with English, especially emphasizing that left hemisphere (LH) areas, both posterior and anterior, were activated more than right hemisphere (RH) areas by Chinese. Tan et al. (2000) emphasized the left lateralization of Chinese reading to counter a wide-spread belief that Chinese is read by the right hemisphere. However, counter-indicators were also present in these studies, although not emphasized in the papers. Although Tan et al. (2000) correctly emphasized a general LH lateralization, their results for the occipital and occipital-temporal (VWFA) showed bilateral activation. There was no explicit comparison with alphabetic results, but Chinese reading did seem to show more RH activation than had been reported in studies of alphabetic reading.

As other studies were carried out (Tan et al., 2001; Tan et al., 2003), the differences between Chinese and alphabetic reading became impossible to ignore. Not only did results show more bilateral activation for Chinese in occipital and fusiform regions, they showed more activation in a frontal area, the left middle frontal gyrus (LMFG). Siok et al. (2004) added the finding that Chinese children who were poor in reading showed under activation of the LMFG, compared with children who were skilled readers. Activation of the LMFG has been found consistently enough in research to warrant the conclusion that it has a specific role in reading Chinese. The function of the LMFG remains to be clarified, but its importance is not in doubt. At the same time, studies of Chinese typically were not finding the same levels of activation of the temporal-parietal region nor the inferior frontal gyrus as found in alphabetic reading, where both are assumed to support phonological processes.

Two recent meta-analyses that include Chinese tend to confirm these differences, although the use of different task selection criteria seems to have produced less than complete agreement. Bolger et al. (2005) reviewed nine studies of Chinese and five of Japanese, along with thirty-five studies of alphabetic languages, across a wide range of single word reading tasks. They observed overlapping areas of activation across languages in the left ventral visual cortex, including the VWFA, but also observed that Chinese showed greater bilateral activation.

Tan, Laird et al. (2005) reviewed six studies of Chinese reading and thirteen studies of alphabetic reading that used a more restricted set of explicit phonology tasks. They concluded that alphabetic word and character phonological processing shared a network of three areas: (1) ventral prefrontal areas involving superior portions of the left inferior frontal gyrus; (2) a left dorsal temporoparietal system including mid-superior temporal gyri and the ventral aspect of inferior parietal cortex (supramarginal region); (3) left ventral occipito-temporal areas that include the VWFA. However, two areas showed distinctly more activation in Chinese than alphabetic reading: (1) the left dorsal lateral frontal area at BA 9, and (2) a dorsal left inferior parietal area. Moreover, although both alphabetic and Chinese reading showed activation in ventral occipito-temporal areas that include portions of the fusiform gyrus, Chinese showed a bilateral pattern.

These meta-analyses, despite some points of non-comparability, point to a clear shared conclusion across the studies: Chinese reading recruits bilateral occipital-temporal areas. Moreover, the frontal system for Chinese reading includes the LMFG at least when phonology is involved. The frontal system for alphabetic reading, in contrast, makes greater use of the left inferior frontal cortex. These conclusions are represented in Figure 1, which draws on the Tan, Laird et al. (2005) meta-analysis, showing the areas found in Chinese studies and where they depart from the alphabetic reading network.

Some uncertainty remains on the role of temporal and parietal areas that support word-level phonology. The left superior temporal gyrus is important in alphabetic reading and, according to Bolger et al.'s (2005) meta-analysis, it is also functional in Chinese reading; however, Tan, Laird et al. (2005) concluded that, instead of the left superior temporal gyrus, the dorsal left inferior parietal area is more important for Chinese phonology. The Tan, Laird et al. (2005) conclusion accords with the distinction between assembled phonology (grapheme–phoneme conversion) and retrieved phonology (based on syllables or whole words). The assembly of phonology has been attributed to the left superior temporal gyrus (e.g., Shaywitz et al., 1998; Poldrack et al., 2001; Booth et al., 2003; Eden et al., 2004). The dorsal left inferior parietal area, on the other hand, has been connected to phonological memory (Smith and Jonides, 1999; Ravizza et al., 2004), a function that would be required by syllable-level comparisons involved in the studies reviewed by Tan, Laird et al. (2005).

We can conclude that a universal reading network will have to allow for some variations. Parts of the network are used in both alphabetic and non-alphabetic reading, but non-alphabetic reading makes use of additional areas in all three general subsystems (posterior, temporal-parietal, and frontal) and makes less use of some of the areas used in alphabetic reading. Bilateral areas are recruited for visual processing. Different or partially overlapping temporal-parietal and frontal areas are recruited for phonological (and perhaps semantic processing). Adding to the picture is that although Chinese readers show similar activation patterns for characters and pinyin (alphabetic writing), characters show more bilaterality, including in posterior areas (Fu et al., 2002).

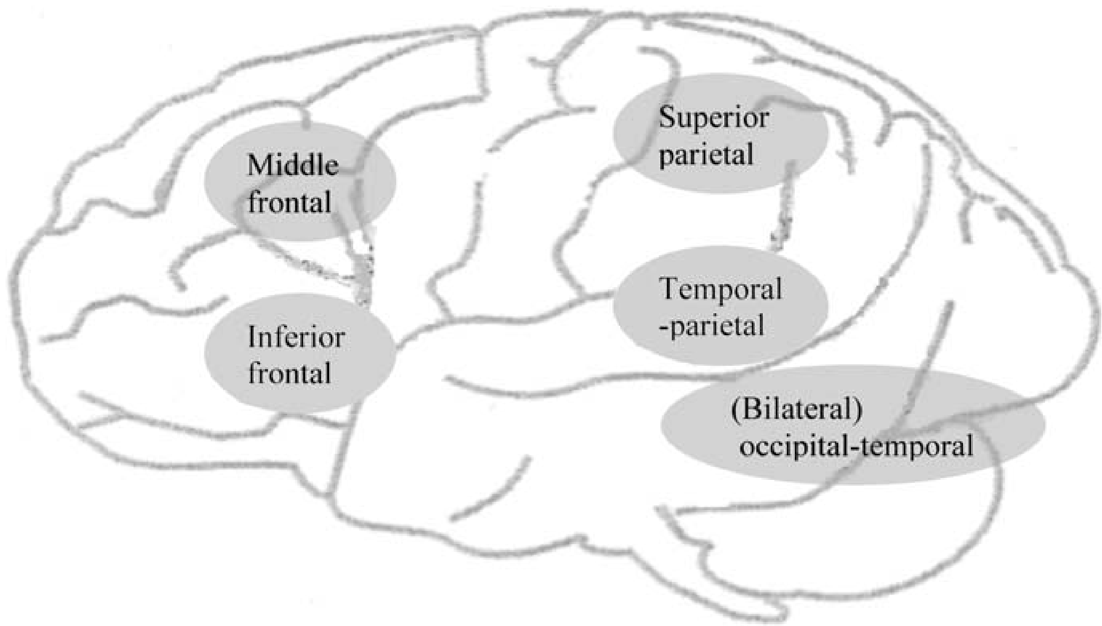

Figure 1. A coarse schematic of the left hemisphere (LH) reading network for Chinese reading showing points of departure from the alphabetic reading network. Occipital and occipital-temporal areas include the left fusiform that is important in alphabetic reading, while adding right hemisphere (RH) areas to form a bilateral character recognition system. The left middle frontal area is distinctive for Chinese reading, whereas the part of the left inferior frontal gyrus that is said to support assembled phonology in alphabetic reading has a reduced function in Chinese. The left temporal parietal area important for alphabetic phonology is not usually found to function in Chinese, which uses the phonological memory function of the superior parietal areas. Each subsystem contains additional subsystems that could be functionally distinct.

The role of the LMFG

If the LMFG has a role in reading that is distinctive for Chinese, the question is: Why? Although the answer is far from clear, there are some plausible conjectures. One is the covariant learning hypothesis, proposed by Tan, Laird et al. (2005), following general proposals that the procedures for learning to read tune the brain systems that support skilled reading (Booth et al., 2001; Kochunov et al., 2003; McCandliss et al., 2003; Booth, Burman, Meyer, Gitelman, Parrish and Mesulam, 2004). Children learning to read an alphabetic writing system either explicitly or implicitly learn to take account of the phonemic structure of speech. This supports the learning of grapheme–phoneme connections and accounts for the high correlations between phonemic awareness and learning to read. This learning procedure forges connections between speech and print, and leads to the tuning of a brain system that links the auditory mechanisms used in speech to the visual mechanisms used for print. The superior temporal gyrus, located near primary auditory areas, develops as this linking system in alphabetic reading.

In Chinese, the procedures for learning are slightly different. Although all writing systems connect to spoken language, the details of this connection are critically different, and characters encode whole syllables. A consequence of this is that the phoneme-level of speech is less accessible to Chinese children (Leong et al., 2005), reducing the role of analytic phonology compared with alphabetic learners. Second, because of the many homophones in Chinese, the syllable pronunciation of the character does not determine its meaning. For this the character is needed, and children learn to use the character in reading for meaning. Third, Chinese children, unlike alphabetic learners, spend a great deal of time copying single characters. Tan, Spinks et al. (2005) found that children's reading ability in Chinese is more strongly related to handwriting skills than to phonological awareness. These three facts suggest that in learning to read Chinese, character forms – the visual-spatial layout of the strokes and the radicals – play a critical role in learning to read. This role is weaker in alphabetic reading.

Thus, learning to read Chinese is based on the acquisition of specific character forms rather than generalized decoding procedures. The LMFG supports the identification of these forms, perhaps by representing character writing, perhaps by supporting a visual memory of the character, or perhaps by supporting the integration of character form with meaning and pronunciation. This last possibility is suggested by the lexical constituency model, in which word identification occurs along independent parallel pathways (Perfetti et al., 2005). One clue to specifying the role of LMFG in reading may be the evidence linking the LMFG to memory and/or executive functions. For example, Courtney et al. (1998) found that the left middle frontal gyrus was involved in spatial working memory (BA 46) and face working memory (BA 9). Verbal working memory (Petrides et al., 1993) and central executive functions (D'Esposito et al., 1995) may also be linked to the LMFG. More research is needed to identify the critical function of the LMFG in reading Chinese. The hypothesis that the brain acquires a reading network that is tuned to the procedures of learning provides a framework for identifying this function.

The system accommodation hypothesis

Are the procedures for reading the new writing system assimilated into the procedures of the existing reading network? Or does learning the new writing system force an accommodation to new procedures? The facts, of course, could be that there is some of each.

Assimilation is the default, the path of least resistance. For a Chinese reader, assimilation says try to read English as if it were Chinese; for an English reader, try to read Chinese as if it were English. Put this way, one can see immediately that total assimilation is unlikely to work, unless what seems to be dramatic differences between the systems are not represented by the brain. The accommodation hypothesis (Perfetti and Liu, 2005) may apply to those circumstances in which what is required by the new writing system exceeds what can be assimilated by the old.

With these contrasting alternatives, we review below studies of ERP and fMRI that we have carried out on Chinese bilinguals and American English speakers learning Chinese. ERP studies can provide information on time course of reading processes, allowing inferences about the emergence of orthographic, phonological, and semantic components of word identification (Bentin et al., 1999). ERPs can also provide coarse spatial information about neural generators, complementing the finer grain spatial information provided by fMRI.

An ERP study of Chinese–English bilinguals

Because bilingual speakers somehow represent two languages in a single brain, they allow cross-language and cross-writing-system comparisons in a single reader. Liu and Perfetti (2003) studied Chinese–English bilinguals, making scalp recordings while the subjects performed a delayed naming task, once in their native Chinese and once in English. The variable (mean, one second) delay between the presentation of the word and the signal to pronounce it allows ERP records to expose orthographic and phonological components that accompany word identification and response preparation.

Liu and Perfetti (2003) tested three hypotheses about word reading, all of which were confirmed: (1) Word frequency effects would be observed in each language as early ERP components that reflect orthographic processing; (2) writing-system–language differences would be observed in early ERP components that reflect initial visual-graphic encoding; and (3) phonological processes would be observed in speech motor areas as the reader prepared a pronunciation, and these would occur earlier in the native language than in the second language.

The grand average ERP waveform for each of the four experimental conditions recorded from a single electrode (the vertex electrode, Cz) is shown in Figure 2.

Language differences appeared quickly (as did frequency effects) and unfolded rapidly. Chinese and English were different within 150 ms of exposure to a

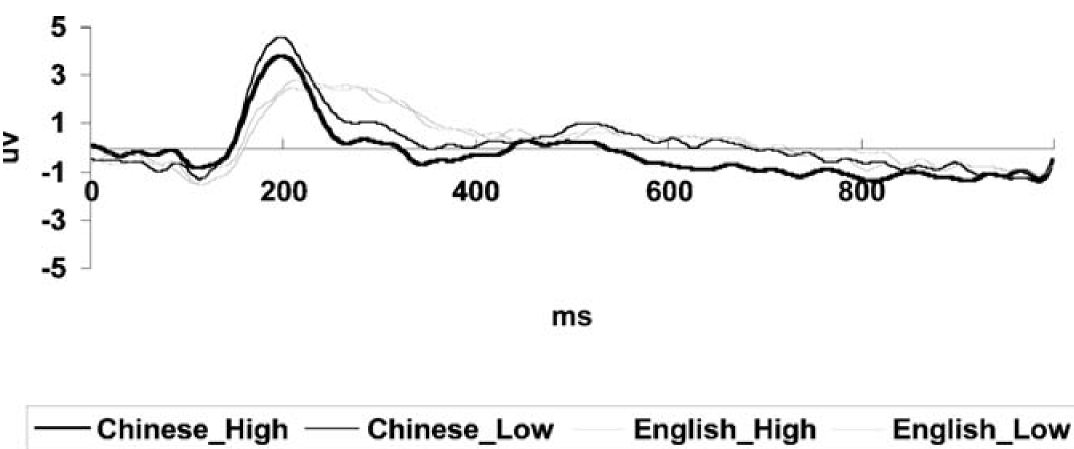

Figure 2. ERP bilingual results: waveform (at electrode Cz) from the onset of the target word read by Chinese–English bilinguals. Note that native language words, Chinese characters, produced an earlier peak of higher amplitude at 200 ms, compared with English words. Based on Liu and Perfetti, 2003.

word, and the peak latencies of the N150 and N250, two of the significant components, occurred earlier for Chinese than English words. The N250 signaled frequency differences in both languages, and the English frequency effect continued to be observed at 450 ms (N450). Given our discussion of the Chinese bilateral posterior system, it is interesting that, according to source analysis, this frequency effect (more negative for low frequency English words) was generated in the right hemisphere occipital area (BA 18). The source analysis also showed that Chinese produced left lateralized visual areas that overlapped those found in English fMRI and PET studies (Fiez and Petersen, 1998).

There were also some language-specific patterns observed in the source analysis. At 150 ms, Chinese produced left occipital activation in BA 17. At 200 ms, the activation source had shifted to right occipital areas (BA 18). Finding right occipital activation for Chinese characters converges with fMRI results reviewed in the preceding section. The temporal oscillation pattern, which can be observed in ERP but not fMRI methods at this time-scale, is especially interesting. As a speculative interpretation, this pattern of left-then-right occipital areas for characters may reflect a rapid (within 50 ms) temporal shifting between left hemisphere processes (e.g., high spatial frequencies for stroke patterns) and right hemisphere processes (e.g., global shape and spatial relations) that in a broader time-frame could be thought of as parallel.

Frequency effects for both languages were present at 250 ms in the main ERP analysis, and the source analysis suggested differences even at 100–200 ms. High frequency English words, as in PET and fMRI studies, showed only left occipital sources, but low frequency words produced bilateral sources. This bilateral activation pattern may reflect the "Chinese mode" of reading, procedures used when Chinese-dominant readers identify either Chinese characters or low frequency English words. Another timing observation: at 250 ms, there was more activation for high frequency words in a left superior frontal area (BA 6) at a time when low frequency words were still activating visual areas. This left supplementary motor area has been found in both English and Chinese experiments to be related to articulatory preparation (Fiez and Petersen, 1998; Tan et al., 2000). Thus, our Chinese bilinguals could begin to prepare the pronunciation of high frequency Chinese words as early as 250 ms. Activation then shifted for both high and low frequency Chinese characters to the right prefrontal area (BA 10), an area identified in imaging studies of both English and Chinese (Fiez et al., 1999; Tan et al., 2001). This result adds to the conclusion that Chinese may produce more right hemisphere processing than English (Tan et al., 2001).

In summary, the ERP picture complements conclusions about the reading network gained through fMRI and PET by adding time stamps to components of the network: the temporal pattern begins with posterior regions that support visual analysis and word form identification activated early (within 200 ms) and then moves to frontal regions. The duration of visual area activation depends on familiarity, with low frequency words producing 50 ms longer activation in occipital areas than high frequency words for both languages. Furthermore, visual area activation persists longer for the less familiar (English) writing system, especially for low frequency words, which produce bilateral activation similar to what is observed for Chinese characters.

An ERP study of learning to read Chinese

In an experiment that applied ERP directly to the learning of a new writing system, we studied college students enrolled in a University of Pittsburgh Chinese course that taught both spoken language and reading (Liu, Perfetti and Wang, 2006). Twenty students had completed their first term (12–15 weeks learning, 12 hours a week) and fourteen had completed two terms. This allowed a comparison of ERP indicators of word processing at two levels of elementary skill in Chinese.

In a delayed naming task, four experimental conditions were defined by language and frequency within the course curriculum of 6248 character tokens: Chinese characters, high frequency (43.35) and low frequency (9.675); English, high frequency (136.1/million) and low frequency (1.2/million) (Kucera and Francis, 1967). The radical and stroke numbers were matched between high and low frequency Chinese characters. The word lengths of high and low frequency English words were matched.

The results of temporal principle components analyses for each term were used as dependent measures in ANOVAs to test differences among experimental conditions. These results confirmed differences between Chinese and English that were observable in P200/N200 (positive at frontal and negative at occipital) and N400 components. Figure 3 shows the results across two terms at a frontal and occipital site a 200 ms, along with the central electrode at 400 ms.

In the first term, the P200/N200 component was larger for Chinese than English materials at both frontal and occipital electrodes. At the end of the second term, the larger P200 for Chinese was observed at frontal but not occipital electrodes. For curriculum-defined frequency, the N200 was larger for high frequency than low frequency Chinese characters only at the first term. We suggest that the reduction in occipital differences across one term of learning may be a reflection of the rapid learning of character forms, which we have observed also in learners' behavioral results on lexical decisions (Wang, Perfetti and Liu, 2003).

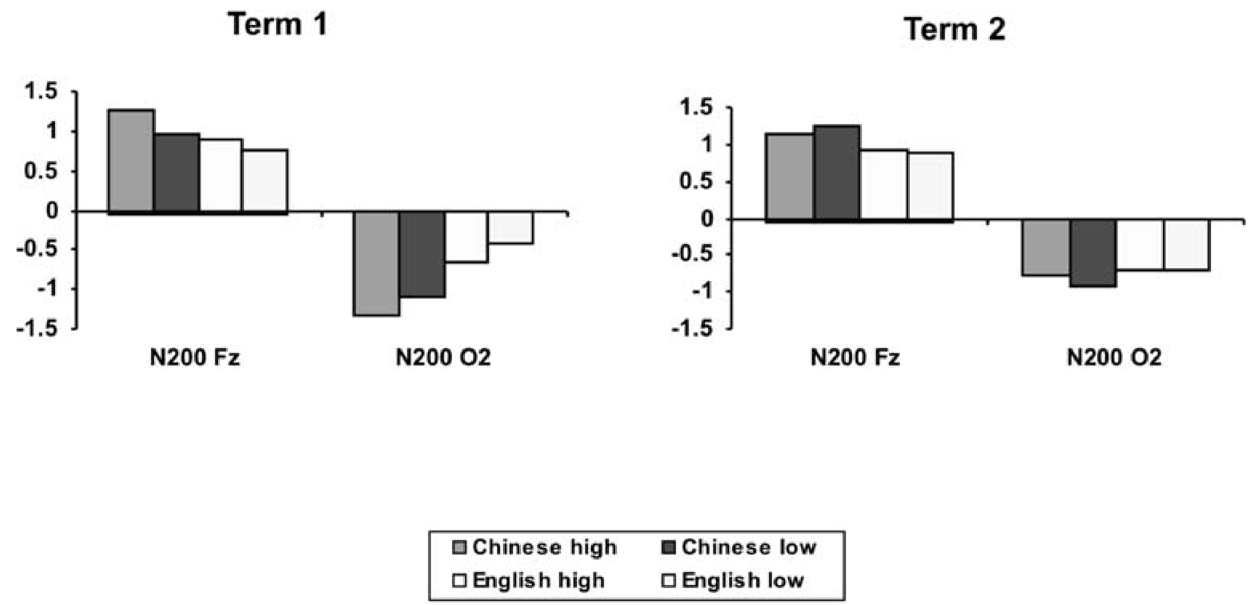

Figure 3. ERP Learning results: component scores from PCA analyses at two electrodes, frontal central (Fz) and right occipital (O2), at 200 ms. During the first term of learning Chinese, Chinese characters evoke differential responses for Chinese and English and for high vs. low frequency characters that are attenuated at term 2. Note for example, the high negativities for Chinese at the right occipital electrode at term 1 and their reduction at term 2. Chinese frequency effects disappear at term 2 across both sites. Based on Liu, Perfetti and Wang, 2006.

We can link some of these ERP results empirically to fMRI results and theoretically to the lexical constituency model (Perfetti et al., 2005). First consider the general interpretation of the P200/N200 observed in the learning study. Liu, Perfetti and Hart (2003) found that the P200/N200 is sensitive to orthographic processing: its amplitude was reduced when a target Chinese character was preceded by an orthographically similar prime character, an effect Liu et al. (2003) attributed to the pre-activation of orthographic form of the target. In another study (Liu and Perfetti, 2003), Chinese–English bilinguals performed a delayed naming task. The amplitude of P200/N200 was larger for English (L2) than Chinese (L1). The P200/N200 in both studies showed a distribution similar to that of the learning study: positive at frontal and central electrodes, and negative at occipital electrodes.

The neural generators of the P200/N200 effect (confirmed by source analysis) can be linked to the conclusions reached about the visual word form area (the left occipital/temporal fusiform region) identified in fMRI research. In Chinese reading, the right as well as the left occipital/fusiform regions are involved (Bolger et al., 2005; Tan, Laird et al., 2005). This general picture appears also in our ERP learning study, where the P200/N200 for Chinese was significantly larger than for English at right occipital and left and middle frontal electrodes, matching within-study fMRI comparisons of English and Chinese reading by Tan et al. (2001) and Tan et al. (2003).

Turning now to how the P200/N200 links to the theoretical model of Chinese reading, consider that the learning study found larger amplitudes at P200/N200 for Chinese learners. We take this to indicate that more visual processing (occipital) and lexical processing (frontal and central) were needed for Chinese for these first-term learners. By the second term, visual processing differences (occipital electrodes N200) had been reduced, while lexical processing difference (frontal electrodes P200) persisted. This separation of visual learning from character identification links to the lexical constituency model (Perfetti et al., 2005) through the threshold mechanism that the model assumes for character identification. Only when a character's orthographic representation reaches threshold is there activation along links to phonology and semantics.

This interpretation receives support from Liu, Wang and Perfetti (in press), who found significant orthographic priming for the first-term learners. In the lexical constituency model, orthographic priming can occur only before the character threshold for identification is reached. (Beyond the threshold, character-level orthographic inhibition and phonological and semantic facilitation occurs.) Thus, we can infer that orthographic priming occurred at the first term because the prime character, which was exposed for 500 ms, had not reached the learners' high threshold. When learners were tested at the second term, however, no orthographic priming was observed, suggesting that their orthographic threshold had been lowered below 500 ms. Instead, semantic priming and (non-significant) phonological priming occurred, consistent with the models' assumption that these effects are possible only after the orthographic threshold is reached.

These behavioral results across two terms of learning show a parallel to the ERP learning results we summarized above: the occipital N200 showed a marked Chinese–English difference in latency and amplitude at the first term that was reduced by the second term, consistent with the behavioral finding of first-term orthographic priming followed by no orthographic priming in the second term (Liu, Wang and Perfetti, in press). The convergent conclusion across these independent behavioral and ERP studies is that learning over two terms of study brought about gains in character familiarity that reduced the amount of visual processing required to reach a threshold of character identification.

A second ERP learning result concerns the N400, widely taken as an indicator of semantic and phonological processing (Kutas and Hillyard, 1980; Rugg, 1984). We observed an N400 for priming with English materials but not with Chinese (in either first or second term), perhaps implying that the learners' semantic processing of Chinese characters was too slow or too variable to be observed within the 1000 ms measuring range of the ERP experiments. Here the behavioral results do not converge so clearly, because Liu, Wang and Perfetti (in press) found semantic priming at the 500 ms SOA for the second-term (but not first-term) learners. However, this is a relatively long time window compared with the 85 ms SOA at which native speaker semantic priming has been reported (Perfetti and Tan, 1998) and may suggest a more conscious, less automatic mechanism that is less likely to produce an N400. Furthermore, the relatively long lag of an N400 (relative to the less than 100 ms it requires to identify a word) may make it harder to detect when word identification is very slow. Overall, it appears that by both behavioral and ERP indicators, semantic and phonological activation are relatively weak and variable at this level of learning, compared with orthographic familiarity.

In summary, ERP studies show differences in processing English and Chinese, both when the readers are Chinese–English bilinguals and when they are English speakers learning Chinese. Even for a skilled bilingual, Chinese and English reading produce different temporal patterns across different posterior and frontal sources, including the familiar pattern of right hemisphere activation in visual areas. For learners, we can see changes over two terms of learning, including a reduction in the right hemisphere visual activation areas as Chinese characters become more familiar. The ERP results are consistent with the system accommodation hypothesis in showing language differences in temporal patterns and coarse-grain localizations for both skilled readers and learners.

An fMRI study of classroom learners

According to the system accommodation hypothesis, the writing system imposes constraints on processing that the brain must accommodate. One possible constraint for Chinese arises from the spatial analysis that is needed by characters but not by linear alphabets. The spatial features could include the global shape of characters (Liu, 1995; Yeh and Li, 2002) and also the relationships between radicals. Figure 4 illustrates the spatial demands of both a simple character and a compound character.

The Chinese reader learns to see radicals in left-right, top-down, and inside-outside configurations. And the positioning of the radical is functional in identifying the character. If right hemisphere visual areas are especially tuned for low spatial frequencies (Christman, Kitterle and Hellige, 1991; Hellige, and Bauer Scott, 1997), then we can expect that the low spatial frequencies defined by radical relationships will recruit right hemisphere visual areas. These areas would complement the function of the left fusiform gyrus, which is important for both alphabetic and Chinese reading. We can hypothesize that this is because the left hemisphere system is needed to handle high spatial frequencies of both alphabetic letters and character strokes (Liu and Perfetti, 2003). We can further hypothesize that the spatial demands of characters are immediately appreciated by a learner, and that the brain accommodates to these demands by recruiting visual resources in the right hemisphere that are not needed in alphabetic reading.

In one of two fMRI studies that bear on this question, Nelson et al. (2005) examined activation patterns in posterior visual area brain structures in Chinese–English bilinguals and English-language learners of Chinese. The main question is whether learners show evidence that they recruit new brain regions for visual processing of the second language.

We compared eleven Chinese–English bilinguals who were native Chinese speakers fluent in English with six English learners of Chinese who had completed a year of Chinese at the University of Pittsburgh. fMRI scans were taken while the students (passively) viewed Chinese characters (composed of two radicals), pseudo-characters (formed from two real radicals with at least one in an illegal position), and non-characters (real strokes were combined to make two pseudo-radicals). The English stimuli were English words, English pseudo-words (three-letter CVCs), and consonant strings.

The critical results for word perception areas are that English speakers learning Chinese showed only left fusiform activation for English-like stimuli, but bilateral fusiform activation when viewing Chinese-like stimuli, whereas the left fusiform gyrus showed significantly greater activation for both languages relative to baseline, English speakers learning Chinese show significantly

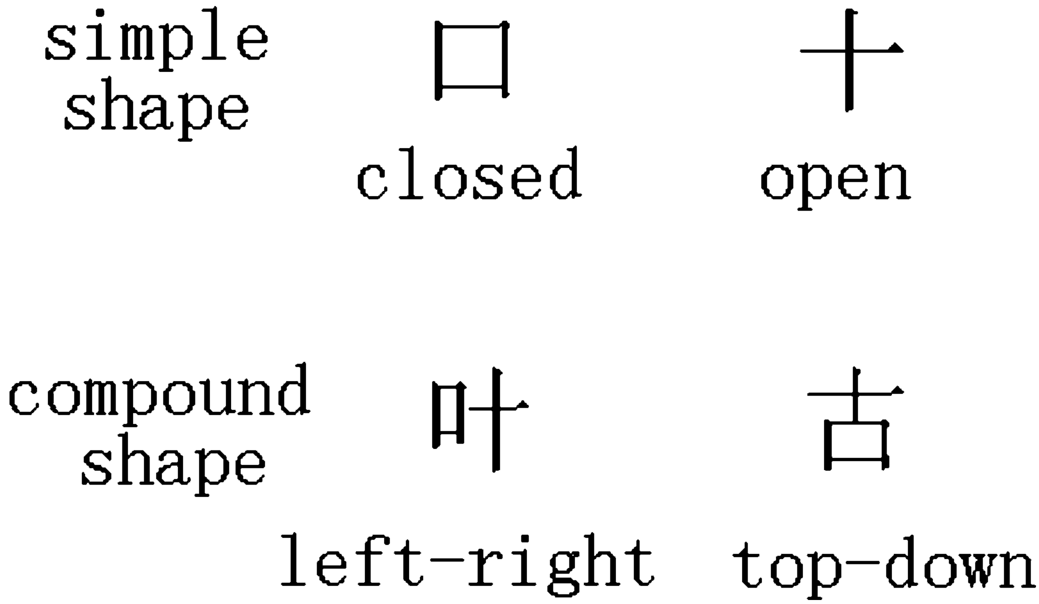

Figure 4. Illustration of visual requirements of Chinese characters. For simple characters (top), the global shape can be distinctive. For compound characters (bottom), the spatial relations between radicals are important. Both cases may be especially suited for visual areas that respond to low spatial frequency information.

more activation for Chinese than English in the right fusiform region. Figure 5 shows this result.

Thus, in agreement with the system accommodation hypothesis, the system for graphic processing depends on the writing system, even for learners. The reading network that has worked for English is supplemented by areas that are specifically adaptive for the properties of Chinese writing.

The Nelson et al. (2005) study produced an interesting asymmetry, however. Whereas alphabetic readers learning Chinese showed the Chinese pattern for occipital and occipital-temporal areas, Chinese native speakers for whom English was a second language did not show the alphabetic (left hemisphere dominant) pattern for English. As can be seen in Figure 5, they showed the Chinese pattern of bilateral occipital and occipital-temporal activation for both Chinese and English. Thus, whereas alphabetic readers showed the accommodation pattern, Chinese readers showed the assimilation pattern, with their native language reading network supporting their second language reading. This conclusion converges with that of Tan et al. (2003).

We cannot say whether this assimilation represents a skill factor or a writing-specific factor. Although our Chinese bilinguals were skilled in reading English, perhaps with further gains in skill, they would show the alphabetic pattern rather than the Chinese pattern for reading. However, we think it is possible that assimilation is actually writing system dependent. A system developed for reading Chinese, in principle, can absorb an alphabetic system. (The reverse pattern, assimilating Chinese into alphabetic reading may be impossible for a skilled reader who is actually using the alphabetic principle.) This possibility implies that Chinese readers at the level of skill represented in the Nelson et al. (2005) study may read English with a greater use of visual shape or global word features and less use of analyzed letter and letter–phoneme constituents. This possibility has been suggested by Wang, Koda and Perfetti (2003), based on their finding that Chinese–English bilinguals showed less phonological coding in reading English compared with comparably skilled Korean–English bilinguals, who could be expected to transfer an alphabetic strategy from their first language to English.

Although the focus of the Nelson et al. (2005) study was on the posterior areas that support the visual processes of word reading, Chinese learners also showed higher activity for Chinese than English in some additional areas, including a left middle frontal region near BA 46 that is close to the "Chinese reading area" in LMFG identified for native Chinese readers. This suggests that accommodation extends beyond the visual areas to frontal brain areas that function at the lexical level.

A laboratory study of learning with fMRI

If the LMFG represents a greater demand for simultaneous representation of form and meaning for Chinese character processing – a possibility implied by a theoretical analysis of Chinese reading (Perfetti et al., 2005) – then controlling the lexical constituents that are learned could help to interpret its function in reading. Liu, Dunlap, Fiez and

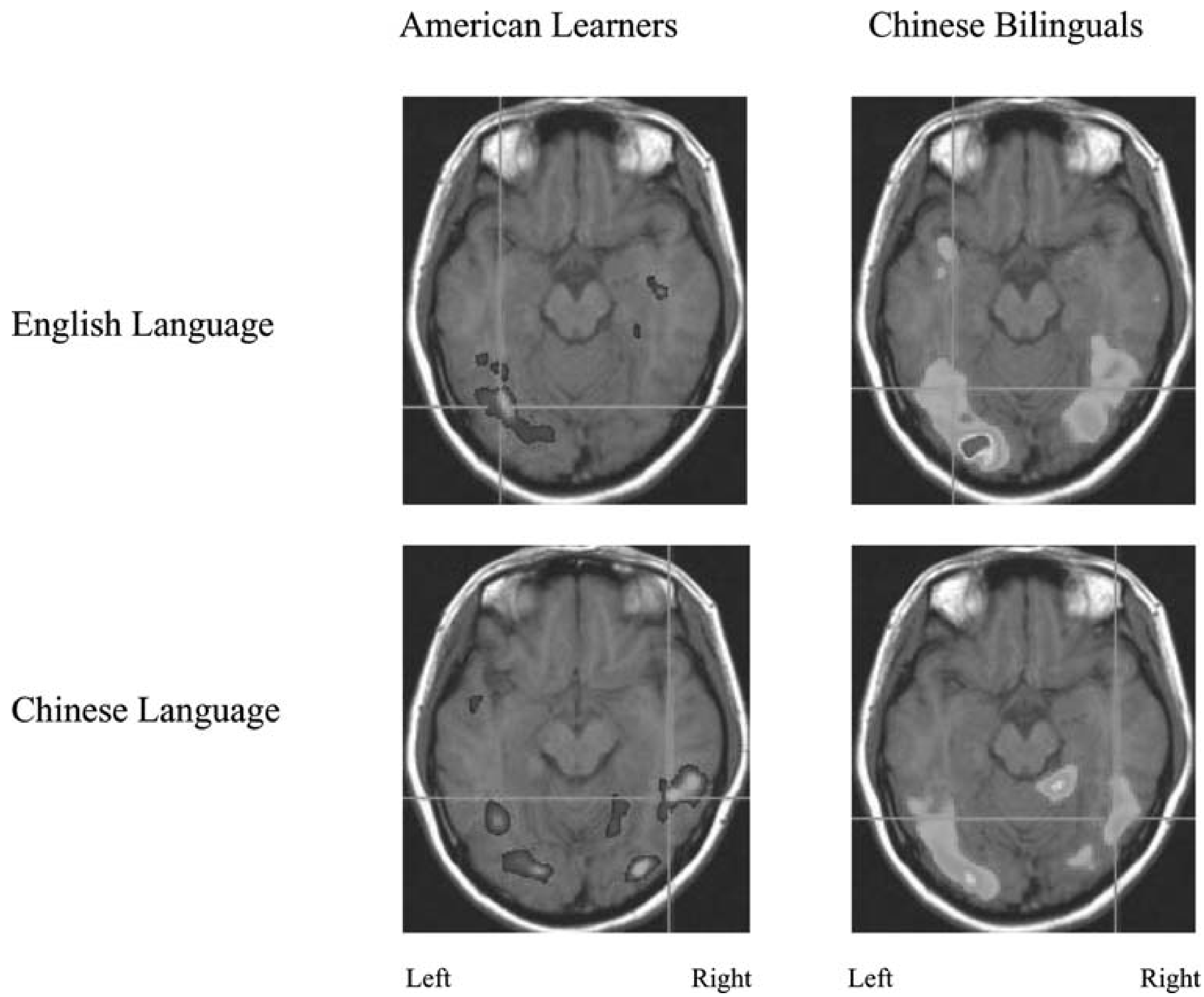

Figure 5. Horizontal views showing comparisons of classroom learners and native Chinese reading Chinese and English. Learners show a bilateral occipital and fusiform "Chinese" pattern for Chinese and a standard alphabetic pattern for English. Chinese natives show a Chinese pattern for both English and Chinese. Talairach coordinates for peak voxel activations are as follows. English learners of Chinese: English stimuli –35, –65, –12; Chinese stimuli –43, –44, –9; Chinese bilinguals: English stimuli –33, –56, –12; Chinese stimuli –43, –54, –12. Based on Nelson et al., 2005.

Perfetti (in press) carried out such a study with volunteer learners, who came into the laboratory to learn 60 Chinesecharacters.

Volunteers learned the characters in the laboratory and through self-paced home study through a web-based tutor that presented characters along with audio recordings of pronunciations and translations (depending on the condition). To control the lexical constituents acquired by the learner, Liu, Dunlap et al. (in press) taught one group (the meaning group) only the character's English translation (but no Chinese pronunciation). For another group (the pronunciation group), they taught the character's Chinese pronunciation, but provided no meaning. The third group was taught both pronunciation and meaning, providing the full set of lexical constituents.

The results showed further evidence for accommodation. During passive viewing, learners showed two activation patterns that are distinctive to reading by native Chinese speakers. First, they showed the bilateral activation pattern for occipital and fusiform regions relative to both baseline fixation and to English. The areas of activation were close to those found in the Nelson et al. (2005) study, although the peak activation in the fusiform was more posterior. Second, learners showed greater left middle frontal activation (BA 9), relative to both fixation and to English words. The right middle frontal gyrus also showed increased activation for Chinese, as can be seen in Figure 6.

Because learning either pronunciation or meaning was sufficient to produce LMFG activation, the results do

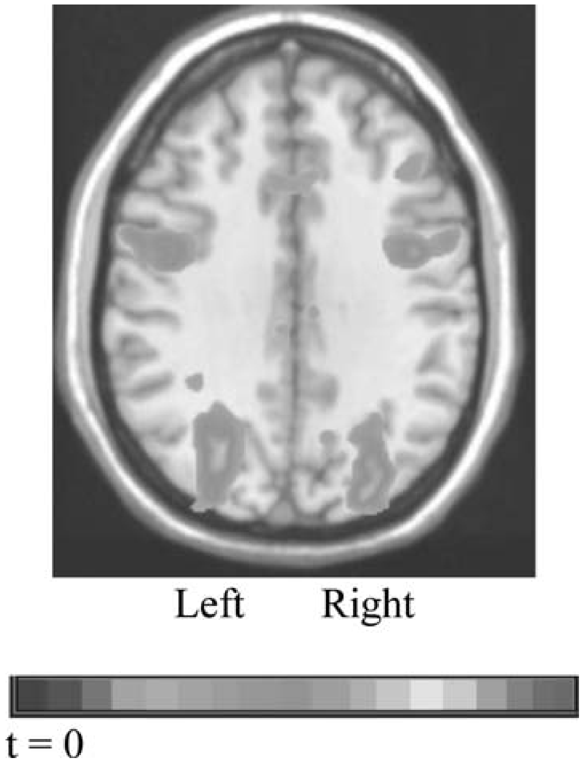

Figure 6. Comparison of laboratory learners showing activation in both left and right middle frontal areas for Chinese, relative to baseline. Horizontal view is at z = 33. Peak activations for learned Chinese characters relative to baseline are left hemisphere (LH) –49, 12, 33 and right hemisphere (RH) 44, 14, 33 (Talairach). Adapted from Liu, Dunlap et al., in press.

not support the hypothesis that the LMFG is needed to hold simultaneously the three lexical constituents (orthography, phonology, and meaning). A second hypothesis is also not supported: that the LMFG is specifically responsive to character writing, because subjects were not asked to write characters during learning. Rather than supporting a more specific hypothesis about the LMFG, the results instead are consistent with a more general hypothesis related to integration: that the left middle frontal area supports a memory for the character so that a constituent stored with the character can be retrieved.

However, an area in LMFG showed more activation in the pronunciation and meaning group than in the other two groups. This area is somewhat superior and medial compared to the area that produced peak activation across all the groups. This suggests that the LMFG has some functional differentiation in character reading, at least for learners. One area seems to support the reading of a character whether it links to phonology or meaning. Another, the more superior area, may become involved when both meaning and phonology are involved or more generally when there are multiple associations to a character. However, because these results were found in a passive viewing task, there is no reason to conclude that explicit retrieval of either phonology or meaning is necessary.

Conclusions from learning studies

The behavioral, ERP, and fMRI studies show complementary parts of an overall picture of writing system accommodation when alphabetic readers begin to learn Chinese. The behavioral studies show rapid progress (one term) in learning to distinguish character forms from character-like forms (Wang, Perfetti and Liu, 2003) and a slower progress (two terms) in learning pronunciations and meanings (Liu, Wang and Perfetti, in press). Within these same time frames, the ERP studies provide an indicator of an initial high level of RH visual activation (N200) that reflects the rapid form learning and a frontal indicator (also at 200 ms) that may mark the effort of retrieving pronunciation and meanings. (An absence of an N400 may further mark the slowness of acquiring efficient meaning retrieval.) These indicators generally correspond to results of behavioral studies (Liu, Wang and Perfetti, in press).

The learning studies produce a consistent convergence with both fMRI and ERP studies of native Chinese readers in showing bilateral occipital and occipital-temporal activation for learners as well as native speakers. Finally, the fMRI learning studies show a remarkable convergence with fMRI studies of native speakers in identifying the importance of the left middle frontal gyrus for reading characters. That the LMFG is important even in learning by relatively unskilled second language readers suggests that the system accommodation hypothesis applies not only to the visual areas that respond to superficial differences in writing, but to frontal areas that carry out integrative lexical processes.

General discussion and conclusion

Reading universally involves the mapping of written graphs to units of language. Accordingly, we should expect to find manifestations of this universality in behavioral studies of reading and in studies of the neural correlates of reading. And we do. When we compare alphabetic reading with Chinese, a writing system of maximal contrast for alphabetic comparisons, the results of cognitive-behavioral research show a highly general role for phonology across writing systems; and the results of imaging studies show networks of brain areas that partially overlap across writing systems. However, along with the universals come variations that are imposed by all three dimensions of writing variation – script, orthography, and writing system. These variations produce corresponding differences in the critical details of reading procedures that respond to the visual-spatial properties of the script, the consistency of grapheme–phoneme mappings within the family of alphabetic systems, and the deep mapping features that distinguish one writing system from another. Each of these differences is accompanied by corresponding differences in the neural basis of reading.

Our focus here has been how the brain's reading network compares across English and Chinese. Cognitive-behavioral studies have suggested that phonology, while important in both systems, is implemented in different ways. Comparative ERP and fMRI studies converge with this conclusion in general terms, and suggest some specific possibilities for how the brain's reading network accommodates these differences. Chinese brain imaging studies and meta-analyses of these studies point to several departures from the results of alphabetic studies. One is the bilateral activation of occipital and fusiform regions that support the initial perceptual process of word identification, as opposed to the left-dominant pattern for alphabetic reading. This difference appears to reflect specific spatial demands of Chinese characters, perhaps associated with spatial relations among component radicals.

A second point of departure is the distinctive role of the left middle frontal gyrus (LMFG) in Chinese, a role that has been revealed in nearly every imaging study. Although the exact role of the mid-frontal gyrus remains to be determined, our suggestion is that this part of the Chinese reading network supports a brief but sustained memory for the orthographic form of the character during the retrieval of its associated phonological and semantic constituents. Other differences include reduced roles for both the left inferior frontal gyrus and the left superior temporal-parietal regions for Chinese compared with alphabetic reading.

To this general picture, we add studies of learning Chinese that we have carried out using both ERP and fMRI procedures. We find ERP evidence that characters require more visual processing at the beginning of learning, as one would expect. However, significant gains in experience with Chinese characters appear within two terms of classroom learning, with results showing reduced differences between English and Chinese and between high and low frequency characters. ERP evidence also suggests that semantic processing of characters continues to be slow or weak, even after two terms. These results help support the interpretation of changes with learning of orthographic priming effects and are consistent with the lexical constituency model of reading (Perfetti et al., 2005). In fMRI studies of Chinese learners, two different experiments converge to show activation in two areas that are found in studies of native Chinese speakers: Learners show (1) bilateral occipital and fusiform activation, and (2) activation of LMFG (and also RMFG). This area of LMFG is close to that observed in studies of native speakers. For learners who acquired both phonology and meaning links for the characters, we find an additional LMFG area, slightly superior to that observed for native speakers, which may be involved when both pronunciation and meaning are connected to orthography.

Our learning results are consistent with the accommodation hypothesis, which assumes that the brain's reading network must adapt to features of a new writing system to the extent that those features require different reading procedures. In learning Chinese, the brain's reading network accommodates the script demands of characters by recruiting right hemisphere visual areas that are suited for the global spatial analysis required by the characters. And it responds to the distinctive mapping demands of Chinese, which requires non-mediated syllable-level phonology and meaning to be retrieved, by recruiting the LMFG, which is suited for retaining the character form during lexical processing.

The accommodation process may be asymmetrical, applying to an alphabetic learner of Chinese more than to a Chinese learner of English. We found the Chinese–English bilinguals tend to show the same bilateral activation of visual areas, including the fusiform, when they read English as well as when they read Chinese. We also found some evidence that Chinese–English bilinguals may use frontal Chinese L1 areas for English. This is assimilation rather than accommodation. The interesting implication of this asymmetry is that it is actually Chinese that provides the more universal system for reading. Chinese reading procedures can be applied to English and other alphabetic writing in a way the alphabetic reading procedures cannot be applied to Chinese.

We caution, however, against drawing too strong an inference from this assimilation conclusion. The success of Chinese reading procedures in assimilating alphabetic reading may be limited. Higher levels of second language skill show brain-related as well as behavioral differences from lower levels of skill (Abutalebi, Cappa and Perani, 2001). We should not be surprised to discover a similar result in cross-writing-system reading skill. High levels of L2 alphabetic reading skill for an L1 Chinese reader may arise with experience at alphabetic decoding that requires accommodation to brain structures that serve alphabetic procedures.

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