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2

How the Mind Can Meet the Brain in Reading: A Comparative Writing Systems Approach

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Reading is at once both simple and rich — simple enough for cognitive research to have gained an increasingly clear picture of how it works; rich enough to yield important lingering questions to be addressed by the convergence of cognitive and neurocognitive methods. One particular characteristic of reading can illustrate this simplicity and richness: it begins with a reader looking at marks that are encoded in a system — a writing system. We have to take into account that the world has different writing systems if we want to achieve a full understanding of the reading processes. In what follows, we will highlight some of the issues that have been informed by taking a writing system approach and to point to some possibilities for how neuroscience methods will add to the picture.

To be clear, it is the cognitive-behavioral approach that has dominated our own research and it has produced the most information on reading, including how writing systems make a difference. Thus, our treatment of the cognitive neuroscience approach is in proportion to its relative contribution to our thinking about the general questions of reading. One way the cognitive approach forms the foundation for other approaches is that it establishes a heuristic architecture for reading.

A Cognitive Architecture for Reading

Figure 1 shows an overall cognitive architecture, according to more or less standard views that have emerged from research. Although generally it reflects a consensus, there is one way in which this architecture might be controversial. The assumption that word identification includes a routine early phase of mutual orthographic-phonological activation — as opposed to a one-direction route from orthography with an optional route for phonology — is probably not a consensus view. It reflects a hypothesis that visual processing of writing system units immediately initiates phonological processing. The representation of word meaning is immediate but, typically, slightly lagged with this orthographic-phonological activation.

Figure 1 reflects the question of how writing systems influence reading in a most general way, representing the fact that the orthographic units are provided by the writing system. The details of this influence are an empirical matter. A basic constraint on these details provided by the relationship between writing systems and the spoken language is critical: that all writing systems encode spoken languages in one way or another (DeFrancis, 1989). The Chinese writing system has some important differences from alphabetic and true syllabic systems that allow it to make more direct contact with meanings, certainly linguistic meanings and perhaps non-linguistic meanings as well. But its characters ultimately are connected to language at the level of the syllable-morpheme, giving them both a phonological and semantic correspondence.

The standard way to consider the connection between writing system and language is as follows: each system has a basic writing unit that is mapped onto one unit of the language system. Alphabetic systems map phonemes; syllabary systems map syllables, and logographic systems map words. It is interesting to note that the only example of a currently used logographic system is Chinese (and the Japanese adaptation of Chinese characters). And it is questionable whether one ought to accept this designation even for Chinese. Certainly the mapping of single characters onto syllables gives it a syllabic aspect. It fails to be essentially syllabic because the character is not taken to be a unit that is used productively to represent pronunciations but rather a unit of spoken language that has a meaning as well as a pronunciation. Rather than logographic, however, the system can be considered morphemic (e.g., Leong, 1973) or even morphosyllabic (e.g., DeFrancis, 1989; Mattingly, 1992). This is because the character often contains components that provide information about pronunciation or meaning. In any case, the direct expression of

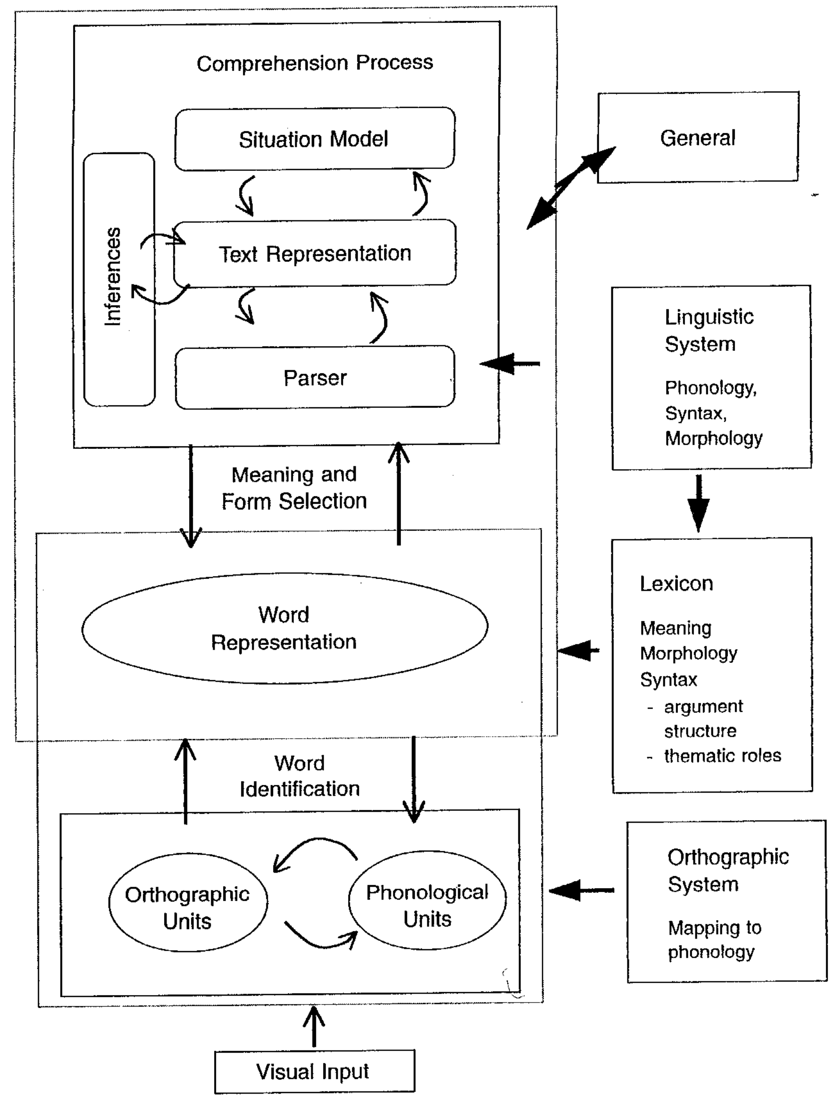

Figure 1. A schematic blueprint showing the general components of reading. Arrows indicate flow of information or direction of influence. Linguistic knowledge informs the components of phonology, morphology, and syntax that are used in word reading and sentence comprehension. General (nonlinguistic) knowledge informs the lexicon and the comprehension process. Word identification is represented as a process that establishes phonological-orthographic identities. Other views of word reading may not share this assumption. However, in most respects, the blueprint makes no commitment to particular architectural assumption. In particular whether bidirectional arrows are needed everywhere, is an empirical question.

morphemes in the writing system — as units of meaning and form (grammatical and phonological) — give characters a status that is unique among the world's writing systems.

Comparisons of Reading English and Chinese

Given the important differences between an alphabetic and a logographic system, one expects to see equally profound differences in the way reading works in the two systems. Differences are apparent immediately at the script level, the conventions for displaying the graphic units of a writing system. Indeed, the visual display differences are quite dramatic. For example, Chinese not only builds its simple graphic units (radicals) out of independent ordered stroke sequences, it also builds its compound graphic units out of compositional units (simple characters) in a number of different ways: left and right; top and bottom; inside and outside. English, and most alphabetic systems, compose all complex units out of linear arrays of basic units (letters). Korean is an exception, demonstrating clearly that linear arrays are not defining characteristics of alphabetic writing. As a second example, the equal spacing of Chinese characters, and the resulting ambiguity about word boundaries, stands in contrast to the word-based spacing in English and most other examples of an alphabetic system. However, in all cases the question is not merely whether there are differences in the visual expression of the systems, but also what differences in reading follow from each difference in visual display. For example, does the linear composition of English compared with the non-linear composition of a single character (compound) word lead to relatively holistic perception of characters and more serial processing of letters?

It is not only differences that are important, however, but also similarities. If all writing systems encode language, then language based reading is a likely process in all writing systems.

Phonology: Some Similarities Between Chinese and English Reading

We have been especially interested in the universal hypothesis that spoken language provides a basis for reading in all writing systems, even when a system such as Chinese allows other possibilities. Could not the phonological word forms of the spoken language be an intrinsic part of reading in Chinese as well as English? Contrarily, could it be that in neither system do spoken language forms play anything more than an incidental role? Both possibilities for finding similarity have seemed plausible at some point.

Indeed, there is an interesting parallel in research on English and Chinese reading. In both systems, there has existed the potential for readers to bypass phonology while accessing only meaning. In both systems, the conclusion that readers did exactly this has been modified in the light of further research. Earlier, it seemed reasonable, even in English, to suppose that skilled readers, with much practice at word reading, used mainly a visual form-to-meaning process, with phonology limited to lending support for difficult reading. Research on alphabetic writing systems, however, has led to the conclusion that phonology is involved in a broad range of ordinary word processing tasks (Berent & Perfetti, 1995; Frost, 1998). This generalization now is incorporated into a variety of models of word reading, including Dual Route (Coltheart, Curtis, Atkins, & Haller, 1993) and distributed non-symbolic models (Harm & Seidenberg, 1999; Plaut, McClelland, Seidenberg, & Patterson, 1996; van Orden, Pennington & Stone, 1990).

In the case of Chinese, it seemed even more reasonable to suppose that Chinese worked as a visual form-to-meaning system. After all, the Chinese writing system has been viewed as meaning-based rather than speech based. But the research has forced a new understanding of Chinese reading: As summarized in a recent review by Tan and Perfetti (1998), the evidence is that Chinese reading involves phonology at the word level as well as at the text level (Tzeng, Hung, & Wang, 1977; Zhang & Perfetti, 1993). The explanation for these discoveries seems to require highly general, perhaps universal, processes, even with constraints imposed by writing systems.

The morphemic nature of Chinese writing led easily to the assumption of a close connection between graphic form and meaning. First, simple Chinese characters (pictographs and their derivatives), according to some, were encoded as images that vividly signal meaning (Liu, 1995; Wang, 1973). Second, in compound characters, one or more semantic components may suggest the character's meaning. About 80% of compounds have a degree of semantic validity: some aspect of their meaning is suggested by a semantic component (Fan, 1986). Some compound characters have two semantic components; others have one semantic and one phonetic component (phonetic compounds). About 85% of present-day characters are phonetic compounds (Perfetti & Tan, 1998; Zhu, 1988). However, the validity of the phonetic component — whether the phonetic component, when pronounced as a stand-alone character, actually is the pronunciation of the whole character — is estimated at about 38% (Zhou, 1978), higher with different computational assumptions. Interestingly, both semantic validity and phonetic validity increase with decreasing printed frequency of the compound character (Perfetti, Zhang, & Berent, 1992). Most important for comparisons with alphabetic writing systems is that a phonetic component always maps to a syllable, never a phoneme. Whereas the *b* in *beech* maps to a segment of the spoken word, a phonetic maps not to a piece of the word but to a syllable that may (or may not) be the whole word. Thus, Chinese writing does not reflect the segmental structure fundamental to alphabetic systems (Mattingly, 1987; Leong, 1997).

Another important property of Chinese is its extensive homophony. Modern-day usage includes about 4,574 characters according to the *Modern Chinese Frequency Dictionary* (Beijing Language College, 1986) and 420 distinct syllables (disregarding tone). Thus, on average, 11 characters share a pronunciation. Context plays a big role in selecting a spoken word from among its phonetically similar cohorts (Li & Yip, 1996). In reading, characters with the same pronunciation are disambiguated by their graphic forms. A graphic form serves, in principle, to select meaning and escape homophony.

It is easy to see why a writing system with these properties encourages the hypothesis that reading is strictly a visual-form-to-meaning process (e.g., Baron & Strawson, 1976; Chen, Yung & Ng, 1988; Hoosain & Osgood, 1983; Tzeng & Hung, 1978; Wang, 1973; Zhou & Marslen-Wilson, 1996). However, the evidence now clearly is otherwise (e.g., Cheng & Shih, 1988; Hung, Tzeng, & Tzeng, 1992; Lam, Perfetti, & Bell, 1991; Perfetti & Zhang, 1991, and other studies reviewed in Tan & Perfetti, 1998). The *identification-with-phonology* hypothesis (Perfetti & Zhang, 1995, Perfetti & Tan, 1998, 1999; Tan & Perfetti, 1997) places phonology as a constituent of word recognition (rather than a by-product), a characterization earlier applied to alphabetic writing (Perfetti, Bell, and Delaney, 1988). Thus, across writing systems, phonology may provide an early source of constraint in word reading (van Orden et al., 1990). Based on experimental results, Perfetti and Tan (1998) suggest that phonology is activated at the moment of orthographic recognition — the point at which the identification system distinguishes a given graphic representation from other (similar and partly activated) representations. Thus, although graphic information initiates identification, phonological activation does not lag behind; rather it is part of a *psychological moment of identification*.

This hypothesis has received support form many studies (see Tan & Perfetti, 1998 for a review), including recent studies by Xu, Pollatsek & Potter (1999) and Chua (1999), who independently report evidence for phonological activation in a semantic categorization task. In addition, Weekes, Chen, and Lin (1998) report effects in lexical decision tasks, where such effects are not always found (Zhou & Marslen-Wilson, 1996.)

This places alphabetic and non-alphabetic reading much closer together on one point than one might have supposed. Phonology has a role in word identification in both systems. This is not to say that role is identical in the two systems.

Phonology: Some Differences Between Chinese and English Reading

The research to date has established that phonology is rapid, probably automatic, and perhaps universal. It emerges in less than 90 ms in semantic tasks (Perfetti & Zhang, 1995) and less than 60 ms in naming (Perfetti & Tan, 1998) and brief exposure masked identification tasks (Tan, Hoosain & Peng, 1995). The research also has exposed some differences that arise from the writing systems. A summary of some of these is shown in Figure 2, based on experimental results from our current or previous work, along with analyses of the writing systems.

Orthography-phonology process

The first difference is the most interesting and the most tentative because it rests on the data from one published study by Perfetti and Tan (1998). In a primed naming task, they found that briefly presented graphic primes first facilitated and then inhibited the naming of a target. This inhibition lasted for about 28 ms before returning to baseline. At the same time that graphic facilitation turned to inhibition, phonological facilitation occurred from a homophone prime to a target. Thus, there was an oscillation phasing effect due to graphic form that was correlated with a phonological effect. No similar situation has been reported for English. Figure 2a shows the effect of Perfetti and Tan (1998), while Figure 2b shows an effect of Perfetti and Bell (1991), who used primed identification with masking rather than naming, and pseudo-word primes instead of real word primes. Although this makes for an imprecise comparison, there is little reason to suppose that a different state of affairs would be found with primed naming in English.

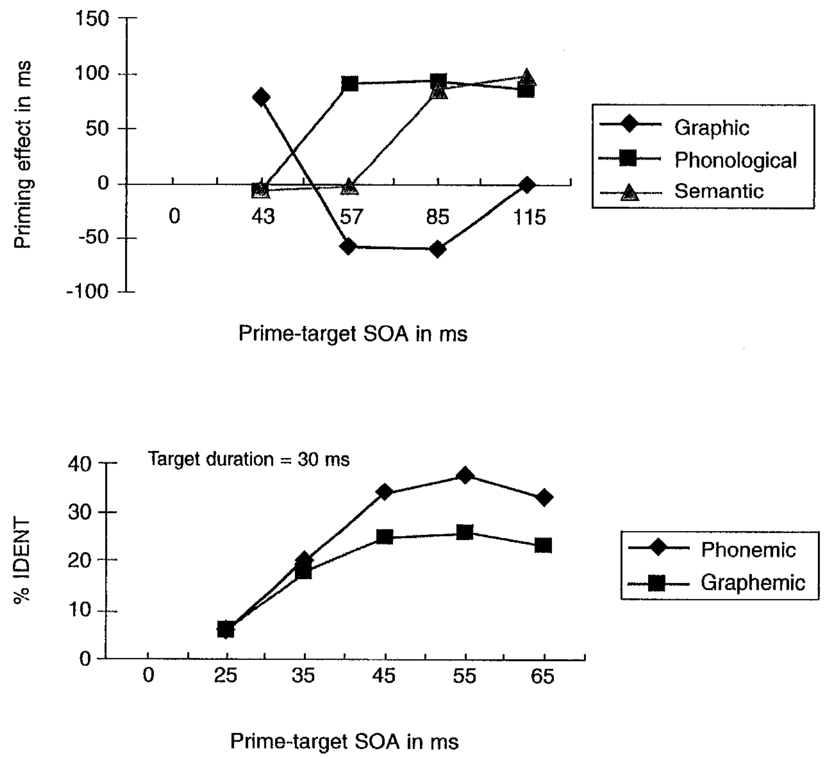

Figure 2. Figure 2a shows data adopted from Perfetti & Tan (1998), who varied the relationship between a prime and a target across several short SOAs (stimulus onset-asynchrony). An early graphic facilitation effect turned into an inhibition effect at the same SOA at which a phonological prime produced facilitation. This bi-phasic alternation of graphic and phonological effects contrasts with English, shown in Figure 2b, based on data in a brief exposure task (with non-word primes) adapted from Perfetti & Bell (1991).

Table 1 summarizes this difference as one between cascade-style and threshold style activation of phonology. The idea is that in an alphabetic system, the word level units do not wait for a complete specification of all letter units prior to activating word level phonology — hence, *cascade* style. In Chinese, the word-level phonology is not activated prior to a full orthographic specification of the character — hence, *threshold* style. Inhibition from visually similar characters occurs upon reaching the threshold of the target because these characters have received activation. Prior to threshold this activation is facilitative, but once a character has been identified (activated at threshold) it is inhibitory.

Table 1
A Comparison of Phonological Aspects of Alphabetic and Non-alphabetic Word Reading

Alphabetic (English)	Logographic (Chinese)
Phonology activated with orthography — cascade style	Phonology activated with orthography — threshold style
Sublexical units: proper parts	Sublexical units: wholes are parts
Phonology can be 'pre-lexical'	'Pre-lexical' is not a coherent concept
Phonology can 'mediate' meaning (but phonological coherence more apt)	'Mediation' is a dubious concept phonological diffusion more apt

Sublexical units

This difference is inherent in the writing system comparison. In English the letters are at a lower level than the words and become constituent parts (wholly contained within) of the whole word. In Chinese, the components themselves are characters. Thus they participate in the system at the higher word level and are not contained wholly within a lower constituent level. The question is whether this matters for processing. Indeed it does. It could be the main difference responsible for the cascade vs. threshold difference described above. The threshold feature of Chinese identification may derive from the fact that a component of a character (e.g., a semantic radical) activates all characters that contain it in addition to activating its own character representation. The inhibition of highly activated competitors then follows as a means for the identification system to secure a lexical identity (including its phonology).

Pre-lexical phonology

This difference follows from the basic differences in sublexical units. The phonology that is activated in a Chinese character may include that of its components as well as the character as a whole. Because the component is not 'pre-lexical', its phonology, whether activated before that of the character as a whole or not, cannot be pre-lexical in the same sense it can be in an alphabetic system.

Mediation

Because a Chinese character typically has so many homophones, the pronunciation of the character — by itself — is not adequately constraining. It will not pick out a unique morpheme. This means that using the phonology to access the meaning — the usual sense of phonological mediation — would be maladaptive process. Indeed, it would be an indeterminate process. Although one might want to say this a basic difference in the two systems — thus allowing mediation in this sense for alphabetic reading — we think there is a lesson to apply from this analysis of Chinese to alphabetic systems. In both systems, one can think of phonology, not as an instrument to meaning, but rather as a constituent of a word that constrains the identification process. The triple constituents of graphic form, phonological form and meaning uniquely constrain the identification of a word, or at least a lexical root. This is a concept of phonological mediation that can replace the instrumental sense in all writing systems.

The Interactive Constituency Model of Chinese Reading

Perfetti and Tan (1998, 1999) and Tan and Perfetti (1997) described a model of character identification that incorporates multi-level representations and interactions among the levels. Taft and Zhu (1997) describe a model that is similar in its use of multi-level representations, while differing in other respects, including the treatment of radicals. Here we want to illustrate a computational instantiation of this model.

Currently, the model is a network of linked units across which activation spreads. The radical input and the phonological levels of the model can be considered distributed representations, whereas the

orthographic and semantic representations can be considered localized representations. An illustration and a description of the model are presented in Figure 3.

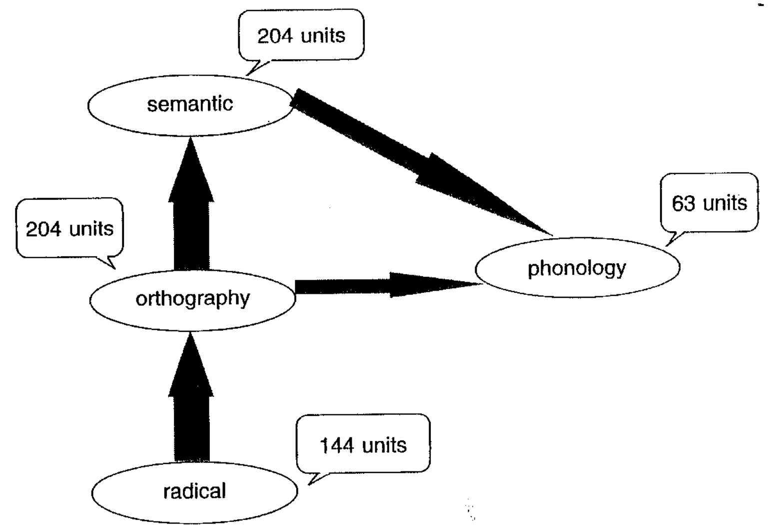

Figure 3. The constituency model. The input units are 144 radicals that begin activation in a three-constituent system. The three constituent levels — orthography, phonology, and semantic — combine to produce a three-constituent identification event.

The model in its current version is a mix of localist and distributed representations with limited scope. It is designed to recognize 204 characters, but we believe it can be easily expanded within the general design principles. Its goal is modestly to capture some of the naming data in experiments. We summarize briefly the main features of the model.

Model framework

Input (radical) level

The 144 input units represent radicals, the basic components of Chinese characters, distributed across 9 slots × 16 binary-code units per slot. Each slot is one radical, assigned according to writing sequence within a character. Because no character in the National Standard Chinese Character Set (GB2312–80) has more than 9 radicals according to the *Chinese Character Information Dictionary* (Beijing Science Publishers, 1988), 9 slots can represent all characters in our simulation set. The 16 binary-code units match the 16 binary codes of the Chinese National Character Component Standard for Information Processing (GB2312–80), and with slots to represent the writing sequence, this system is sufficient to represent the shared radical structure between almost any two Chinese characters. (Two characters sharing all radicals with same writing sequence, but in different positions such as one left-right and one top-down, a rare occurrence, are not distinguished in this system.)

Orthography level

This is a localized representation of the abstract orthography of characters. Each unit of this level represents one of 204 characters.

Phonology level

This distributed representation uses the Chinese national standard Pinyin system, with each syllable coded across 3 units — onset, vowel and tone. To represent the syllables of Mandarin, 23 onsets, 34 vowels and 5 tones are sufficient. With the addition of one additional unit to represent null onsets, the phonological level consisted of 63 units. Because this level is a distributed representation, there are no within-level linkages, in contrast to the orthography and semantic levels.

Semantic level

This is a localized representation of 204 units, each corresponding to a unique meaning of a character. Meaning precision is represented by connection weights between orthographic and semantic levels. The semantic level currently does not represent meaning components.

Connections within orthographic level

There are negative (inhibitory) connections between each pair of orthographic units, reflecting competition between characters at the input level.

Connections within semantic level

Two related meanings are connected at a weight of .5, arbitrarily reflecting the assumption that semantic relations are not perfectly determinate, hence <1. Other connections are set at 0.

Connections between radical level and orthographic level

The radical level is fully connected to the orthography level, sending activation to the 204 character units along hand-adjusted weighted connections. The weights reflect the presence of input radicals in specific characters.

Connections between orthography and phonology

Each orthographic unit has three connections weighted 1: one to its onset, one to the vowel and one to the tone. All other weights are set to 0.

Connections between orthography and semantics

A precise meaning character is connected to one semantic unit with weight 1. A vague meaning character connects to one semantic unit at weight .9 and to all other 203 semantic units at randomly distributed weights summed .1.

Connections between semantic and phonology levels

Each semantic unit is connected with its three phonology units (onset, vowel, and tone) at weight 1.

Similarity representation

A key idea of the model is to represent similarity along graphic, phonological, and semantic dimensions, implemented as follows: Graphic similarity results from shared radicals. A given radical input activates a cohort of similar characters. Phonological similarity results from shared phonological activation patterns. Homophones have identical patterns; lower levels of similarity result from shared onsets, vowels, or tones. Related meanings arise from connections between the semantic units of characters that are semantically related. For example, semantically related primes and targets are linked with connection weights .5.

Threshold

Each unit in all three levels has a threshold below which the unit cannot send output to another level. For example, below threshold, orthographic units send no output to phonology. The threshold of a character is lowered by the presentation of an orthographically similar prime.

Simulation

Certain assumptions of the model — especially a threshold setting for orthographic units — turn out to be useful for simulating Perfetti and Tan's (1998) time course results for graphic, phonological, and semantic priming effects. Of special interest is the oscillation effect for orthographically similar primes and the rise of phonological priming, coincident with orthographic inhibition. The simulation of this effect is shown below in Figure 4. (The X axis shows processing cycles; the Y axis shows activation level, <0 reflects inhibition.)

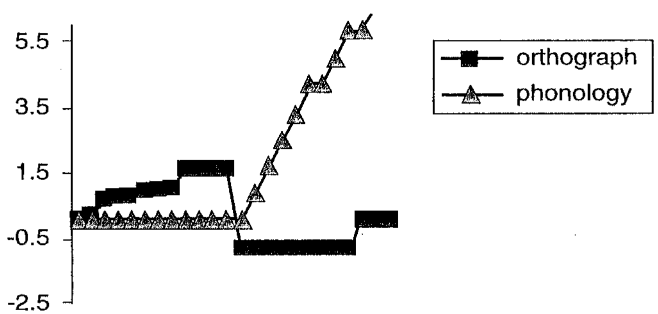

Figure 4. A simulation of the oscillation effect for graphic and phonological priming (Perfetti & Tan, 1998).

What the simulation captures clearly is the pattern of graphic oscillation, with the onset of inhibition coinciding with the onset of phonological facilitation. This occurs because visually similar orthographic units are activated by the same radical. If one of these activated units turns out to be the target, its activation level is nearer to threshold than it would be otherwise; hence, graphic facilitation at first. But when an orthographic unit reaches threshold, it sends its activation to the phonological unit, immediately allowing a phonological priming effect if the activated unit happens to be a homophone — i.e., a pronunciation shared with the target.

At the same time, inhibition results from this longer presentation of a prime, because it reaches threshold and begins to compete with other orthographic units — including the target. For a few processing cycles, the target actually supports activation of the prime character through their shared orthographic units. This competition delays identification of the target.

Phonological priming effects are successfully simulated based on preactivation of phonological units, which occurs as the orthographic unit reaches threshold and activates its connected phonological unit. Semantic priming results also from an orthographic unit that reaches threshold and sends its output to its semantic unit, which can activate related orthographic units, especially the target. However, this priming is not as rapid as phonological priming, because the link between a target's semantic unit and that of a related prime is not as strong as the link between the target's orthographic unit and its phonological units.

This difference in semantic and phonological linkages is an indirect implementation of the assumption of differential determinacy of semantics and phonology, given an orthographic form. It might equivalently be characterized as capturing the idea that while forms can be identical (homophones), meanings cannot. At the present these two related assumptions are not distinguished.

The model also simulates the meaning precision effect — faster priming for precise primes, but only for meaning-related primes. This is because the system doesn't care about semantics at the phonological or graphic level; a vague homophone prime is not different from a precise homophone prime. But at the semantic level, precision is represented directly in the distribution of meaning activation across the semantic units.

A further implication of the model

Important to the model's ability to simulate the graphic-phonological oscillation effect is the role of the orthographic level and its relation to the radical input level. In particular, the important assumption is that both phonology and similarity-based orthographic competition arise from an orthographic character when its threshold is reached. An implication of the model, then, is that the orthographic interference effect requires character-level competition and will not occur based on visual similarity at the radical level. An unpublished experiment carried out by Liu and Perfetti gives some support for this prediction. When the primes were pseudo-characters, composed of legal radicals and made to be visually similar to the target, there was no interference observed across three short SOAs (54 to 140 ms). Real character primes with visual similarity showed interference at 86 ms in error rates, an SOA at which pseudo-characters produced facilitation. Although the interference effect for visually similar primes was somewhat less than that observed by Perfetti and Tan (1998), the pattern of facilitation-without-interference by pseudo-characters, and facilitation then interference from actual characters, is consistent with that study and with the implemented Interactive Constituency Model.

The significance of the modeling effort lies not so much in its specific implementation, which will undergo further development, as in the instantiation of the principles that are central to the Interactive Constituency Model. The basic principle is the organization of word identity as a triple of its three constituents, all of which are activated in normal reading processes. This entails rapid phonology through direct connections between orthographic word forms and phonological word forms. When a character maps to a spoken word-syllable, the spoken syllable is automatically activated. The evidence is that this activation applies to semantic tasks as well, although the simulations have been concerned only with naming. It also entails rapid semantics. But semantic processes at the word level are less constrained, less deterministic, than phonological processes.

Finally, we note that the implemented model, but not the general framework of the Interactive Constituency theory, privileges whole characters over components. It seems likely, based on a variety of results, that whole character forms control output from the orthographic level. This does not mean that character components do not play a role in this, and, in fact they do. For example, a dissertation by Yang (1999) on the role of components in the time course of priming effects of the sort modeled here showed that the phonology of both whole character primes and their phonologically valid components affected the naming times of related targets. Such multiple unit effects are consistent with the general model, and particular implementations could incorporate the connections needed to produce them.

What Can Cognitive Neuroscience Methods Add?

The development of neuroimaging techniques, especially fMRI, has led to a dramatic surge in research aimed at identifying the functional

neuroanatomy of reading. (For reviews, see Fiez & Petersen, 1998; Price, Indefrey, & van Turennout, 1999.) This goal does not supplant, but rather complements, the identification of components of reading that have been the fruit of cognitive behavioral studies. However, there have been some inconsistencies in the results from neuroimaging studies within English, and it may be fair to say that more studies and perhaps new techniques (Horwitz, Rumsey, & Donohue, 1998) are needed before such studies actually add clearly to the cognitive understanding of how reading works.

Cross language and cross-writing systems comparisons may actually help with this problem because such comparisons may expose those shared functional mappings that are robust enough to survive the profound differences in both the principles and the visual appearance of the world's writing systems. Unlike the question of trying to identify 'the phonological decoder' or the 'semantic access network', the cross systems comparison seeks the answer to a simpler question that may produce leads to the more detailed goals. Thus, the question of 'same process' vs. 'different process' can be directly cast onto neuroanatomy: Do the same neuroanatomical networks involved in reading an alphabetic writing system also function in the reading of Chinese?

There is already an indication that *within* the class of alphabetic writing systems, the depth of the orthography makes a difference in the procedures used for reading words (Paulesu, McCrory, Fazio, Menoncello, Brunswick, Cappa, Cotelli, Cossu, Corte, Lorusso, Pesenti, Gallagher, Perani, Price, Frith, & Frith, 2000). In the case of Chinese-English comparisons, one might expect more profound differences, based on the traditional understanding of Chinese. However, considering the cognitive research showing pervasive phonology in Chinese reading, perhaps any differences will be accompanied by critical similarities that reflect the universal appearance of word-level phonology in reading.

To illustrate how a neuroimaging approach can help in a specific case, consider the question of hemispheric specialization for Chinese character reading. Based on behavioral methods that control bilateral processing (e.g., hemifield visual presentation), a number of studies suggested that processing of single Chinese characters is right lateralized (Cheng & Yang, 1989; Tzeng, Hung, Cotton, & Wang, 1979). From such studies arose the *Chinese character-word dissociation hypothesis*, reviewed in Fang (1997). The idea is that a single character is processed in the right hemisphere (by perceptual and semantic processes), whereas two characters (always a word) are processed in the left hemisphere, evoking the spoken language systems. Support for this dissociation hypothesis has not been consistent, however, with some studies finding no right hemisphere advantage for single characters (Besner, Daniels, & Slade, 1982; Fang, 1997; Leong, Wong, Wong, & Hiscock, 1985). Data from neuroimaging might be helpful.

Such data come from a recent study by Tan, Spinks, Gao, Liu, Perfetti, Xiong, Stofer, Pu, Liu, and Fox (2000). In this fMRI study, subjects performed a word generation task in which they implicitly produced a word semantically related to a visually presented target. This task, which requires semantic analysis and implicit word retrieval, was performed for one-character words with either vague or precise meanings, and two-character words (precise meanings). Activation was compared across these stimulus types and with a fixation control. The results clearly exposed a shared neural network across the one and two character tasks. This network included strong left-lateralized components in frontal (BAs 9, 46, and 47) and temporal (BA 37) cortices along with right-lateralized components in the visual (BAs 17–19) and parietal areas (BA 3), as well as the cerebellum. The left frontal regions showed peak activation patterns that were nearly identical for one- and two-character words and for vague as well as precise-meaning characters. In addition, left frontal activations were more pronounced for vague compared with precise meanings.

The fMRI results thus converge with one hypothesis from the cognitive research and contradict another. They suggest that the distinction between vague and precise meanings, which is functional in cognitive studies of naming and brief exposure identification, has a neuro-anatomical correlate. Approximately speaking, vague-meaning characters require more effort after meaning, and this is reflected in left frontal cortical regions. The contradiction is that the study provides no evidence for the dissociation hypothesis. It appears that the neuroanatomical networks that support one character processes are the same ones that support two character processes, at least in implicit semantic association tasks. These networks overlap substantially with those identified in English word reading.

Of course, what one wants is converging evidence. And there are other studies suggesting that the dissociation hypothesis is wrong. A neuroimaging study of Chinese single character processing by Chee, Tan and Thiel (1999) showed peak activations in the left hemisphere regions (e.g., BA 44/45, BAs 46/9 and 37) and strong activations in bilateral occipital and bilateral parietal regions (BA 7). This result and the Tan et al. (2000) result are in substantial agreement. In addition, clinical studies of selective impairments with Japanese patients indicate similar neural pathways support both Japanese Kanji and Kana reading (Koyama, Kakigi, Hoshiyama, & Kitamura, 1998; Sugishita, Otomo, Kabe, & Yunoki, 1992). Although there is much to learn about the differences in processes that are associated with different writing systems, and even within systems (Paulesu et al., 2000), it appears that there may be some shared functional neuroanatomy that is responsible for reading. We should expect this shared structure to reflect reading's dependence on shared visual processes and language processes, both of which appear to be intrinsic and hence universal to reading.

One thing that even event-related fMRI is unlikely to provide is temporal information on processes that is comparable to the temporal grain that our models of cognitive processes have developed. For example, the timing of semantic and phonological outcomes is a matter of milliseconds, as are the even smaller differences between them. For such timing observations, event-related potentials (ERP) are promising, and indeed have been very informative on issues of language processing (Hagoort, Brown, & Osterhout, 1999). Of special interest in language processing has been the N400, a mid-latency endogenous component related to subjects' semantic and pragmatic expectations. Kutas and Hillyard (1980), who first described this component, found a larger N400 when a sentence ended with a semantically anomalous word. Furthermore, the more consistent or predictable the sentence endings, the smaller the N400 (Kutas, Lindamood, & Hillyard, 1984). The N400 amplitude also is influenced by the characteristics of single words. Repeated words, high frequency words, and concrete words elicit smaller N400s than do novel, low frequency, and abstract words (Kutas, Federmeier, & Sereno, 1999; Kutas & Van Petten, 1994). Interestingly, a phonological prime prior to a target word reduces the N400 latency (Radeau, Besson, Fonteneau, & Castro, 1998).

ERP data can help inform some of the comparative issues we have raised. One particular example is the role of phonology as reported by Perfetti and Zhang (1995) for meaning judgments and by Xu, Pollatsek and Potter (1999) and Chua (1999) for semantic categorization. In the meaning judgment experiments, the critical finding is that when subjects judge whether two characters have the same meaning, interference (in decision times and error rates) is observed if they instead happen to have the same pronunciation. And inversely, when subjects judge whether the characters have the same pronunciation, there is interference when they have the same meaning. The time course of these interference effects suggested phonological interference before semantic interference. In an

ERP version of this experiment, we can ask whether interpretable ERP components are associated with the various tasks and conditions. For example, the N400 might be associated with processing the second word as a function of its relationship to the first word.

Our preliminary data show ERP components vary in interesting ways in this task. For example, the N400 component during the second stimulus is reduced when the reader is judging meaning compared with pronunciation (homophony). This is consistent with the semantic interpretation of the N400. Additionally, the subject's processing mode is seen in the N400. When the task is meaning judgment, a second stimulus that is semantically similar to the first stimulus produces a reduced N400 compared with one that is unrelated. This too is to be expected on the semantic interpretation of the N400. However, when the task is homophone judgment and the second stimulus is indeed a homophone, the N400 is also reduced compared with when the second stimulus is unrelated. Thus in a homophone task, the homophone is congruent with the task and the N400 reflects this fact. In English rhyme judgments, similar results have been reported (reduced N400 for rhymes compared with controls; Rugg, 1984).

Beyond these processing mode effects, the interesting questions concern the 'out-of-mode' effects — when a homophone occurs during semantic judgments and when a synonym occurs during homophone judgments. The general picture is that reduced P200 components are produced by homophones during meaning judgment and reduced N400 by synonyms during homophone judgment. It appears we can identify task dependent and strictly word (form and meaning) effects in either P200 or N400 (Barnea & Breznitz, 1998). In particular, P200 may signal early phonological activation in word identification across languages. This encourages the belief that ERP data will prove to be informative on questions of the time course of the form and meaning constituent of words and that cross writing system comparisons will be useful.

Conclusion

A cross-writing systems approach to reading is important to an understanding of the basic universal processes in reading. The cognitive behavioral research has pointed to the possibility of a universal linguistic underpinning to reading. Results that we've reviewed point to both universal and writing-system specific processes when Chinese is compared with English. The Interactive Constituency Model gives a general account of the components of reading, and its computational implementation can simulate some specific results. Further understanding of how reading processes are expressed in different writing systems and different languages can benefit from the convergence of neuroimaging and electrophysiological methods with cognitive behavioral methods; progress probably depends on studies using different methods. Despite its complexity at some levels, the relative simplicity of reading at the word level makes it a particularly good problem to see how the mind meets the brain. The comparative approach helps to expose the most general function-structure relations in reading.

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