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Specialization and Universals in the Development of Reading Skill: How Chinese Research Informs a Universal Science of Reading

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Abstract

Understanding Chinese reading is important for identifying the universal aspects of reading, separated from those aspects that are specific to alphabetic writing or to English in particular. Chinese and alphabetic writing make different demands on reading and learning to read, despite reading procedures and their supporting brain networks that are partly universal. Learning to read accommodates the demands of a writing system through the specialization of brain networks that support word identification. This specialization increases with reading development, leading to differences in the brain networks for alphabetic and Chinese reading. We suggest that beyond reading procedures that are partly universal and partly writing-system specific, functional reading universals arise across writing systems in their adaptation to human cognitive abilities.

The scientific study of reading has emerged over 100 years of research, concentrated in two bursts. One was in the late 19th and early 20th centuries and was summarized by E. B. Huey's (1908) masterpiece volume on the psychology and pedagogy of reading. The second began in the 1970s, following a long period of relative quiet after Huey, with studies that revisited word superiority effect (Reicher, 1969; Wheeler, 1970), later exploding to the flourishing science of reading of the present day.

However, the research in this new golden age has been largely studies of reading English. Is it possible that the science of reading thus is really the science of reading English? David Share (2008) reviewed evidence that led him to answer this question in the affirmative: "The idiosyncrasies of English, an exceptional, indeed, outlier orthography in terms of spelling-sound correspondence, have shaped a contemporary reading science preoccupied with distinctly narrow Anglocentric research issues that have only limited significance for a universal science of reading" (p. 584).

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To appreciate this argument from a different perspective, consider Chinese instead of English. Research on Chinese reading is no more (and no less) about reading Chinese than research on reading English is about reading English. In both cases, the writing system imposes specificity on research observations. Studies on reading English are thus first about reading English, and studies of reading Chinese are first about reading Chinese. Their conclusions apply to reading in general to the extent that studies with other writing systems lead to similar conclusions.

Now, putting Chinese and English together, we escape the consequences of Share's conclusion, without altogether dismissing the conclusion itself. (The conclusion is apt only to specific issues, e.g., word identification models containing separate routes for irregular and regular words, nonphonological dyslexia, and the importance of phonemic awareness.) Thus, research on Chinese, because of its high contrast with alphabetic systems, can support or qualify conclusions based on alphabetic systems. And research on English can support or qualify conclusions based either on Chinese or on more consistent alphabetic systems. In fact, research on languages other than English has flourished, allowing comparisons across a wide range of more consistent alphabetic orthographies from the nearly perfectly consistent Finnish and Welsh to the mainly consistent Italian, Spanish, Dutch, and German to the much maligned English. Rounding out the picture is research on the alphabetic-without-vowels Hebrew and the nonlinear alphabetic Korean. The many languages and orthographies of India and South Asia remain less studied, but generally research on reading is much more universal than it was 30 years ago and more universal than implied by Share's argument.

In what follows, we focus on Chinese to illuminate universal and writing-system specific aspects of reading. We seek not just to explain Chinese reading, but also to ask how research on Chinese reading informs universal reading science. First, we review (a) the critical writing system features, from a reading viewpoint, that distinguish Chinese and alphabetic writing; (b) evidence for the unity to be found across these writing systems, despite their diversity; and (c) evidence that writing systems affect the processes of reading and the emergence of reading problems in important ways. The second part of the article examines new work on the neural bases of reading in Chinese and English, arguing that neural specialization develops in response to the demands of the writing system as children learn to read while also following universal pathways.

WHAT MAKES CHINESE WRITING DIFFERENT FROM ALPHABETIC WRITING?

Because many descriptions of Chinese writing are available in writing scholarship (e.g., DeFrancis, 1989) and in reading research (e.g., Perfetti, 2003), we provide only an essential summary here. There are two dimensions of contrast with alphabetic writing: one at the script level, which concerns the visual form of the writing, and one at the mapping principle level.

At the script level, Chinese departs from the linear layout of most alphabetic writing (Korean is an exception) in having a rectangular layout of its graphic components. Components of characters are arranged side by side, top to bottom, or inside–outside. For example, the same two radicals, 口 and 木 can be combined to make the single-character words 杏 (apricot), 呆 (stupid), and 困 (sleepy). 木 can also stand alone as the character for tree. Even more complex characters can be formed by vertically or horizontally inserting a radical between two others. For example, 鼻 (nose) is formed by combining the component radicals 自, 田, and 廾 vertically.

This Chinese–alphabetic contrast in visual appearance could matter for reading. For example, character reading may include configural visual processing analogous to the configural information used in recognizing faces (Young, Hellawell, & Hay, 1987). This configural information, which defines spatial relations (e.g., up–down, right–left) between components, contrasts with the denser visual information carried by stroke sequences within a component. The stroke sequences contain high spatial frequency information, whereas the configural relations among components contain low spatial frequency information. All writing contains a range of spatial frequencies, but Chinese, more than linear alphabetic writing, uses configural (low spatial frequencies) information to differentiate its written morphemes. Accordingly, visual processes tuned to low spatial frequencies could be especially useful for Chinese in a way they are not for alphabetic reading. In English, the difference between *deer* and *dear* is one of high spatial frequencies, as is the Chinese difference between 凡 and 风. However, the difference between 杏 (apricot) and 呆 (stupid) is one of low spatial frequencies.

The second dimension of contrast is the principle by which graphic units are mapped to linguistic units. Unlike alphabetic writing, Chinese writing does not reflect the segmental structure of speech (Leong, 1997; Mattingly, 1987). Whereas the *b* in *bike* maps to the initial segment (/b/) of the spoken word, a Chinese character contains no representation of phoneme segments, instead mapping to a whole morpheme syllable. The many compound characters can contain cues to both pronunciation (phonetic radicals) and meaning (semantic radicals). The locations of the phonetic (usually right side in left–right configurations) and semantic radicals (usually left-side) are predictable enough to be useful. Chinese children learning to read gain implicit knowledge about the function and location of phonetic radicals (Shu, Anderson, & Wu, 2000) and information about these components can become functional in character identification. Indeed, it is possible to model learning to read characters by using such information within the same kinds of general-purpose connectionist learning networks that model learning to read English (Yang, McCandliss, Shu, & Zevin, 2009). However, the phonetic often provides no more than the onset or the rime of the correct syllable and provides the whole spoken syllable (not counting tone) for less than 50% of compound characters (De Francis, 1989; Zhou, 1978). Thus, Chinese is a system of coarse-grain units that provide syllable level rather than phoneme-level mapping, with relatively low reliability of cues to pronunciation.

UNITY ACROSS WRITING SYSTEMS

Given these two-level contrasts between alphabetic and Chinese writing, which reading processes are general enough that they are engaged by both writing systems? Which processes are less general, applying to one writing system more than the other? These questions are more complex than they appear at first glance, however. In the case of phonological reading processes, the question must take into account the units of language and the units of the writing system. Is a phonological process the same when syllables are the units as when phonemes are the units? Is phonological awareness the same?

One effect of thinking comparatively is that we notice some of the misleading expressions that were part of English-only research. “Phonological awareness,” for example, has mainly been about phonemic awareness in English research, even though the distinction between phonemic awareness and syllabic awareness was critical in the early observations of prereaders by Liberman, Shankweiler, Fischer, and Carter (1974). Similarly, research on English “phonological processes” in word reading has been mainly about letter-to-phoneme conversion and when it occurs relative to “lexical access.” The broader idea—that spoken linguistic forms are part of the identification process—has been less visible because of this focus on “prelexical” phonemic processes. An obvious corrective is to refer to “phonemic awareness” and “phonemic processes” where, as in English, phonemes are the objects of study, reserving “phonological” for a noncommittal or multilevel phonology.

Other nonuniversal conclusions from English-based research arise less from misleading language choices than from invisible assumptions about writing systems and languages. Because of English writing conventions, words are well defined (the letter strings that are bounded by spaces) as inputs for reading. Word identification research thus focuses on those processes that operate on the input of a space-bounded letter string. However, not all writing presents such neatly packaged word objects. Chinese words vary from one character to three and even four characters, with each character mapping to a syllable-morpheme. A character could be a single character word, the first character of a two-character word, or the first-character of a three-character word. This suggests a more complex set of word identification processes that include character string parsing and context dependent character-to-word matches. Word identification may be a universal part of reading, but the processes that bring it about go beyond those studied in English.

At first glance, these observations might seem to argue against the prospects of universals. On the contrary, they merely demonstrate that it is a mistake to assume that processes observed in any one system are universal. In this respect, they converge with observations made by Share (2008) on the risks of English-only research. The goal is to take a step back from a single system and ask what we can see across systems that might be universal.

Universal Hypotheses

In fact, comparisons across orthographies and writing systems have been in the literature for a number of years. For example, the orthographic depth hypothesis (ODH; Katz & Frost, 1992) aimed to explain how variations among orthographies in the transparency of their grapheme– phoneme mappings affect word-reading processes. Shallower (transparent) orthographies such as Serbo-Croatian and Italian could be read by uniformly applying sublexical grapheme-to-phoneme conversion procedures, whereas deeper orthographies additionally required lexical procedures to access words from whole word orthography.

The universal phonological principle (UPP) proposed about the same time by Perfetti, Zhang, and Berent (1992) was the explicitly universal claim that reading engages phonology at the earliest moment and smallest unit allowed by the writing system. The UPP thus united the Chinese and alphabetic writing systems at the functional principle level. Specific mapping differences across systems affect fine-grain reading procedures but as part of a universal dependence of reading on spoken language. Thus, Chinese maps graphs to syllabic morphemes and alphabets map graphs to phonemes, and this difference produces differences in the units of language that are activated at the earliest stages of reading. The big-picture conclusion is that reading in both systems involves phonology.

Finally, in what might be considered a refined combination of the UPP and the orthographic depth hypothesis, Ziegler and Goswami (2005) hypothesized that reading procedures assemble phonology according to the grain size of the orthography. The small grain size of alphabets supports a phoneme-level assembly of phonology, whereas the larger grain size of syllabaries supports syllable-level assembly. Each of these overlapping ideas—orthographic depth, universal phonology, and grain size—has been the object of experimental testing and has guided thinking about what is universal and what is particular across writing systems and orthographies.

In light of this history of comparative study and universal hypotheses, it hardly seems credible to claim that reading research continues to suffer from chronic English-centrism. Instead, it has gradually recovered and now flourishes as an internationally grounded universal reading science.

ENGLISH–CHINESE COMPARISONS: UNIVERSALS AND WRITING SYSTEM CONSTRAINTS

The comparative study of Chinese reading is a focus on how reading procedures are shaped by universal tendencies in combination with writing system constraints. Other articles in this issue report some of this research, with an emphasis on learning to read. In what follows, we highlight only some high-level conclusions about word reading.

Phonology, Orthography, and Semantics in Chinese and English

The UPP claimed that both alphabetic and Chinese reading engaged phonology, with Chinese doing so at the syllable level as a routine or automatic part of character reading. When one considers that a given syllable is associated with many morphemes, automatic phonology in Chinese is a nontrivial claim. It should be adaptive for the reader to be able to go directly from character to meaning, because a route from character to syllable to meaning, because there are so many homo-phones, does not lead to a unique meaning. Despite the high level of homophony in Chinese, the conclusion from a substantial body of research was that when a character is read, phonology is activated anyway. (For some of this evidence see Perfetti, 2003; Perfetti, Liu, & Tan, 2005.) Thus, phonology is part of reading characters in Chinese, just as it is part of reading words in English.

The implementations of phonology in the two systems, however, are significantly different, as shown in Table 1. For English, phonological activation can grow rapidly in synchrony with letter identification, in “cascade” style (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). For Chinese, the model proposed by Perfetti et al. (2005) links the onset of phonology to an orthographic threshold in character identification. At the point of orthographic character access (a match between an input and memory representation of the character), this threshold is reached and activation spreads in parallel to the pronunciation of the character and to its meaning. The time course of phonology activation and meaning selection should vary with properties of the character and syllable (number of homophones, character frequency, meaning, and phonological consistency of radicals), allowing its phonological activation sometimes to be in evidence prior to semantic activation (Tan & Perfetti, 1998). The function of phonology, despite the homophony, is the same as in alphabetic writing: not to *mediate* access to meaning but to *stabilize* the word identity. Thus, we have a generalization across writing systems modified by writing-systems constraints. Phonology is a universal component of reading but the procedures that bring it about depend on the linguistic units provided by the writing system.

What about orthography—is it somehow “more important” in Chinese than in English? Although orthography is the universal gateway to reading, the fact that alphabetic writing establishes a more intimate, fine-grain connection between graphs and spoken language has consequences for the role of orthography. Thus, in alphabetic reading, orthography develops a stronger association with phonology through the acquisition of redundant unit connections (individual letters, letter strings, words). Decoding supports acquiring orthographic representations, because the phoneme string that is decoded from a letter string can reinforce the memory for the letter string (Share, 1995). In Chinese, this building of orthography through decoding is of more limited value, although it is not absent entirely. The phonetic component may allow the reader to try to associate a candidate syllable morpheme with the character, thus potentially reinforcing the orthographic representation analogous to what can happen in alphabetic reading. However, direct evidence that phonology “boot straps” orthography in Chinese is lacking, and the overall low reliability of phonetic components would make it less valuable. Thus, there is a sense in which the orthographic form in Chinese may be more “important,” or more carefully, less systematically supported by phonology, than in alphabetic writing and thus more dependent on specific item learning.

Finally, retrieving meaning from written units (orthographic morphemes and orthographic words) is universal because such units are associated with meaning-bearing language units. The procedures for meaning activation and selection are also general across writing systems. Meaning activation depends on general memory association processes that yield meanings associated with linguistic units (words and morphemes). Because all writing systems encode these linguistic units, written Chinese and written English both lead to the retrieval of meanings associated with linguistic units. Again, there are differences in the details of the associative retrieval processes across writing systems. For example, in Chinese, this process can be triggered by a semantic radical that is part of the character as well as by the whole character. The process of meaning *selection*—that is, selecting a candidate meaning from among those associated in memory with a given word (or morpheme)—is context dependent across writing systems. However, the detailed procedures for meaning selection are likely to differ somewhat. Because Chinese often requires multiple characters to be encoded (as morphemes) on the way to word identification, the process may allow more complex interactions with context-level factors.

In summary, the universality of phonology, orthography, and morphology as lexical constituents yields highly general descriptions of word reading across Chinese and alphabetic writing. Orthography initiates reading universally and skilled readers acquire high-quality orthographic representations. Phonology is activated universally by orthographic inputs and meaning activation and selection are outcomes of all reading. At more detailed levels, important differences emerge. Nothing in this account, however, implies that these differences are qualitative. Indeed, at a still more detailed level of description, the processes are likely the same— matching inputs to memory, association, retrieval, decomposition, decoding, and assembly or other candidates for basic processes. They differ in the graphic and linguistic units involved, the visual demands of the input, and the reiteration of processes. Nevertheless, the differences have implications both for learning to read and for reading problems.

Problems in Learning to Read

Because phonology is universally involved in reading, reading disability in Chinese, as in English, can arise from a phonological deficit. However, it follows from parallel access models of Chinese reading (Perfetti et al., 2005) that a phonological disability can be more selective in its Chinese reading manifestations: more specific to phonological aspects of reading and less disabling to reading for meaning when characters can become sufficiently familiar as orthographic objects. The research on Chinese reading difficulty indeed points to factors beyond phonology. Ho, Chan, Tsang, Lee, and Luan (2004) reported that, among the various correlates of reading difficulty associated with subtyping profiles, rapid naming was the most important. Moreover, knowledge of both orthography (e.g., Ho et al., 2004) and morphology (McBride-Chang, Shu, Zhou, Wat, & Wagner, 2003) are important in Chinese reading success. For example, McBride-Chang et al. (2003) found that after controlling for phonological awareness (and vocabulary), the ability to manipulate morphology in spoken language predicted character reading in young readers. Furthermore, reading difficulties are associated more with morphological awareness measures than with phonological awareness (Shu, McBride-Chang, Wu, & Liu, 2006).

One reason for the importance of nonphonological factors in Chinese reading is that orthographic knowledge, with limited support from sublexical phonology, consists of characters as perceptual forms whose visual and compositional structures must be learned. Reading Chinese requires high-quality orthographic representations and these are obtained through practice, both reading and writing. Difficulties in forming orthographic representations would lead to reading problems. Whether such problems, if they arise without a phonological cause, would be a disability in the usual sense or merely a "developmental delay" would remain an issue. Orthographic weaknesses could result from insufficient practice rather than a disorder, as Manis, Seidenberg, Doi, McBride-Chang, and Peterson (1996) suggested for English.

The character-specific orthographic skills that are important in Chinese may be supported by practice in writing (Chan, Ho, Tsang, Lee, & Chung, 2006; Tan, Spinks, Eden, Perfetti, & Siok, 2005). It is not only a cultural tradition that children in China spend their homework hours writing characters; the demands of recognizing several thousand characters place a premium on a quality representation that is enhanced by practice at producing the character. Although there is more to learn about the nonphonological contributors to Chinese word reading, the general point is that the detailed functioning of lexical constituents (phonology, orthography, morphology) is shaped by the writing system and the specific orthography that implements the system. This causes writing-specific adaptations in learning to read.

THE NEURAL SYSTEMS FOR ALPHABETIC AND CHINESE READING

With principle-level universals at the general level and specific writing system factors at the implementation level, do the neural systems for reading reflect this duality? A single general-purpose neural network for reading is implied by the conclusions from comparative studies of European alphabetic reading by Paulesu and colleagues (Paulesu et al., 2001; Paulesu et al., 2000), as captured in the title of Paulesu et al.'s (2001) article, "Dyslexia: Cultural Diversity and Biological Unity." The basis for this conclusion is evidence that consistency of grapheme– phoneme mapping affects the relative use of lexical and sublexical pathways in reading and a corresponding variation in the expression of reading disability across different orthographies.

Such "biological unity" of neural circuits for reading should be expected just to the extent that all reading (a) begins with visual analysis; (b) is dependent on connections to language, so that reading circuits come to include language processing areas of the brain; and (c) is implemented by visual, orthographic, phonological, and semantic components that are unaffected by variations in writing. Our argument that principle-level universals are complemented by writing-specific implementation implies that whereas (a) and (b) are satisfied in all reading, (c) may not be.

First, because all reading must involve visual processing in the brain, reading universally shows activation of posterior (occipital and occipital-temporal) areas. However, writing system differences also show their effects in these posterior areas. Alphabetic writing shows strong left-lateralized effects in visual areas (including the left fusiform gyrus [LFG]; Fiez & Petersen, 1998; Price, 2000; Turkeltaub, Eden, Jones, & Zeffiro, 2002). Chinese, in contrast, shows bilateral effects, sharing with alphabetic reading the left-hemisphere visual areas and the LFG (Bolger, Perfetti, & Schneider, 2005) while adding corresponding right hemisphere areas (Bolger et al., 2005; Tan, Laird, Li, & Fox, 2005). The LFG acquires importance for identifying wordlike objects in all writing systems, so is part of the universal reading neural network.

The importance of the LFG, rather than purely visual, may reflect its connectivity to phonological areas. Magnetoencephalography evidence in alphabetic reading suggests phonological activation in left inferior frontal gyrus (IFG; Broca's area) is concurrent with the peak of activation in the LFG (Cornelissen, Kringelbach, Ellis, Whitney, Holliday, & Hansen, 2009; Pammer et al., 2004; Wheat, Cornelissen, Frost, & Hansen, 2010). It remains to be seen whether such intimate connections between phonological and orthographic areas will be observed in Chinese.

As to the bilateral effects found in Chinese, right hemisphere visual areas may support the spatial processing that Chinese character layout requires. On this account, LH word identification areas (LFG) process the stroke-defined character components, whereas the RH areas process the spatial configurations of character components (left-right, top-down). Liu and Perfetti (2003), in an ERP study, found that Chinese readers showed activation first in LH posterior areas (within 150 ms) followed by a shift to RH (by 200 ms). This may imply a process of rapid LH identification of high spatial frequency stroke information and slightly delayed RH identification of low spatial frequency radical configuration (Perfetti et al., 2007). Such a difference is a matter of script, how the graphic elements are displayed, rather than the mapping system principles.

In addition to bilateral posterior functions in visual orthographic processing, Chinese reading consistently shows greater frontal activation in the left middle frontal gyrus (LMFG) and less activation in left IFG compared with alphabetic reading (Tan, Laird, et al., 2005). Siok, Perfetti, Jin, and Tan (2004) further reported that Chinese children who were poor in reading showed underactivation of the LMFG, compared with children who were skilled readers. Figure 1 illustrates the general results of multiple neuroimaging studies to indicate the brain areas that support reading across both writing systems and those that show more activation during reading in one or the other.

LMFG involvement in Chinese reading is consistent with the demands of Chinese reading. Its function could reflect character composition (i.e., stroke sequences), consistent with its location near Exner's area in BA 6, where damage is associated with loss of writing ability. A second possibility is that the LMFG functions to support lexical selection through an orthographic memory, which could reduce the cost of the homophone problem in Chinese. In alphabetic reading, spelling information can be "discarded" as phonological processes stabilize word identity. In Chinese reading, with phonology dependent on an orthographic threshold, reading would benefit from continued access to the character form to select character identity over competing activations from homophones. Although this function would be especially helpful for Chinese, it could support reading in alphabetic writing when selection is difficult. Left frontal areas near the LMFG show increased activation in English when there is grapheme–phoneme inconsistency (Binder et al., 2003; Bolger, Hornickel, Cone, Burman, & Booth, 2008).

SPECIALIZATION IN THE DEVELOPMENT OF READING SKILL

The Chinese/English comparisons show both shared and distinctive features in skilled reading and the neural systems that support it. What about the development of reading skill in the two systems?

Although we expect to see both universal and writing specific aspects of development, we suggest an overarching hypothesis: The development of reading skill requires the reader to gain those procedures that are specifically required by the writing system. This specialization hypothesis assumes that because universal principles—for example, the UPP—reflect adaptive reading processes, failures to implement those procedures that are specifically tuned for the writing system lead to reading difficulty. The developing reader increasingly uses reading procedures that accommodate the demands of the writing system.[1]

This accommodation requires increased specialization to meet the script-related requirements for visual processes and the mapping requirements for graphic unit-to-language-unit processes. This hypothesis implies that comparison across levels of reading experience will show differences in the brain areas that support reading. Indeed, Cao and colleagues (Cao, Lee, et al., 2010; Cao et al., 2009) found that Chinese adult readers, compared with children, showed more involvement of brain areas that support the specific demands of Chinese writing. These areas include the bilateral visual-orthographic regions (both the middle occipital gyrus and the fusiform gyrus), the inferior temporal gyrus, the superior parietal lobules (SPLs), and left frontal areas (anterior frontal and dorsal IFGs). This suggests that with increased reading experience comes increased specialization to accommodate both the visual demands of Chinese characters (bilateral visual-orthographic areas) and their syllabic phonological mapping demands (superior parietal lobule). With experience, orthographic representations become higher in quality, both as familiar and precisely detailed graphic forms and as linguistically mapped units.

The accommodation to the visual (script-based) demands of Chinese may respond to the additional spatial demands of characters. The combination of high-spatial frequency information (stroke-level differences between characters) and low-spatial frequency information (relational information between radicals) requires resources from right as well as left visual areas. Thus, with increasing skill in reading, the rapid analysis of characters is supported by these areas.

The accommodation to the mapping demands of Chinese is more complex, centering on the need to associate a whole character with a unique syllable/morpheme without the support of subsyllabic connections and to meet the memory demands that this entails. Because some assistance to mapping is provided by phonetic and semantic radicals, the overall mapping problem can be characterized as one dependent on a mix of whole character memory and component radical-mediated heuristics. Complicating the mapping problem is the high density of homophones, which adds to the pressure on acquiring high-quality, whole-character representations that can support links to meaning. These mapping features combine to place a premium on sustained access to orthographic representations during character identification. The neural accommodation to these demands may be reflected in the increased functioning of the SPL, as found by Cao and colleagues (Cao, Lee, et al., 2010; Cao et al., 2009).

The more complex part of the mapping function is the role of the LMFG, whose increased role in Chinese, as we suggested earlier, may support lexical selection against the demands of many-to-one mappings from orthography to phonology. The studies by Cao, Booth, and colleagues found greater involvement of the LMFG in Chinese adults than in children in various tasks, including rhyme and orthographic judgments to visually or auditorily presented words (Cao, Lee, et al., 2010; Cao et al., 2009). The fact that the LMFG involvement increases across tasks that demand selecting either orthography or phonology may suggest a control function, one that modulates posterior areas specialized for

[1]The accommodation hypothesis was first applied to learners of Chinese whose first language was English (Perfetti & Liu, 2005) and whose reading procedures had already accommodated the demands of English alphabetic writing.

orthography or phonology or meaning association. Thus the LMFG may be involved in mapping mainly through a control function. If so, then the development of reading skill includes an increase in this top-down modulation from frontal areas, including LMFG.

A related aspect of this mapping accommodation is suggested by another result from the Cao et al. studies: With reading experience and increased skill in Chinese reading, there is a shift in the role of the left superior temporal gyrus (STG). The left STG is associated with phonemic processes in alphabetic reading (e.g., Simos et al., 2000) and can show increased activation in English for children following phonologically based intervention (Shaywitz et al., 2004). However, Cao, Lee, et al. (2010) found that this “phonological” region actually showed reduced activation across age in Chinese reading. Although left STG may be supportive of phonology in some broader sense, the common interpretation that it functions for phonological “assembly” implies a simple grapheme-phoneme computation (e.g., Simos et al., 2000). If that interpretation is correct, the course of acquiring skill in Chinese is associated with a decrease in the functioning of this assembly area.

Providing a more direct comparison of Chinese and English age-related changes is a recent study (Brennan, Cao, & Booth, 2010) that found developmental increases in left IFG and left superior temporal gyrus—but only in English, not in Chinese. They also observed increases in activation of bilateral middle occipital gyri—but only in Chinese, not English. This pattern suggests that there are accommodations required in each writing system to its specific demands. In Chinese, the reader accommodates to a demand for precise orthographic representations by increased use of procedures that activate right hemisphere as well as left hemisphere orthographic areas. In English, the reader accommodates to a demand for orthographic-phonological connections that are partly general (consistent grapheme–phoneme relations) and partly word-specific (inconsistent grapheme–phoneme relations).

Writing Effects on Orthographic Representations

Finally, we draw attention to another implication of the specific demands of Chinese writing. The need for a high-quality, character-specific orthography can be partly met through writing as well as through reading experience. Writing characters, which is intrinsic to traditional Chinese literacy, strengthens orthographic representations, forcing attention to spatial relations and detailed stroke sequences. With writing, character memories can add sensory-motor components, as practiced stroke sequences lead to neuro-motor patterns associated with characters. In fact, the sequential stroke memory can serve as an additional support for character recognition (Flores d’Aracis, 1994).

In a series of studies of adult learners of Chinese, we have tested the effects of character writing as part of learning to read characters. Across various conditions in different studies, the results are that writing characters from memory (following brief exposure) improves later measures of character recognition, especially lexical decisions and character meaning decisions (Cao, Vu, et al., 2010; Guan, Liu, Chan, & Perfetti, 2011).

In a recent fMRI study, we compared training in character writing with training in pinyin (an alphabetic system) writing. Brain activation patterns suggest that character writing training produced a brain network that is more similar to that of native Chinese speakers: greater activation in bilateral fusiform gyrus, bilateral SPLs, left inferior parietal lobule (IPL) and LMFG (Cao, Vu, et al., 2010). Greater activation in bilateral fusiform gyrus and SPL suggests that writing provides a more native-like accommodation to the visual-orthographic features of Chinese characters. Greater activation in left IPL and LMFG suggests accommodation to the demands of the Chinese mapping system, although both areas play a role in alphabetic reading as well. The behavioral data show that writing enhances character reading and the neuroimaging data suggest that writing promotes an accommodation of the brain's reading network for Chinese toward more writing-system specificity.

Universal Paths in Development

Once again, as was the case with comparative behavioral research, the story is part universal as well as part writing-specific. Table 2 shows a general picture of developmental changes with reading skill in Chinese and English, both the specialization part, which we have just reviewed, and the universal part.

The reading network becomes specialized to a writing system, showing increased involvement of regions that support the reading procedures for that writing system and decreased involvement of other regions. The universal aspects are present in regions of the reading network that show similar changes with age across writing systems. Whereas the mapping between orthography and phonology is at the syllable level in Chinese and at the phoneme level in English, there is a common need in both systems to map graphic units to spoken language units. The activation of the brain region that may be associated with a more general mapping function, the left IPL, shows age-related increases in *both* writing systems (Booth et al., 2002, 2004; Cao, Lee, et al., 2010; Cao et al., 2009). This developmental increase in the involvement of left IPL is especially detectable when the task is difficult, for example, when the words share orthography but differ in phonology (e.g., *pint–mint*) or when they differ in orthography but share phonology (e.g., *jazz–has*). It is possible that the left IPL can be thought of as supporting word-specific mapping processes, both Chinese characters and English inconsistent words. Given the IPL's wide ranging role in memory, its activation during reading may reflect memory demands that are shared by character reading and alphabetic reading under certain conditions, including conflict.

It is also possible that the LMFG, seemingly specifically important for Chinese, may serve more general functions across writing systems. As we suggested earlier, the fact that LMFG activation has been observed across a variety of tasks is consistent with a frontal control function that happens to be more often needed in Chinese than in English. The developmental pattern for the LMFG in Chinese (increased activation in adults compared with children) has also been found for a number of linguistic tasks in English in a region that is close to LMFG, the left dorsal IFG (Bitan et al., 2007; Cone, Burman, Bitan, Bolger, & Booth, 2008; Schlaggar et al., 2002; Szaflarski et al., 2006). Neuroimaging studies in nonlinguistic domains—spatial working memory (Kwon, Reiss, & Menon, 2002), executive attention (Konrad et al., 2005), music processing (Koelsch, Fritz, Schulze, Alsop, & Schlaug, 2005), and others—also find consistent age-related increases in the involvement of the dorsal prefrontal area. This does not mean these frontal areas function in this same way in all tasks. It allows, however, the general proposition that LMFG and other frontal areas may be serving a broader cognitive function that accommodates demands of Chinese writing that are shared by other cognitive tasks.

The universal paths of development thus include broad themes. One of these themes may be the increased value of control functions that allow readers to handle the specific demands of varied reading-related tasks, allowing attention to be directed toward orthography, phonology, or semantics. Another may be the settling of a basic network that connects the posterior areas that handle graphic inputs to linguistic (phonological and meaning) areas, allowing rapid stabilization of word identity. These connections, despite some variations in their neural anatomy, reflect the universal mapping of writing to language, which is fundamental to all true writing systems. Specific features of the writing system must be accommodated and this leads to specialization. With increasing skill, reading procedures increasingly accommodate to the demands of the writing system so as to function with efficiency. Thus, we see some specialization in the reading network. This trend in specialization should be seen in all combinations of language and writing systems, and thus may itself be a biologically instantiated reading universal.

CONCLUSION

A universal science of reading seeks to discover what is general or universal, but also what varies systematically with the mapping of writing to language. We have illustrated what is gained for just one kind of comparison across the most highly contrastive of writing systems, the logographic or morphosyllabic system of Chinese compared with alphabetic systems. We note that we have ignored a very important source of variation: the linguistic system itself, which critically contributes to some differences that masquerade as writing-based differences (Ngyen-Hoan & Taft, 2010; Yoon, Bolger, Kwon, & Perfetti, 2002).

The comparisons across behavioral and neuroimaging studies of adults and children suggest that writing systems affect reading through both their visual layout and their graph-to-language mapping functions (e.g., Liu & Perfetti, 2003). Chinese writing encourages high-quality, whole-character representations, even when the components can support identification. Alphabetic writing allows successful word reading even with variability in the quality of whole word orthographic representations, because grapheme-to-phoneme connections allow unlimited regeneration of a linguistic output from a graphic input. This redundancy of printed-word-to-spoken-language connections supports alphabetic reading; for example, even low-frequency words can be read if they are decodable.

Chinese writing has an interesting compensation for its limited decomposability. The validity (usually but misleadingly called “regularity”) of a phonetic component as a cue to the character’s pronunciation increases with decreasing character frequency (Perfetti et al., 1992). Chinese children learning to read gradually take advantage of the phonetic component of characters (Chen, Shu, Wu, & Anderson, 2003), and this should serve them when they encounter low-frequency words, just as English readers are helped by decoding when they encounter a low-frequency regular word.

This point brings full circle the complexity of the question of whether writing systems affect reading procedures fundamentally or merely produce superficial differences. The fact that both English and Chinese provide support for reading less familiar words is an example of a *functional* universal, as opposed to a *procedural* universal. The procedures by which readers gain access to the meanings and pronunciations of written words include some universal components and both behavioral and brain measures show these universals. These procedures also show writing-system specific components. At the functional level the question is how success in reading can be attained through different writing systems. Even a limited decomposition system such as Chinese has evolved to allow reading to not be dependent solely on familiarity, conforming perhaps to a functional universal that reflects accommodation of writing to human cognitive capacities. The success of general purpose learning models applied to character reading (Yang et al., 2009) keeps open the possibility that the basic mechanisms of associating decomposable graphic input patterns with linguistic units is a part of learning to read across writing systems.

Finally, we note that whether or not these analyses are correct, it is only by comparing reading across writing systems that we can even begin to ask questions such as the ones we have raised. A reading science preoccupied with English would not be raising these fundamental questions. The fact that research raises these questions and examines reading across languages, writing systems, and orthographies means that reading science is indeed universal.

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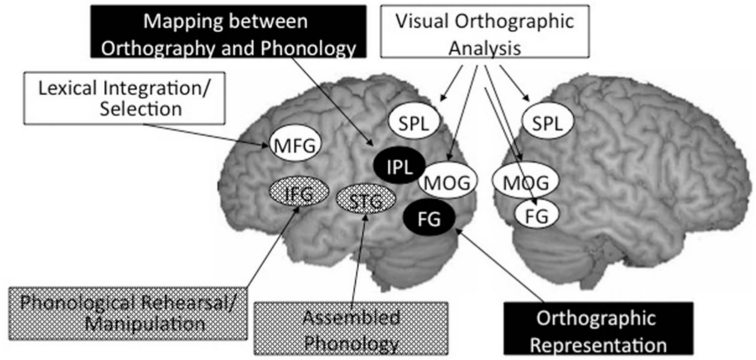

FIGURE 1.

Brain areas that support reading in English and Chinese. Activation for both systems is seen in left hemisphere posterior regions that support visual identification and a left hemispheres parietal region that may support graphic-to-linguistic mapping. Differences between the two systems include greater activation for Chinese of right-hemisphere posterior areas that support character identification and greater activation in a frontal area that may support selection of character connections to meaning and pronunciation. Cross-hatches mark areas more involved in English than Chinese reading (IFG and STG). Areas with white backgrounds are involved in Chinese more than English. Areas with black backgrounds (IPL, FG) are involved in both Chinese and English for adults. (See Table 2 for developmental trends.) Based on research by Cao et al., 2010.

TABLE 1

Writing Systems Comparison

	Alphabetic	Chinese	Notes
Sublexical graphic units	Hierarchically compositional	Embedded lexical units	Both systems reflect statistical regularities in the relation of subunits to lexical units
Basic phonological unit	Phoneme	Syllable	For both systems, activation of phonology is rapid and may precede meaning activation. Phonological coherence supports identification
Phonological activation	Cascade style	Threshold style	
		Diffuse because of homophones	
Meaning activation	May be “mediated” by phonology	Less mediation by phonology	

TABLE 2

Changes in Involvement of Reading Network Components With the Development of Skill

Brain Areas Within the Reading Network	Chinese	English	Interpretation
Left visual-orthographic areas (FG, ITG)	Increase	Increase	Word identification at basic unit level (radical, word) level. Important universally.
Right visual-orthographic areas (SPL, MOG, FG)	Increase	Decrease	Word identification at spatial relations level. More important for Chinese.
Sublexical phonology (Left STG)	Decrease	Increase	Phonology at the submorpheme level (phonemic “assembly”). More important for alphabetic reading.
Orthographic-phonological mapping (Left IPL)	Increase	Increase	Integrating phonology and orthography in word identification. Important universally.
Lexical integration/ selection (Left MFG)	Increase	Increase	Control of reading network. Important for both, but more so for Chinese.

Note. FG= frontal gyrus; ITG = inferior temporal gyrus; SPL = superior parietal lobule; MOG = middle occipital gyrus; STG = superior temporal gyrus; IPL = inferior parietal lobule; MFG = middle FG.