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Orthography to phonology and meaning: Comparisons across and within writing systems*

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Abstract. According to the Universal Writing System Constraint, all writing systems encode language, and thus reflect basic properties of the linguistic system they encode. According to a second universal, the Universal Phonological Principle, the activation of word pronunciations occurs for skilled readers across all writing systems. We review recent research that illustrates the implications of these two universal principles both across and within writing systems. Within the family of alphabetic systems, differences between Korean and English arise in the languages, rather than the orthographies, while the reverse appears to be true for German and English differences. Across writing systems, new Event Related Potentials (ERP) experiments show the robustness of phonology across Chinese and English systems and chart the time course of word reading in Chinese and English for Chinese bilinguals and for English speakers learning Chinese. The ERP results show differences between Chinese and English for both groups and suggest that the time course of word processes and the brain areas identified as sources for the ERP components differ both as a result of writing system and the skill of the reader. We propose the System Accommodation Hypothesis, that reading processes and the neural structures that support them accommodate to specific visual and structural features of a new writing system.

Key words: Chinese, English, ERP, Reading

Introduction

Reading is fundamentally about converting graphic input to linguistic-conceptual objects (words and morphemes). Understood this way, a viable theory of reading must include attention to the nature of both the graphic input and the nature of the linguistic-conceptual objects to which they connect. On this formulation, learning to read is learning how one's writing system encodes one's language.

Although research on reading has been dominated by research on English, a recent surge of attention to other writing systems and orthographies has dramatically increased information on how writing systems affect reading. In what follows, we attempt to bring some of this work into an overall theoretical perspective, while also presenting some new research that adds to the developing picture of reading that is informed by comparative studies.

It is useful to try to maintain a distinction between two levels of analysis that are often conflated: A writing system and an orthography. A *writing system* reflects the principles reflected in the fundamental writing-language relationships. Thus, an alphabetic system is fundamentally different from a syllabic system and both are fundamentally different from a logographic system (if pure logographic systems were to actually exist, which arguably they might not). *Orthographies*, by contrast, express differences within a writing system. Thus, English and German are the same at the writing system level, but differ in their orthographies, whereas English and Chinese are different at the writing system level (It is then trivially true that English and Chinese differ in their orthographies). A third level that is sometimes misleadingly used to refer to one or the other of these more basic distinctions is the *script*, which is a specific graphic implementation of the writing system among many that are possible. No doubt scripts can make a difference in reading, because they control the initial visual input that gets the process going. But unlike the other two levels of analysis, they are logically independent of the writing-language relationship.

Comparisons across writing systems

Comparative writing research has made clear both the universal dependence of reading on language and the accommodation of this universal to the properties of the writing system (Perfetti, 2003). The highest-level universal is the *Language Constraint on Writing Systems*, which is that writing systems encode spoken language, not meaning. Put to rest by research on logographic systems (Chinese, Japanese Kanji) is the idea that reading in such systems implements a simple visual-to-meaning process that allows the reader to by-pass language. Instead, reading appears to depend on language in the most fundamental way: When a reader encounters printed words, he or she understands their meaning within the context of his language, not as signs that derive their meaning independently. The Universal Phonological Principle (UPP) (Perfetti, Zhang, & Berent, 1992) captures one important universal with the generalization that word reading activates phonology at the lowest level of language allowed by the writing system (phoneme, syllable, morpheme, or word). Research in support of this conclusion is summarized in Tan and Perfetti (1998).

Within the scope of the UPP is a corollary principle about the functionality and timing of phonology in word identification. This corollary departs from the usual dichotomy that phonology is either pre-lexical or post-lexical, a distinction that places phonology in relation to lexical access, a putative meaning-free moment of access to a word's written entry in a mental dictionary. Instead the *identification-with-phonology* hypothesis (Perfetti & Zhang, 1995; Perfetti & Tan, 1998) places phonology as a *constituent* of word recognition. This is a distinction with a difference, because it claims that the identification of a word is the retrieval of its linguistic identity (phonologically specified morpheme or word). Phonology is thus not a by-product of identification, as it is in when phonology is "post-lexical". Instead the moment of orthographic recognition – the point at which the identification system distinguishes a given graphic representation from other (similar and partly activated) representations – is the moment of phonological identification. The difference among writing systems is that in an alphabetic system the elementary graphic units that initiate phonology correspond to phonemes. In a syllabic system, the elementary units correspond to spoken syllables; in Chinese, the elementary unit is also a spoken syllable that happens to be a morpheme, often a word.

These general conclusions about universal aspects of phonology in reading have complementary conclusions about writing system influences on reading. Writing systems and orthographies do make a difference in the specific implementation of reading. Even within the class of alphabetic orthographies, research points toward important differences in reading. English and German comparisons, for example, suggest that German children and adults can trust their orthography to implement a reliable grapheme–phoneme conversion, whereas English children and adults come to rely more on orthographic whole-word reading (Frith, Wimmer, & Landerl, 1998; Landerl & Wimmer, 2000; Wimmer & Goswami, 1994). Thus, German children read pseudowords nearly as well as real words, whereas English children do much more poorly on pseudowords. The interpretation of these differences is not completely clear, but it is unlikely that the activation of phonology is what is different, because English readers engage phonology when they read (Perfetti & Bell, 1991; Van Orden, 1987). Instead, the unreliability of English grapheme–phoneme mappings leads to more variability in the size of units that are successful in the orthography-to-phonology mappings. German, although it too has some inconsistencies (Ziegler, Jacobs, & Stone, 1996), provides a more uniform mapping-pair at the lowest level allowed by writing systems (grapheme–phoneme). At the highest level, both Japanese Kanji (grapheme-word) and Japanese Kana (grapheme-syllable) provide relatively uniform mapping pairs that may serve word reading well (Wydell & Buttterworth, 1999).

Across writing systems, the potential for differences in reading is even more dramatic. Reading Chinese activates phonology, just as reading English and German does. However, unlike alphabetic systems, Chinese phonology is not activated by sub-syllabic connections, because there are none. It is activated at the syllable level, where whole characters and phonetic radicals – constituents of compound characters that are themselves characters – are associated with spoken syllables. Because the characters themselves have meaning, either as single syllable words or as single syllable morphemes that are constituents of multi-syllabic words, reading Chinese is a process that simultaneously (more or less) yields both pronunciation and meaning. This process can be modeled computationally by connections from orthographic characters to meaning units and to syllable units that are activated in parallel (Perfetti, Liu, & Tan, 2002). Experiments on naming Chinese show an interesting phenomenon that does not occur in alphabetic reading – an inhibitory effect of a graphic prime that is synchronous with the facilitative effect of a phonological prime (Perfetti & Tan, 1998). The facilitative effect of a graphically similar prime turns to inhibition at the same temporal point (measured by the prime-target SOA) at which facilitation by a phonologically identical prime (homophone) begins. This reflects the discrete, threshold nature of phonological coding in Chinese: only as the orthographic character is recognized as a unit does it activate the corresponding syllable phonology. In contrast, alphabetic systems allow their phonology to be activated incrementally with each letter-phoneme pair.

In summary, a general conclusion is that reading has a universal character across writing systems. This universal character is reflected in the writing system constraint (all writing systems encode language) and the Universal Phonological Principle (reading engages phonology at the smallest unit – or earliest moment – allowed by the writing system). Differences between writing systems and between orthographies of the same writing system exist within the constraints of these universals. These differences arise from the functionality of graphic units within the system. Thus, for example, Chinese reading includes automatic phonology, but this phonology occurs with the recognition of a whole orthographic syllable unit. For other examples of reading differences that arise from the fundamental principles of the writing system see Perfetti et al. (2002).

Comparisons across languages within a writing system

Korean is an alphabetic system that provides a very different look compared with the linear alphabetic systems of the Middle East and

Europe. Although Korean was originally written in characters borrowed from China, its main writing system since the mid-15th century has been the Hangul, an alphabetic system. Hangul is nonlinear, arranged in square figures or Kulja, in which the letters are arranged left-to-right, top-to-bottom, as illustrated in Figure 1. Each square pattern can contain up to four letters and corresponds to a single syllable. Also in contrast to other writing systems, Hangul was more invented than developed, and its letter-phoneme correspondences are completely transparent. (See DeFrancis, 1989) Although some deviation from its purity as an alphabetic system has developed in the last century (see Perfetti, 2003, for examples), the Hangul remains, from an orthographic depth point of view, more similar to German than to English.

If the writing system were the only controlling factor in the details of reading, then Korean should be read more like English (or perhaps even more like German) than like Chinese. And so it is at the system level. Readers of Korean use the transparency of its orthography to map letters onto phonemes. However, the languages are very different and it is an implication of the Language Constraint on Writing Systems that the forms of the language are encoded during reading. Thus, language factors should be observable in reading processes. Among the differences between Korean and English are the following: Korean has fewer phonemes than English and German, an inventory of 19 consonants, 10 vowels, and 2 glides. Also in contrast to English and German, there is no voicing contrast in Korean. Thus, /k/ and /g/ are not distinguished. However, Korean distinguishes among three manners of stop consonants in terms of vocal tract constriction (tenseness); for example, /p/, /pp/, and /p′/ are three different levels of the voiceless bilabial. A tendency toward open syllables and a lack of consonant clusters provides further contrast with English and European languages.

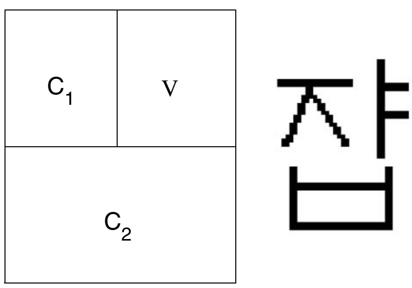

Figure 1. An example of the CVC orthographic pattern of a Korean syllable.

Language differences of this sort, especially the differences in syllable structure, could be relevant for the kinds of subsyllabic units that are reflected in reading and learning to read. Studies of English have observed that the rime unit, the vowel plus coda of a syllable, is functional during learning to read (Goswami, 1993; Treiman, 1992). Some studies of adult reading using naming tasks have also shown rime units to be functional (Bowey & Hansen, 1994). However, brief exposure procedures seem not to find evidence for rime units (Booth & Perfetti, 2002). In Dutch, a more transparent orthography, rime units are less in evidence (Geudens & Sandra, 1999, 2002). So there is some question about what controls the tendency for reading to use the rime unit. It might be the orthography, with a less transparent system like English specifically promoting units larger than the unreliable letter-phoneme pair. Another possibility is that language differences play a role. Korean can provide a test of this possibility.

We investigated this language possibility (Yoon, Bolger, Kwon, & Perfetti, 2002), building on research by Yoon (1997), who had found that Korean 4–6 year olds did not show a rime preference in a grapheme substitution task but rather a body preference. In Yoon's task, the child first learned to read a one-syllable "clue word", e.g. 갈 (/kal/)., and then heard words that shared some part of this syllable. With the written word visible, the child selected which part should be changed to produce this spoken word. To illustrate using Roman letters instead of Korean letters: when hearing /dal/, the child should select the first letter 'k'; for /kul/, the child should pick out the 'a', and for /kam/, the 'l'. If the onset-rime unit is salient, then children would perform best on the kal-/dal/ substitution. However, Yoon (1997) found that subjects performed more accurately in substituting the final consonant grapheme. So /kal/ and /dal/ were treated as less similar than /kal/ and /kam/. Although the grapheme substitution task has some differences with the analogy task that has been used in English (Goswami, 1993), Yoon's (1997) results suggested that Korean children, unlike English children, assign no privilege to the onset-rime structure within a syllable. Instead, they seem more sensitive to the syllable body, the onset plus the vowel.

Yoon, Bolger, Kwon, and Perfetti (2002) extended these results to explicit comparisons of English and Korean in both reading and spoken language judgments. Two key results bear on the argument we are making here. First, in tasks that involved reading, Korean children again showed not an onset/rime preference but a syllable body preference, replicating Yoon (1997), whereas American English speaking adults preferred the onset/rime structure. The interesting result is what happened when spoken words and nonwords were presented for similarity judgments, using phoneme sequences that were either words in both English and Korean or were nonwords in both. Korean children judged both words and nonwords with shared bodies (e.g. koon and koop) as more similar than stimuli with shared rimes (koon and poon). Thus, in this comparison, the preference for a particular subsyllabic unit in reading appears to have its origin in the spoken language rather than in the orthography.

New comparisons across writing systems using event related potentials (ERP)

The Korean comparison drives home the general point that languages themselves can be the source of the variability in reading process, while also showing that *subsyllabic units* such as the rime are not likely to be universal. Reading makes accommodation to the language. Recent ERP research on Chinese brings a complementary perspective: Reading accommodates the writing system.

ERPs are useful indicators of cognitive processes that occur rapidly, such as word identification. ERPs are Electroencephalographs (EEGs) recorded on the scalp surface to reflect rapid voltage shifts that originate from the neuronal activity in the brain. Because they are time-locked to specific stimulus events, ERPs can reflect the perceptual and cognitive events triggered by these events. For reading, the experimental control of the reader's task and stimulus variables (e.g., language, word frequency, orthography) allows observed ERPs to be linked to reading events that unfold over very brief periods of time. For example, the N400 is a negative going component peaked around 400 ms, which is sensitive to semantic and phonological processing (Kutas & Hillyard, 1980; Rugg, 1984). An earlier component, the P200 (a positive component with a peak at 200 ms) was found to be related with orthographic processing in Chinese (Liu, Perfetti, & Hart, 2003). Although a given ERP voltage shift can have an indefinite number of cortical sources because the number of neuronal cylinders involved in a cognitive task is much higher than ERP recording channels (currently 256 is the maximum), source identification can still be inferred reasonably well on the basis of various algorithms (Koles, 1998).

We summarize here some results from recent ERP research directed at writing system comparisons. One study focused on Chinese character decisions, a second on a comparison of Chinese and English reading by Chinese–English bilinguals (native Chinese speakers), and a third on English monolinguals who are in the beginning stages of learning to read Chinese.

Pronunciation and meaning judgments by native speakers. Liu et al. (2003) studied the time course of graphic, phonological, and semantic information when readers judge whether a character is related in meaning or pronunciation to a previously presented character. The two characters represented one of four meaning and form relationships: (1) Graphically similar, (2) Phonologically identical (homophones), (3) Semantically related, (4) Unrelated. Graphically similar characters generally shared a component radical, sometimes a right-side (phonetic) and sometimes a left-side (semantic) radical, but never shared phonological or semantic information. For example, 凉-[pronounced LIANG2 (meaning cool)] and 惊-[JING1, frighten] both have 京-[JING1, capital] on the right side as a phonetic radical, but only the second character shares the pronunciation with the phonetic radical. Homophone pairs shared phonology, including tone, (e.g., 惊-[JING1, frighten] and 晶-[JING1, crystal]), but shared no graphical or semantic information. Semantically related pairs shared meaning, (e.g. 惊-[JING1, frighten] and 扰-[RAO3, disturbing]), while sharing no graphical or phonological components.

In the experiment, the two characters were presented one at a time with 640 ms from the onset of the first to the onset of the second. This relatively long SOA assured that there was ample time for both phonological and semantic interference to develop (Perfetti & Zhang, 1995) and was long enough to allow ERP signals to be taken from the second word without carryover signals from the first word.

A main question concerned the negative trials, which can provide evidence for interference of the kind reported by Perfetti and Zhang (1995) and others (Hung, Tzeng, & Tzeng, 1992; Xu, Pollatsek, & Potter, 1999; Zhang & Perfetti, 1993; Zhang, Perfetti, & Yang, 1999), and extend this evidence to cases of graphical similarity. Specifically, would homophone pairs interfere with a negative decision in the meaning task, compared with unrelated pairs? ERP signals can reflect mental processes prior to the reader's overt decision.

The results we summarize here are based on Principle Components Analysis of 129 electrodes followed by analysis of variance of experimental variables on 9 electrodes (the 10–20 system). In the pronunciation decision task, graphic similarity effects were observed at 200 ms after the onset of the second character in the reduction of a positive-going shift (P200) associated with graphic processing. Source analysis low resolution electromagnetic tomography (LORETA Pascual; Marqui, Michel, & Lehmann, 1994) identified the source of this graphic component at bilateral occipital and prefrontal motor areas, identified also by Liu et al. (2003) in an ERP study of Chinese word identification and by Tan et al. (2001) in an fMRI study.

Phonological interference during a meaning judgment emerged at 400 ms, in the form of a reduction of the N400. For both homophones and graphically similar pairs, related trials were less negative than control trials. According to the LORETA analysis, the source of this homophone effect is left BA 6 and BA 3/4 (superior frontal and parietal), and right BA 22 (superior temporal) and BA 44 (middle frontal). The graphic similarity effect in the meaning decision task at 400 ms was generated in the same right hemisphere areas (BA 22 and 44), but showed no left hemisphere sources. This result might indicate more left hemisphere language area activation at the character-level in the processing of phonology. Especially interesting is that all the brain areas mentioned above were also found to be active in an fMRI study using this task (Tan et al., 2001). Thus, the areas for Chinese character constituent processing were successfully separated by ERP with localization as well as by fMRI.

Chinese provides a picture of temporal unfolding that we think should be quite general across writing systems, with ERPs reflecting first the effects of graphic form, and, somewhat later, the processing of phonology and meaning. In the constituency model (Perfetti et al., 2002), the activation of graphic, phonological, and semantic constituents occurs in this same order, with partly overlapping processes.

To provide a comparison with English, we carried out a parallel ERP experiment. Such a comparison is interesting because English, as an alphabetic system, correlates graphic and phonological similarity, whereas Chinese disassociates the two. In the English materials, an example of a graphic pair is MAIN and MAIL and a homophone pair is PANE and PAIN. In English, the ERP record showed an early separation of the homophone pairs from the graphically similar pairs, at 200 ms after the onset of the second word. This phonological effect is much earlier than the homophone effect we found in Chinese at 400 ms. Thus, according to ERP evidence, both English and Chinese processing show phonological processing in a semantic decision task within 400 ms. In English, perhaps because of the coupling of graphic with phonological form, phonology may be detected even earlier. We caution, however, that a comparison such as this is not straightforward, because of the differences associated with the two language groups and the two sets of linguistic materials, especially in a decision task where the degree of similarity is the basis for judgment.

Chinese–English bilinguals: Single word naming. Another way to make these writing system comparisons is to make observations in both languages for the same speaker, a bilingual. For this purpose, Liu et al.

(2003) compared English and Chinese word reading by native speakers of Chinese who were also fluent in English. In this study, we chose a simpler task free of decisions about word meanings and pronunciations, delayed word naming. The delay between the presentation of the word and the signal to pronounce the word is important in this procedure. Recording ERPs prior to the naming response allows orthographic and phonological components to be exposed implicitly as the reader identifies the word and prepares to pronounce it. Thus, we should see direct evidence of the retrieval of phonology as well as the encoding of the orthography during the 1000 ms interval that preceded a signal to say the word. Three hypotheses about word reading were tested: (1) Word frequency effects would be observed in 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. (3) Phonological processes would be observed in speech motor areas as the subject prepared a pronunciation, and these would occur earlier in the native language than in the second language.

We illustrate the key results, which confirm all these hypotheses, by a single electrode (the vertex electrode, Cz) that shows the grand average ERP waveform for each of the four experimental conditions in Figure 2. A Principle Component Analysis showed 4 major components: A slow-wave component with a late peak; a component that emerged at 200 ms with a peak loading at 468 ms (named the N450 for its peak latency and shape); a third component that rose quickly from 150 ms, peaking at 260 ms and producing positive loadings for frontal and central electrodes and negative loadings at parietal, temporal and occipital electrodes (named the N250); a fourth component that rose sharply from 130 ms through 250 ms, with a peak at 156 ms (named N150). ANOVAs on the factor scores of slow wave, N450, N250, and N150 components produced reliable differences among conditions, as described below and supplemented by LORETA source localization algorithm.

Language and frequency effects appeared quickly and unfolded over time. Chinese and English were different within 150 ms of exposure to a word, and the peak latencies of the N150 and N250 occurred earlier for Chinese than English words. The N250 signaled frequency differences in both languages. The N450 was sensitive to English word frequency, with low frequency English words eliciting more negative N450 at right hemisphere electrodes, the source of which was right hemisphere occipital (BA 18), according to LORETA. In addition, the source localization analysis suggested shared and distinctive areas of the brain networks that support reading in the two languages.

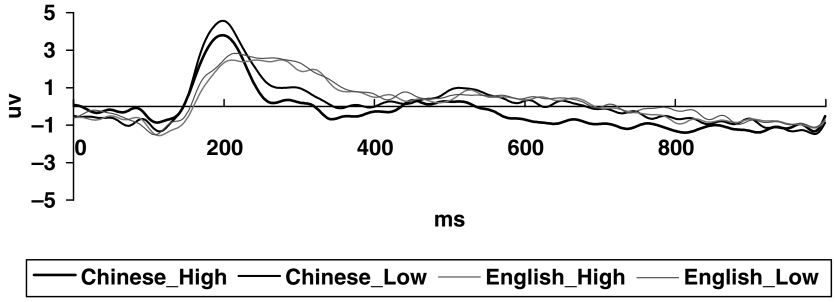

Figure 2. ERP waveform (at electrode Cz) from the onset of the target word read by Chinese–English bilinguals. Note that native language words, Chinese characters, produced an earlier peak of higher amplitude at 200 ms, compared with English words.

For the shared areas, we found left lateralized visual areas for Chinese, overlapping those found in English fMRI and PET studies (Fiez & Petersen, 1998). However, we found additional right occipital activation (BA18) for Chinese at 200 ms (following left occipital activation, BA17, at 150 ms), a result consistent across frequency. Our finding of right occipital activation for Chinese characters may be compared with the fMRI results of Tan et al. (2000, 2001), who found greater right than left activation in occipital cortex and with Chee et al. (2000), who found bilateral occipital activation in Chinese–English bilinguals. Our data included both patterns, depending on the time window involved – bilateral overall, with left and then right visual areas early in processing. A longer period of occipital activation was observed for the less familiar language (English) and for low frequency compared with high frequency Chinese words.

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 they do in PET and fMRI studies, showed only left occipital sources; however, low frequency words produced bilateral sources. This bilateral activation pattern may reflect the "Chinese mode", reading procedures used when Chinese-dominant readers identify low frequency English words as well as Chinese characters. The analysis also showed later and longer activation in visual areas for low frequency English words. For Chinese characters, the source analysis showed an early (100 ms) occipital activation for low frequency characters. 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 & Petersen, 1998; Tan et al., 2000). Thus, our Chinese bilinguals were able 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, Balota, Raichle, & Petersen, 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 general picture is as follows: First, there are reasonable temporal orderings for parts of the reading network, with posterior regions that support visual analysis or word form identification activated early (within 200 ms) followed by 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 for both languages. Furthermore, visual area activation persists longer for the less familiar (English) writing system, especially for low frequency words, diminishing only beyond 350 ms (beyond 300 ms for high frequency).

English language learners of Chinese: Chinese and English delayed naming. The first two studies provide a convergent picture of the time course of activation of word components in reading by Chinese native speakers and show sensible orderings of visual-graphic, orthographic–phonological, (Liu and Perfetti, 2003) and semantic processes (Liu et al, in press). The study of delayed naming provides the first clear evidence that writing system effects emerge during the brief time it takes to identify a word. The final of our three ERP studies (Liu, Perfetti, & Wang, 2003, March) adds to this picture by observing language and writing system effects in learners of Chinese.

Students recruited from a University of Pittsburgh Chinese class performed the same kind of delayed naming task described above, with ERPs recorded during the interval prior to the production of response. Words to be named represented two orthogonal variables, language (Chinese versus English) and frequency (high versus low). For English, frequency was defined as is typical for monolingual studies, the printed word frequency from the printed corpus of Francis and Kucera (1967); for Chinese, frequency was determined by the number of appearances in the student's curriculum to the point of testing (an average of 43 appearances for the high frequency characters and 10 for the low). Words were presented in blocks by language, with frequency mixed within a block.

An ERP waveform at a middle frontal electrode (Fz) is shown in Figure 3, illustrating important comparisons revealed in the PCA analysis, which produced four components: a slow wave component that rose slowly from 200 ms to its maximum at 1000 ms; a second component that rose from 150 ms to 350 ms, with a peak loading at 190 ms (named the N200); a third component rising from the onset of the stimulus to 150 ms. A fourth peaked at 450 ms, rising from 350 ms through 600 ms (named the N450 to reflect its peak latency and shape). The N200, the very early component, and the N450 produced interesting and statistically reliable differences among conditions, as described below.

Very early (0–150 ms) component: This component was more negative for Chinese than English at central frontal electrode and more negative for English at left occipital electrode.

N200: The Chinese N200 component scores were more positive at frontal electrodes, and more negative at parietal and right occipital electrodes than English. Chinese high frequency characters were more positive than low frequency characters at central frontal electrodes, and English high frequency words were more positive than low frequency words at left central electrode.

N450: English words were significantly more negative than Chinese at medial frontal, central and parietal electrodes, and right frontal and right central electrodes. Compared with the high frequency English words, low frequency English words elicited more negative N450 at left frontal electrode.

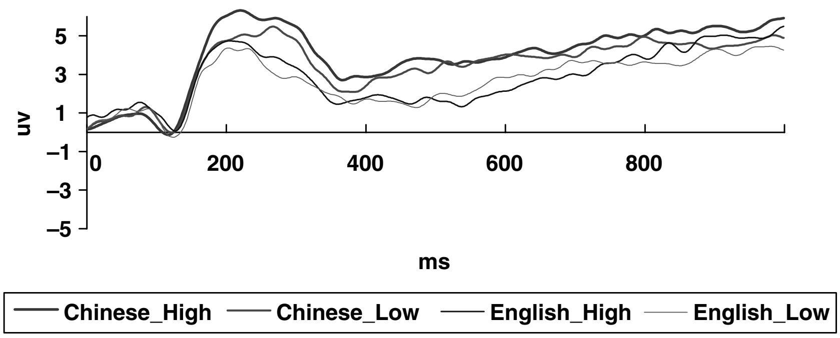

Figure 3. ERP waveform (at electrode Fz) from the onset of the target word read by English speakers learning Chinese. At 200 ms, Chinese shows a higher peak amplitude than English and more familiar (high curriculum frequency) characters are more positive than less familiar (low curriculum frequency) characters.

Non-parametric tests between LORETA maps of different conditions showed sources more associated with Chinese than English included areas identified in studies of Chinese native speakers, e.g., left prefrontal (BA8/9/10) and right middle and inferior temporal (see Figure 4). Thus, based on the source analysis, English readers learning Chinese showed activation in brain areas that overlap those found for native Chinese readers.

This observation that Chinese reading activates distinctive brain areas by native Chinese readers and by alphabetic learners of Chinese needs corroboration. Tentatively, however, it suggests the *system accommodation hypothesis*: that brain areas that distinctively reflect specific writing system process are also used to learn the system. In most cases, these areas are those normally used by native speakers.

Summary: What ERP studies of Chinese and English add to comparative knowledge of reading. Based strictly on behavioral studies and the analysis of writing systems, there has been substantial progress in figuring out how writing systems make a difference for word identification. Impressive similarities have been established across various language comparisons, even when the comparisons go across a fundamental divide in the principles that organize writing systems. Differences also have been observed across instances of alphabetic systems (German and English; Korean and English), and these reflect specific variation in orthographic implementation and language structure.

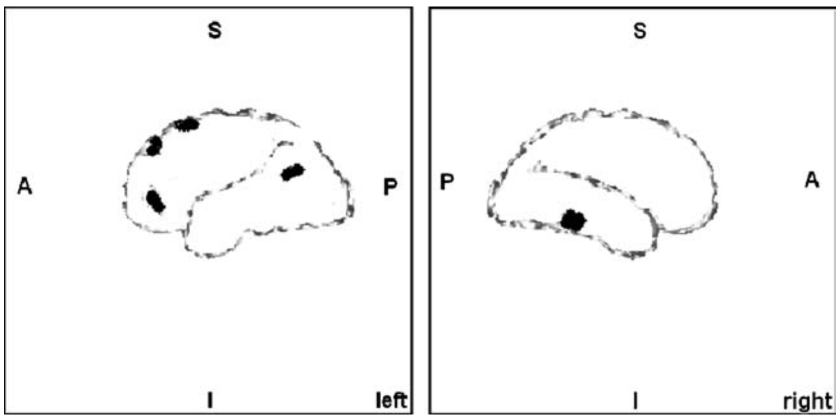

Figure 4. Sources of a learning effect during 150–350 ms for English speakers learning Chinese characters. The darkened areas mark locations of differences (based on LORETA sourcing procedures) between less familiar and more familiar Chinese characters (less familiar subtracted from more familiar), as measured by curriculum frequency. (A = Anterior, P = Posterior, S = Superior, I = Inferior).

In bringing neuroscience methods to bear on fundamental issues of word identification, the assumption is that we can get a more detailed view of both similarities and differences across time (ERP) and space (fMRI studies). We have focused here on ERP studies, but it is important to note the fMRI studies that show that reading Chinese and reading English involve both shared brain regions and some different regions (Chee et al., 2000; Tan et al., 2001; Tan et al., 2000). As for the ERP studies, we see that the constituents of word representation – orthographic, phonological, and semantic constituents (Perfetti et al., 2002) – can be detected during the reading process. The ERP studies reviewed here suggest an early process of visual-graphic analysis that is more prolonged for a writing system being learned. They expose also a slightly later stage of orthographic-phonological processing that may be essentially about decoding – at a lexical level in Chinese, at a prelexical level in English. The retrieval of semantic information was not specifically targeted in two of our three experiments, but in the Liu et al. (in press) study, we see meaning retrieval when the subject decides that a second word is related in meaning to a first word.

Especially interesting is the evidence we see for frequency effects that emerge very rapidly in processing – and also very early in learning. When readers, whether Chinese or English, read a word in their native language, a more familiar word is distinguished from a less familiar word within 200 ms of processing. And a word in the reader's more familiar language shows an earlier processing peak than one in the less familiar language. Even when learning is new and the frequency difference is one between 10 exposures versus 40 exposures in a curriculum, there is a clear difference owing to familiarity. Writing system differences show themselves as well, and the difference between Chinese and English appears to be not only about the readers but about the writing system itself. Thus, learners of Chinese show ERP sources in cortical regions that have been found also for native Chinese readers. We think that there are visual processing demands that accompany the visual analysis of the script – not necessarily the writing system – might require more analysis or more support from additional regions. This conclusion has been argued by Tan and his colleagues (Tan et al., 2000, 2001), who consistently find activation in RH areas for Chinese that are not found in studies of English. It is important to be clear that these right hemisphere areas are in addition to left hemisphere areas that are functional for both languages.

Conclusion

In the simple question of how a reader goes from a graphic input to meaning lies some complexity that can be addressed by comparative analysis. As research on orthographies other than English and writing systems other than alphabetic has developed, we see more clearly some of the universal character of word reading, as reflected in the language constraint on writing systems and the UPP. At the same time, we see that reading is very much affected by the writing system, the orthography, and the language that is mapped by them. Even within the family of alphabetic systems, the consistency of graphic to phoneme mappings appears to be reflected in the brain structures that support word reading (Paulesu et al., 2001). Cognitive neuroscience methods are adding to our understanding of both the universal and particular aspects of reading across different systems. ERP studies point to temporal differences during word identification that depend on the reader's skill in the language and writing system, both for relatively fluent bi-linguals and for beginning learners. Coupled with spatial brain information from ERP as well fMRI, the evidence suggests that additional brain areas are called on to support reading as a function of the demands of the writing system, and that learners as well as fluent speakers show this result.

References

Booth, J. R., & Perfetti, C. A. (2002). Onset and rime structure influences naming but not early word identification in children and adults. *Scientific Studies of Reading, 6*(1), 1–23.

Bowey, J. A., & Hansen, J. (1994). The development of orthographic rimes as units of word recognition. *Journal of Experimental Child psychology, 58*, 465–488.

Chee, M. W., Weekes, B., Lee, K. M., Soon, C. S., Schreiber, A., Hoon, J. J., et al. (2000). Overlap and dissociation of semantic processing of Chinese characters, English words, and pictures: evidence from FMRI [In Process Citation]. *Neuroimage, 12*(4), 392–403.

DeFrancis, J. (1989). *Visible speech: The diverse oneness of writing systems*. Honolulu, HI, US: University of Hawaii Press.

Fiez, J. A., Balota, D. A., Raichle, M. E., & Petersen, S. E. (1999). Effects of lexicality, frequency, and spelling-to-sound consistency on the functional anatomy of reading. *Neuron, 24*, 205–218.

Fiez, J. A., & Petersen, S. E. (1998). Neuroimaing studies of word reading. *Proceedings of the National Academy of Sciences of the United States of America, 95*, 914–921.

Francis, S., & Kucera, H. (1967). *Computing Analysis of Present-day American English*. Providence, RI: Brown University Press.

Hung, D. L., Tzeng, O. J. L., & Tzeng, A. K. Y. (1992). Automatic activation of linguistic information in Chinese character recognition. In R. Frost (Ed.), *Orthography, phonology, morphology, and meaning* (pp. 119–130). Amsterdam, Netherlands: North-Holland.

Koles, Z. J. (1998). Trends in EEG source localization. *Electroencephalography and Clinical Neurophysiology: Evoked Potentials, 106*, 127–137.

Kutas, M., & Hillyard, S. A. (1980). Event-related brain potentials to semantically inappropriate and surprisingly large words. *Biological Psychology, 11*(2), 99–116.

Liu, Y., Perfetti, C. A., & Hart, L. (2003). ERP evidence for the time course of graphic, phonological and semantic information in Chinese meaning and pronunciation decisions. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 29*(6), 1231–1247.

Liu, Y., Perfetti, C. A., & Wang, M. (2003, March). *Learning to read in a new writing system: Evidence from event related potentials*. Paper presented as a poster at the 10th Annual Meeting of Cognitive Neuroscience Society, New York, US.

Pascual Marqui, R. D., Michel, C. M., & Lehmann, D. (1994). Low resolution electromagnetic tomography: A new method for localizing electrical activity in the brain. *International Journal of Psychophysiology, 18*(1), 49–65.

Paulesu, E., Démonet, J. F., Fazio, F., McCrory, E., Chanoine, V., Brunswick, N., Cappa, S. F., Cossu, G., Habib, M., Frith, C. D., & Frith. U. (2001). Dyslexia: Cultural Diversity and Biological Unity. *Science*, 16, 291:2165–2167.

Perfetti, C. A. & Bell, L. (1991). Phonemic activation during the first 40 ms of word identification: Evidence from backward masking and masked priming. *Journal of Memory and Language, 30*, 473–485.

Perfetti, C. A., Liu, Y., & Tan, L. H. (2002). How the mind meets the brain in reading: A comparative writing systems approach. In H. S. R. Kao, C. K. Leong & D. G. Gao (Eds.), *Cognitive Neuroscience Studies of the Chinese language*, Hong Kong: Hong Kong University Press.

Perfetti, C. A., & Tan, L. H. (1998). The time course of graphic, phonological, and semantic activation in Chinese character identification. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 24*(1), 101–118.

Perfetti, C. A., & Zhang, S. (1995). Very early phonological activation in Chinese reading. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 21*(1), 24–33.

Perfetti, C. A., Zhang, S., & Berent, I. (1992). Reading in English and Chinese: Evidence for a "universal" phonological principle. In R. Frost (Ed.), *Orthography, phonology, morphology, and meaning* (pp. 227–248), Amsterdam, Netherlands: North-Holland.

Rugg, M. D. (1984). Event-related potentials in phonological matching tasks. *Brain and Language, 23*(2), 225–240.

Tan, L. H., Liu, H.-L., Perfetti, C. A., Spinks, J. A., Fox, P. T., & Gao, J.-H. (2001). The neural system underlying Chinese logograph reading. *NeuroImage, 13*, 836–846.

Tan, L. H., & Perfetti, C. A. (1998). Phonological codes as early sources of constraint in Chinese word identification: A review of current discoveries and theoretical accounts. *Reading and Writing, 10*(3–5), 165–200.

Tan, L. H., Spinks, J. A., Gao, J. H., Liu, H. L., Perfetti, C. A., Xiong, J., et al. (2000). Brain activation in the processing of Chinese characters and words: A functional MRI study. *Human Brain Mapping, 10*(1), 16–27.

Van Orden, G. C. (1987). A ROWS is a ROSE: spelling, sound, and reading. *Memory and Cognition, 15*(3), 181–198.

Xu, Y., Pollatsek, A., & Potter, M. C. (1999). The activation of phonology during silent Chinese word reading. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 25*(4), 838–857.

Zhang, S., & Perfetti, C. A. (1993). The tongue-twister effect in reading Chinese. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 19*(5), 1082–1093.

Zhang, S., Perfetti, C. A., & Yang, H. (1999). Whole word, frequency-general phonology in semantic processing of Chinese characters. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 25*(4), 858–875.

Ziegler, J. C., Jacobs, A. M., & Stone, G. O. (1996). Statistical analysis of the bidirectional inconsistency of spelling and sound in French. *Behavior Research Methods, Instruments, & Computers, 28,* 504–515.

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