Cognitive Neuroscience Studies of the Chinese Language

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'Cognitive Conjunction' Analysis of Processing Chinese

Che-Kan Leong

In as much as any one person can be so credited, Nobel laureate Herbert Simon is usually regarded as the founder of cognitive science. He explained the field as 'the study of intelligence and its computational processes in humans (and animals), in computers, and in the abstract' (Simon & Kaplan, 1989, p. 2). Intelligence systems in this context are identified with adaptability, with learning, problem solving and evolution. Simon and Kaplan discussed from a computational standpoint the contributions to cognitive science from psychology, artificial intelligence, linguistics, philosophy and neuroscience to explain the architecture of intelligence systems and different levels of abstraction. Just as they considered neuroscience as important in 'providing hypotheses about fruitful architectures for machine intelligence (and presumably also human intelligence)' (p. 6), so Sejnowski and Churchland (1989, p. 343) emphasized the brain and cognition connection in that 'neurobiological data provide essential constraints on computational theories'. In their elegant paper Sejnowski and Churchland discussed neural and connectionist models to the late 1980s and stressed that knowledge of brain architecture could explain the problem solving level and the algorithmic level of analyses of human cognition. They detailed different anatomical and physiological techniques, including imaging technology, to buttress their argument that integration should consist of intertwined theories such that phenomena at one level are explained by those from another level.

More recently, Price and Friston (1997) introduced the concept of *cognitive conjunction* as a new approach to designing and analysing cognitive experiments. Price and Friston explained that, 'Cognitive conjunction studies are designed such that two or more distinct task pairs each share a common processing difference. The neural correlates of the process of interest are then associated with the common areas of activation for each task pair ...' (1997, p. 261). While these scientists' interest is in brain activation and cognitive components, together with their statistical considerations, it may not be inappropriate to borrow both the concept and the term *cognitive conjunction* for this edited volume on cognitive neuroscience studies of the Chinese language.

As is well known, an edited volume suffers from some diffusion of conceptual underpinnings and methodological sophistication, but gains from enrichment of ideas from diverse schools of thoughts. This volume is no exception. It contains cutting edge papers discussing research into the processing of Chinese from connectionist and functional neuroimaging perspectives and the acquisition of lexical meaning and semantic structures from computational viewpoints. It has insightful papers on phonological, orthographic and semantic strategies in reading two character Chinese words and picture naming and recognition of Chinese words. It has critical psycholinguistic analyses in mapping phonology and meaning of Chinese words and early phonological activation in processing the Japanese kanji, which is derived basically from Chinese characters. It has clear exposition of a psycho-geometric theory with supporting data in explaining the analysis of visual spatial patterns of Chinese characters. It also has succinct papers in the spirit of corpus linguistics on the development of vocabulary in Chinese secondary school students. Thus the fifteen chapters span from the basic to the more applied research and all are based on current theories in explicating the processing of Chinese.

From the set of rather diverse papers as outlined above, it is the aim of this commentary to show some 'common processing difference', to borrow from the neuroscientists Price and Friston (1997). We attempt to provide some moderate coverage on the cognitive processing of Chinese characters and words to show what the linguist DeFrancis (1989) calls the 'diverse oneness' even in dealing with one-language systems such as Chinese. We are conscious of the lack of coverage of other key areas in processing Chinese, such as the parsing of sentences and discourse processing. It is hoped this selective coverage with its diverse topics, methods and research findings will further stimulate the cognitive and neuroscience study of Chinese and other language systems.

Cognitive Neuroscience Approaches

The pioneering work by Tzeng, Hung and Wang (1977) on speech recoding in reading Chinese characters nearly thirty years ago may be said to provide the impetus to enhance further systematic studies of information processing of the Chinese language system. In the intervening years there have been investigations of inter-related issues of cognitive processing of Chinese as reported in edited volumes (Chen & Tzeng, 1992; Kao & Hoosain, 1984, 1986; Leong & Tamaoka, 1998; Liu, Chen, & Chen, 1988; Peng, Shu, & Chen, 1997; Wang, Inhoff, & Chen, 1999), books (e.g., Hoosain, 1991), in addition to cumulative research papers from laboratories in Pittsburgh (e.g., Perfetti & Tan, 1998; Tan & Perfetti, 1998, 1999), in Sydney (e.g., Taft & Zhu, 1997), in London (e.g., Zhou & Marslen-Wilson, 1995), in Taiwan (e.g., Liu, Wu, & Chou, 1996), in Beijing (e.g., Peng, Liu, & Wang, 1999), among other sources. Some of the authors in these research studies are represented in this volume.

Process-oriented approach

Careful reading of the above works suggests several trends. One is the process-oriented approach to explore the general properties of language systems within the framework of human cognition (Alegria, Holender, Morais, & Radeau, 1992). This information processing approach has been applied with considerable success to show fine-grained differences in cognitive processing of alphabetic language systems. Take for example the Romance languages such as Spanish and Portuguese. These language systems are syllable-timed with phonemic constraints operating on syllables, and provide easier access to phonology as compared with the stress-based English (Morais, 1995). For the highly regular Dutch alphabetic language system, research findings with children indicate that grapheme-phoneme conversion can go on in parallel with the lexical look-up in cascading processes (see Leong & Joshi, 1997).

The same information processing approach to understanding lexical access to the non-alphabetic Chinese and Japanese language systems has provided theories and research findings into the cognitive analysis of these systems. Take the biscriptal (kanji and kana), or more correctly, the tri-scriptal (kanji, hiragana and katakana) Japanese syllabary as an example. The processing of kanji symbols (basically Chinese characters) with their On- and Kun-reading to represent meaning, and of kana (basically phonetic) symbols with their moraic segments to represent subsyllabic and timing units, may involve different cognitive structures (Inagaki, Hatano, & Otake, 2000; Leong & Tamaoka, 1998). In the case of the morphosyllabic Chinese, the phonological basis in analytic character and word reading has been shown in psychological studies (e.g., Perfetti & Zhang, 1995) and this phonological activation occurs 'at lexicality' or 'lexically' (Perfetti, Liu, & Tan, chapter 2; Perfetti, Zhang, & Berent, 1992, p. 228). Thus some of the critical and interesting research questions are the extent to which recognition and naming Chinese characters and words is aided by phonological representation.

Cross-language studies

The other trend is the need for cross-language studies to examine underlying mechanisms of processing shallow or transparent and deep or opaque alphabetic language systems and the morphosyllabic Chinese. While this volume is concerned almost solely with Chinese, we should bear in mind that the morphosyllabic nature of Chinese entails a phonetic component of Chinese characters (DeFrancis, 1989). This term is preferred over the earlier term of 'phonosemantic' proposed by Boodberg (1937), which stresses the meaning part as important over the syllabic aspect of Chinese characters. Noted linguists such as Yuen Ren Chao (1968, 1976) and Michael Halliday (1981) all emphasize the shape-sound-meaning interrelationship of the 'complex of character-syllable morpheme' characteristic of Chinese characters (Halliday, 1981).

All these linguists emphasize from diachronic and synchronic Chinese linguistics the underlying phonological nature of the language system. Chao (1968), for example, carefully distinguishes in Chinese the *zi* 'sociological word' from the *ci* 'syntactic word'. He states: 'By the "sociological word" I mean that type of unit, intermediate in size between a phoneme and a sentence, which the general, non-linguistic public is conscious of, talks about, has an everyday term for, and is practically concerned with in various ways. It is the kind of thing which a child learns to say, which a teacher teaches children to read and write in school' (Chao, 1968, p. 136). Halliday (1981) also emphasizes this syllabic nature of Chinese. He suggests that 'the phonology [for Chinese] remained a phonology of the syllable, always analysed into initial and final, with the initials classified by place and manner of articulation and the finals by rhyme, vowel grade, labialisation and tone' (Halliday, 1981, p. 137).

This paradigmatic process is explained in terms of analogies made between members of a set of utterances sharing speech characteristics in a slot-filling 'network of relationships' (Spencer, 1991, p. 417). The emphasis on the paradigmatic analysis of Chinese characters and words is important for at least two reasons. One reason is that in the current phonetic system (*Pin*[1]*yin*[1] in China or *Zhu*[4]*yin*[1] *Fu*[2]*hao*[4] in Taiwan) for beginning reading, what constitutes a syntactic word will determine the way that word is transcribed phonetically. The other reason is that in real classroom practices, learning to read Chinese integrates the phonological and orthographic components in parallel in building a network of related shape, sound and meaning components (Leong, 1997). It is this paradigmatic nature in linking speech to reading print that seems to be important in learning to read Chinese (Leong, 1997) and one that should be exploited, as shown in two studies with *Pu*[3]*tong*[1]*hua*[4] speaking Chinese children in Beijing (Leong & Tan, 2002). The Leong and Tan work, which highlights the main vowel in the rime part of the intrasyllabic segments of Chinese characters and the involvement of speech-sound segments retrieval and repetition, points to phonological processing skills common to and modulated by language systems. These common and specific phonological representations investigated cross-linguistically should further advance our knowledge of reading as cognitive development and also developmental dyslexia in different language systems (Goswami, 2000).

This discussion on phonological processing and the specific nature of such processing in Chinese in relation to early reading is within the context of the *universal phonological principle* and especially the Interactive Constituency Model (Perfetti, Liu, & Tan, chapter 2; Perfetti & Tan, 1999; Tan & Perfetti, 1999) of visual word identification. The Interactive Constituency Model specifies that the orthographic-phonological form-form mapping at the character or word level is stronger and faster acting than the form-meaning mapping. However, the model also provides for the activation of orthographic units, which should include stroke complexity, printed frequency of characters (e.g., Leong, Cheng, & Mulcahy, 1987) and 'higher' orthographic units of 'stroke patterns' as shown by Chen (chapter 7; Chen, Allport, & Marshall, 1996) and other contributors to this volume. We shall return to these issues in subsequent sections.

Cognitive neuroscience architecture of language

While phonological processing modulated by psycholinguistic consideration of different language systems provides a locus of reading processes, a much more powerful framework should link the cognitive, behavioural and biological levels. This neuro-developmental aspect with emphasis on functional neuroimaging is an important scientific advance to delineate more clearly the basic architecture of cognitive and linguistic operations and their mapping onto neural substrates in different language systems and specific and interrelated domains within each system (Matthews, Fu, Chen, & Iversen, chapter 3; Perfetti, Liu, & Tan, chapter 2).

William James' (1890) reference to changes in cortical blood flow during mental operations and Sherrington's (1940) vision of large-scale visualization of physiological activities can now be tested with the advent of new theories and functional neuroimaging techniques to study the neurocognition of language. Non-invasive neuroimaging technology such as *magnetic resonance imaging* (MRI) with its high anatomic resolution permits in vivo search for subtle and mild changes in geometric configurations of the human brain. *Functional magnetic resonance imaging* (fMRI) provides a measure of the hemodynamic responses in the brain during the performance of cognitive and linguistic tasks; and *positron emission tomography* (PET) allows the measurement of changes in neural activities by measuring changes in regional cerebral blood flow (for details, see Brown & Hagoort, 1999; Eden & Zeffiro, 1997).

These neuroimaging techniques combined with careful experimental strategies of cognitive psychology have led to a more refined understanding of the organization of language in normal human brains and the complexity of brain structure. Some of the advances in addition to what is described in Perfetti et al. (chapter 2) and Matthews et al. (chapter 3) can be outlined. Neuroimaging techniques have led to the observations that there are different routes between word perception in visual cortices and speech production from motor cortices and that practice blocks or novelty would need different neural circuitry for responses (Posner & Raichle, 1994; Raichle, Fox, Videen, MacLeod, Pardo, Fox, & Petersen, 1994). Neuroimaging studies have also led to the observations that the cerebellum plays a role in the cognitive aspects of single word processing in addition to the motor aspects of speech (Leiner, Leiner & Dow, 1993; Posner & Raichle, 1994)

Following a well specified model of processing visual word forms

(Petersen, Fox, Snyder & Raichle, 1990) and that of working memory (Baddeley, 1986), Friedman, Kenny, Wise, Wu, Stuve, Miller, Jesberger & Lewin (1998) used fMRI to study 11 healthy adults during their covert word generation beginning with particular letters in the *Controlled Oral Word Association Task* (COWAT). These researchers constructed from their fMRI results a 'brain-area by cognitive function' matrix based on the co-ordinate systems of Talairach and Tournoux (1988), which can be translated into Brodmann areas. To grossly over-simplify this elegant study, Friedman et al. (1998, p. 248) found that the covert generation of words was associated with the following areas of the left hemisphere: '(1) Brodmann areas 44 and 45 in the inferior frontal gyrus, (2) Brodmann areas 21 and 37 in the caudal portion of the middle and inferior temporal gyri, and (3) striate and/or extrastriate areas (Brodmann areas 17 and/or 18).' While one may speculate on possible results from different brains based on three-dimensional analysis such as Roland and Zilles (1994), these findings are generally consistent with those of other neuroimaging studies. What is important is that these researchers showed that individual brain areas subserve multiple cognitive functions and that individual cognitive functions activate multiple brain areas.

Interrelated Issues of Orthographic and Phonological Forms and Meaning in Processing Chinese

The necessarily succinct discussion above suggests that cognitive activities such as reading and language are typically studied in cognitive science as components in terms of millisecond reaction times to measure the time course of cognitive operations. The advent of neuroscience technology such as functional imaging techniques enables the testing of where these operations are localized in specific areas of the brain. What is important is that the fine-grained latency measures, the visualization of fairly precise brain areas from fMRI and the recording of brain activation from electrophysiological measures such as *event-related potentials* (ERP), all require well-defined theories for the integration of these different levels of component operations. Simon and Kaplan (1989, p. 26) put this *sine qua non* clearly and succinctly: 'What is a reaction time without a theory relating time to amount of processing? What is an image from a microscope without the optical theory that explains what a microscope does?'

Activation models and neural substrates

The various chapters in this volume demonstrate how these deceptively simple questions of Simon and Kaplan (1989) are answered in some ways with reference to the processing of Chinese. **Perfetti, Liu, and Tan** in their *tour de force* paper (chapter 2) reiterate the need for cross-language and cross-writing studies of reading and discuss their updated orthographic-phonological activation model to explain the general components of reading. This Interactive Constituency Model emphasizes that in visual word identification the orthography to phonology activation (form-form mapping) is stronger and faster acting than the orthography to meaning activation (form-meaning mapping). In earlier papers, Perfetti and Tan (1999) and Tan and Perfetti (1999) have demonstrated how this model explains the primacy of phonology to orthography activation over the orthography to meaning activation in the visual recognition of two-character Chinese words. The current model consisting of a network of linked units with spreading activation should also apply to other language systems. Perfetti, Liu and Tan are modest in their findings: 'phonology is rapid, probably automatic, and perhaps universal'.

In addition to their accumulated experimental results from various priming, forward and backward masking experiments, Perfetti et al. educe two further lines of converging evidence to support the general framework of their multi-level representations and interactions amongst the levels as mapped out in their Interactive Constituency Model. One line of research is electrophysiological from event-related potentials (ERP). The other line of work is from functional neuroimaging (fMRI).

In their ERP studies Perfetti et al. ask if the time course of the interference effect in judging characters with the same meaning and the same pronunciation might be associated with the negative wave form N400. The N400 amplitude usually shows a large negative effect when a subject is presented with a final word (especially an open-class word) semantically incongruous in a sentence whereas congruous endings show a positive going wave (Kutas & Van Patten, 1988). In a detailed review of event-related brain potentials in 'electrifying psycholinguistics', Kutas and Van Patten (1994) discuss the significance of peaks, amplitude and polarity of ERP waveforms; the advantages (e.g., large amounts of data, freedom from extraneous task demands, providing a topographic map of the brain in magnetic ERP) and disadvantages (e.g., experimental constraints, overlapping components elicited by the same stimulus) in using ERPs to study language processing.

The approach taken by Perfetti et al. in their ERP study of the time course, when there is a conflict in form-meaning in Chinese characters and words, is analogous to the electrophysiological study of the interactions in amplitude and latency between rhyme and orthographic similarity judgment by Polich, McCarthy, Wang, and Donchin (1983). Similar to Perfetti et al., Polich et al. also found from their ERP recordings that both orthographic and phonological information is accessed early and continues to interact as reflected by P300 latency and response time. The finding by Polich et al. that conflict of English word orthography with phonology produces large reaction time effects adds support to the cascading style of English phonology activated with orthography, as explicated by Perfetti et al. (chapter 2).

Perfetti, Tan and their colleagues provide further converging evidence from fMRI studies to show extensive activities of the neural systems in processing Chinese characters and words with vague and precise meanings (Tan, Spinks, Gao, Liu, Perfetti, Xiong, Stofer, Pu, Liu, & Fox, 2000). The Tan et al. results suggest that linguistic complexity in terms of semantic vagueness and precision modulates brain activation and also challenge the belief that reading single Chinese characters is right lateralized and reading two-character words is left lateralized.

The significance of the Tan et al. (2000) study in challenging the conventional view of dissociation in neural substrates in processing single Chinese characters and two-character words is commented on by **Matthews, Fu, Chen and Iversen** (chapter 3). Matthews et al. provide a clear explication of the nature and characteristics of functional magnetic resonance imaging and positron emission tomography (PET) studies of the organization of language in the brain. Consonant with the earlier views expressed by Simon and Kaplan (1989), they reiterate the need for a 'firm psychological model' and discuss the complexity in teasing out confounds from specific language aspects. They also point to such exciting aspects as brain plasticity in early and late second language acquisition and effects of gender.

Matthews et al. report an imaging study in which native Mandarin or Putonghua speaking Chinese subjects make semantic judgment by first accessing the phonology of stimulus Chinese characters and stimulus Pinyin symbols sounding or not sounding like real Chinese words. Consistent with other studies they found the involvement of Brodmann areas (BA) 44/45 and BA47 in the left inferior frontal areas in both the character and Pinyin reading and further suggest that the right hemisphere may be involved in processing 'phonological units larger than a single phoneme'. Matthews et al. discuss other intricate and significant aspects of their study such as the finding of the involvement of stronger left cerebellum activation for character reading relative to the Pinyin reading in their novel semantic judgment task based on phonological characteristics rather than visual forms of the stimulus materials. They suggest that patterns of brain activation result from phonological, orthographic and meaning processing of Chinese characters and words, and not so much from their 'surface forms'. This notion finds support in Chee, Caplan, Soon, Sriram, Tan, Thiel, and Weekes (1999), who carried out one of a small number of neuroimaging studies characterizing Mandarin Chinese and English sentence processing in fluently bilingual Chinese subjects. Chee et al. demonstrated that their fluently bilingual Singaporean Chinese subjects, exposed early to both language systems, show an overlap of activations of prefrontal regions. They argued that the overlap of common neuronal networks reflects conceptual and syntactic processing of written Chinese and English, rather than surface language forms of these disparate systems.

Very recently, Tan, Feng, Fox and Gao (2001) used event-related fMRI to study the neural substrates subserving the automatic processing of sublexical phonological information in reading aloud regular and exception (irregular) Chinese words by ten subjects. They find a large neural network activated by reading the two types of Chinese stimulus words with the involvement of 'left inferior frontal regions (BAs 44/9, 45/47), left (pre-)motor cortex including supplementary motor area, and left superior temporal lobe' (Tan et al., 2001, p. 85). They show that BA9 and BA47 are important in the orthography to phonology transformation process and also the heavy involvement of the right hemisphere because of the unique square-shaped Chinese characters demanding fine-grained analyses of spatial features. The Tan et al. (2001) event-related fMRI study is important in elucidating the neural involvement in analysing the inter-related sub-processes of phonological, tonal processing and the articulation of Chinese words. Corroborative results are provided by Tan, Liu, Perfetti, Spinks, Fox and Gao (2001) in their recent fMRI study of pairs of semantically related and pairs of homophones of Chinese characters to show the distributed neural system in reading Chinese.

In all the excitement about the use of functional neuroimaging techniques in cognitive neuroscience, we should bear in mind the cautionary note by Rugg (1999, p. 30) that neuroimaging effects 'can only be informative about how cognitive processing is instantiated in the brain if the functional role of the neural activity reflected by the effect can be identified.' Rugg points out several unresolved issues. One is that functional accounts of cognition can take different forms, just as Sejnowski and Churchland (1989) have discussed different levels of investigation of brain-cognition relationship. The other issue is the 'correlational' nature of neuroimaging data in providing neural correlates of one or more cognitive operations. The third issue is the establishment of a causal relationship between the neural activity and the cognitive operations. Rugg makes the innovative suggestion of reversing the role of neuroimaging experiments by manipulating neural systems instantiating cognitive operations and observing the functional consequences, but this manipulation is made difficult in the absence of an animal model of language processing. In a recent study of semantic judgment with two groups of Chinese-English bilinguals, Chee, Hon, Lee and Soon (2001) find changes in the spatial distribution and magnitude of blood oxygenation level dependent (BOLD) imaging commensurate with language proficiency. Their findings of linkage between or among longer processing time, greater BOLD signal change in the left prefrontal and parietal areas and language proficiency suggest the importance of task requirement and cognitive load in imaging studies. With all these cautionary notes, Posner and DiGirolamo (2000) are optimistic that the mapping of cognitive functions in the human brain provides a means of better understanding of human cognition including reading, language, attention and emotion.

Within the framework of neural networks and activation Li (chapter 4) has provided a dynamic and developmental account from connectionist and computational perspectives to explain the acquisition of semantic structures in Chinese. At the risk of over-simplification, we can say that connectionist models emphasize the learning of associative pairs of patterns without reference to explicit rules. These patterns in our context can be the phonological or orthographical form of a word as input and the read or spelled form of a word as output. A connectionist network consists of a large number of computational units behaving in manners resembling those of neurons. For each unit there is an activation level and a weighted connection communicates the activation of one unit to another. The level of activation of a unit is a function of all the activation (total learning experience or weighted sum) received by that unit over a threshold value. In general, the size of activation of a unit and the strength of its connection with another unit determine the amount of influence one unit has over the other. The essential feature of a connectionist network is that it learns about the associations between pairs of patterns through iterative processes by modifying connection strengths and produces the correct output pattern in response to input. A good example is the influential connectionist model by Seidenberg and McClelland (1989) which learns to pronounce 3,000 monosyllabic words from input representations of orthographic forms and pronunciation representation based on phoneme triples. Another example is the extension by Plaut, McClelland, Seidenberg and Patterson (1996) to understand normal reading acquisition and impaired reading following brain injury.

This learning property and the computational aspect, particularly the abstraction of statistical structure of connectionist models, underpin Li's work. He first discusses some cross-language issues (see Li & MacWhinney, 1996) of how children focus on semantic properties of lexical items, especially meanings of verbs and the connection with grammatical tense-aspect morphology in a 'semantic space'. Specifically, he asks the question of how learners extract from their linguistic input the co-occurrences of lexical information in connectionist networks. He argues for a 'high-dimensional input space' and focuses on global rather than local lexical co-occurrences to accommodate the complex semantic relationships in lexical aspects of verbs. Li explains that global co-occurrences of a word are the sum total of the learning experience of that word in the context of other words in certain grammatical structures which include covert, subtle meaning categories termed *cryptotypes*. Local co-occurrences, according to Li, pertain to the immediate lexical environment, such as the form classes of words.

Li proposes a dynamic, self-learning or self-organizing connectionist network in a two-dimensional feature map ('implicit in the multi-dimensional input space') as a more powerful learning mechanism for the organization and reorganization of the abstract, internal lexicon. He shows how the application of this self-organizing network with the pairing of a phonological map and a semantic map successfully models the acquisition of lexical and grammatical aspects. He further demonstrates, from 509 lexical items extracted from a large corpus of nearly 4 million token words, the derivation of more precise lexical semantic representation (89% accuracy). This precision results from the statistical structure inherent in connectionist models in general and the learning experience of the connectionist network (as shown in the clustering and distances from various clusters of different kinds of meanings in the vector space of his self-organizing two-dimensional map) in particular. As Li has shown in his powerful dynamic two-dimensional feature map, the precision of semantic representation is expected to increase when learners are further provided with linguistic and extra-linguistic cues in language acquisition *in situ*. It may be pointed out that the class of 'unsupervised learning' in mapping inputs and outputs in high-dimensional space was shown earlier by Small, Hart, Nguyen and Gordon (1995) in the learning of topographical space of semantic features.

Working within the broad, general framework of connectionist networks, Perfetti, Liu and Tan (chapter 2) have also provided a computational instantiation of multi-level representations and interactions among different levels (orthographic, phonological and semantic) in recognizing 204 Chinese characters. Perfetti et al. have summarized the main features of the computational instantiation of their Interactive Constituency Model and have shown how the activation of cohorts of similar orthographic, phonological and semantic features explains the learning of Chinese characters in a 'threshold style' and as 'phonological diffusion'. Perfetti et al. focused on the more direct and faster acting phonological linkage to orthographic forms of words and deal with phonological and semantic linkages only in an 'indirect implementation'. In contrast, Li has explicated the theory and computation in the acquisition of lexical semantic representations in his topographical two-dimensional map of network learning. Both sets of authors have amply demonstrated, from different learning algorithms and from localized and global representations, the force and precision from connectionist network models of learning Chinese and other languages. The interplay between network architectures and learning algorithms (both *supervised learning* with training sets of input/output pairs to be associated and *unsupervised learning* with no external teaching except the exposure of the network to inputs to build internal representations) explains a great deal of cognitive and linguistic phenomena. What is more, connectionist models provide a link to neural structures in computing cognitive and linguistic functions.

Interfacing orthographic, phonological and semantic processing

From different perspectives of activation models, Weekes, Davies and Chen (chapter 5) use the picture-word interference paradigm (naming picture and ignoring accompanying word or *distractor*) to investigate semantic interference and graphemic-phonological facilitation effects in picture naming and Chinese word recognition. They exploit the rather unique property in Chinese of a large number of visually dissimilar homophones or heterographic homophones to study the locus of semantic decision level interference and the name or lexical retrieval level and raise the possibility of the intermediate *lemma* level (Levelt, 1989). The lemma level focuses on the semantic and syntactic properties of words but not on their conceptual and phonological properties. Specifically, a lexical entry in the abstract, internal lexicon consists of a lemma and a morpho-phonological form and this metaphorical partitioning of the mental lexicon into meaning and form is particularly useful in explaining language production. Levelt (1989) states that speakers use syntactic information in addition to semantic information in retrieving lexical items to build up a framework of utterance. He defines this non-phonological part of an item's lexical information as the item's 'lemma information' or lemma. Levelt's distinction between the functional level (from conceptualization to formulation) and the positional level (from formulation to articulation) explains well a number of phenomena such as the 'slips of the tongue' phenomenon (e.g., 'Chomsky and Halle' becomes 'Homsky and Challe').

Weekes et al., in three reaction-time experiments, show reliable results of a semantic interference effect and a graphemic and phonological facilitation effect in picture naming in Chinese. The categorical interference is due to shared category membership between target and distractor; an orthographic facilitation effect is due to shared orthographic information between target and distractor; and a phonological facilitation effect is due to homophony between target and distractor. Of interest is that they found no significant difference between the amount of graphemic and phonological facilitation and that there was a lack of interaction between graphemic and phonological facilitation, which is considered a 'unique' result. Weekes et al. argue for an additional lemma level of representation between the semantic and name retrieval levels to account for their data. This level is seen by these authors to represent grammatical information for the large number of polysemous words in spoken Chinese and as the locus of graphemic facilitation in picture naming in Chinese. In a broader cross-language perspective, the recent theory of lemma access model (Levelt, Roelofs, & Meyer, 1999) provides a comprehensive account for a wide range of reaction time results in the production lexicon.

Parenthetically, in an important study, Vandenberghe, Price, Wise, Josephs, and Frackowiak (1996) measured neural activation by means of positron-emission tomography in semantic or non-semantic judgment tasks of triplets of either pictures or words. Vandenberghe et al. showed that semantic tasks activate a distributed semantic processing system shared by both pictures and words, as compared with baseline, and these areas are distributed widely in the left frontal, parietal, temporal and occipital cortices. Furthermore, there are some specific areas activated by either pictures or words. This important study also brings up the question of the need to examine different semantic categories and how they are organized in the brain. In a broad sense, some of the physical structures of the lexical system in the brain are also captured in the high-density, self-organizing global feature map reported by Li (chapter 4). With such a map it would be possible to verify the underlying fine neural structure and pathways in the form of connected groups of neurons (see Miikkulainen, 1997; Plaut et al., 1996).

The interface among semantic, orthographic and phonological processing in reading Chinese is further explored by Hoosain (chapter 6) and Y. P. Chen (chapter 7). Hoosain's opening remarks in his chapter about the 'myth' that single Chinese characters have been reported in functional cerebral laterality studies to be right lateralized and two-character words to be left lateralized have been demystified with current functional neuroimaging techniques (see Matthews et al., chapter 3; Perfetti et al., chapter 2; Tan et al., 2000). Tan et al. demonstrate clearly from their fMRI study of tasks requiring semantic analysis and word retrieval that processing single Chinese characters and two-character words does not bring about a significant difference in cerebral laterality and that there is a shared neural network across these lexical items. Tan et al. (2001) have provided corroborative evidence from event-related functional magnetic resonance imaging to show how the human brain processes phonology and transforms a word's orthographic form into a phonological form in reading Chinese.

Hoosain then goes on to discuss some 'working hypotheses' in the speed of processing Chinese and casts his argument in a cross-language context (Chinese and English). He examines the speed of processing meaning of Chinese and English words; accessing phonology and meaning of English words; accessing phonology of Chinese words as compared with accessing phonology of English words; and situational variables affecting accessing phonology and meaning of Chinese words. The issue of time course in the activation of phonology and meaning is addressed by Perfetti and his colleagues (e.g., Perfetti & Tan, 1999; Tan & Perfetti, 1999). Hoosain points out some of the inherent problems in these experiments, such as the more restricted range of pronunciation for a character as compared with denotative and connotative aspects of word meaning, and the need to specify the level of meaning to be activated. His closing remarks about discourse processing is not addressed directly in this volume and is an area that needs further attention.

Chen (chapter 7) investigates in adult Mandarin speaking Chinese readers their differential and selective use of activated orthographic, phonological and semantic information (termed *reading strategies*) in lexical decision of two-character Chinese words. *Reading efficiency* is explained in terms of overall mean latency of the subject in responding to the differential processing of the words. Her data from regression analyses show that there are individual differences in reading strategies, as can be expected, but also there are variations for the same individual over time and contexts. The developmental and contextual aspects have been commented on by Hoosain in his chapter; and as a means to reinforcing unsupervised learning in connectionist models as emphasized by Li in his chapter. Chen takes the more conservative approach, as compared with other authors in this volume and in the literature, that 'phonological decoding strategy' is an 'optional strategy' in segmenting lexical items into constituents. However, her statement that orthographic knowledge such as knowledge of radical patterns may play an important role in Chinese word recognition 'only in so far as phonological decoding is involved' is in accord with the position of Perfetti and his colleagues and related connectionist literature.

Toward the end of chapter 6, Hoosain raises the issue of eye movement studies during text processing. With more refined instrumentation to record eye movements interfaced with the computer and more sophisticated theories of language processing, eye movement data are very useful in studying fined-grained cognitive processes in reading. In particular, the findings of relatively small area of effective vision and word fixation and of no appreciable eye-mind span have helped in the moment-to-moment studies of reading in such areas as word ambiguity and sentential parsing and inferencing (for review, see Rayner, 1999). But there are considerable individual differences between subjects and within subjects and there are task effects such as text difficulty and syntactic complexity. When texts are more difficult, fixations get longer, saccades get shorter and regressions increase (Rayner, 1999). The general findings in the literature of eye movements during reading of Chinese and Japanese sentences are that the perceptual spans are smaller as compared with reading English because of the densely packed Chinese and Japanese (kanji) scripts (Inhoff & Liu, 1998; Osaka, 1992; Rayner, 1999).

In her eye tracking study of native Japanese adult readers reading two versions of newspaper text (the error free version by control subjects and the other containing homophonic or non-homophonic kanji errors by target subjects), **Matsunaga** (chapter 8) addresses the question of the time course of phonological processing in reading natural Japanese text materials. Her general logic is that if there is early phonology (see also Perfetti, Liu, & Tan, chapter 2) there should be *homophonic interference effects* (experimental subjects having more difficulties in noticing homophonic errors). There should be shorter *first fixation durations* and *gaze durations*. First fixation durations are defined as durations of first fixation on a word and gaze durations are the sum of all fixations on a word before moving on to another word (Rayner, 1999). Matsunaga's data show that there was homophonic interference effect on first fixation and gaze fixation durations and difficulty in noticing non-homophonic errors, thereby confirming her hypothesis. Her eye-tracking results add to the recent important study on eye movements in Chinese character identification by Pollatsek, Tan and Rayner (2000).

In three experiments, Pollatsek et al. (2000) provide strong evidence of the early involvement of both lexical and sublexical phonological codes in identifying Chinese characters. They show that phonological information was extracted parafoveally from a target Chinese character and this early phonological information helped the identification of that character when it was subsequently fixated. Furthermore, there was a regularity effect in that high frequency phonetically regular characters were named faster than high frequency phonetically irregular characters, and orthographic information was also involved in integrating information in Chinese characters across saccades. Pollatsek et al. caution against equating their view of 'sublexical phonology' with 'prelexical phonology' and suggest these as matters for further investigation. We are thus brought back to the careful statement of Perfetti et al. (chapter 2) on this empirical issue for further study.

Structural relationship of components of Chinese characters

Thus far, much of the research literature on the cognitive processing of the Chinese language focuses on character and word recognition and with less work on sentence parsing and discourse process. There is a paucity of research studies of Chinese handwriting or calligraphy as a cognitive process. The findings in character and word recognition can be utilized in experimental studies of Chinese calligraphy. The visual search stage model of character recognition of Huang and Wang (1992) in terms of non-accidental visual properties of symmetry, parallelism and collinearity forms a good basis for the analysis of Chinese handwriting. These two-dimensional structural properties, found in the intersections of strokes, have been studied in relation to character recognition by Chen and Huang (1999), Peng and Zhang (1984), Yu, Zhang and Pan (1997), among others. Corresponding roles of structural spatial properties in brush writing Chinese, however, have only slowly received their due share of attention.

Recently, Kao and his associates (see Chen & Kao, chapter 9; Gao & Kao, chapter 10) have conducted a series of experiments on Chinese handwriting, especially brush writing, as a dynamic calligraphic process. In their research program, Kao and his colleagues studied cognitive changes including memory, digit span and perceptual tasks during Chinese handwriting as functions of variations of such structural spatial properties as linearity, closure, symmetry and orientation. Earlier, Wong and Kao (1991) studied the development and skills in the processing of characters including the execution of strokes, their shaping, spacing and framing in internal, cohesive relationships. Kao and his colleagues (Kao, 2000) discussed a systematic psycho-geometric theory of Chinese character brush writing to explain the relationship between writing as a cognitive process, the motor act in executing the calligraphy and accompanying psychophysiological changes such as heart rate, EEG and skin resistance. This theory forms the basis of this line of research and Kao and colleagues reported some preliminary ERP data to substantiate the neural basis of cortical activation during Chinese handwriting.

Although originally developed as a conceptual basis of Chinese character writing, Kao's structural geometric theory is also concerned with the effect of non-accidental properties, such as the intersections of strokes, along with their structural relationship within the character in character identification. Chen and Kao (chapter 9) report two experiments with Chinese primary school children, in which the psycho-geometric nature of the compositionality of Chinese characters was the theoretical framework in character recognition, latency and error measures were the dependent variables. Their first experiment found that non-accidental geometric properties facilitated the orthographic processing of Chinese characters. Their second experiment showed the cumulative effects of these orthographic properties in reading Chinese. These results largely confirm the classical Gestalt principle of *Pragnanz* or 'the goodness of forms' as a parsimonious way of organizing two-dimensional patterns, which are the salient orthographic characteristics of Chinese scripts.

Largely as a result of the encouraging findings of Chen and Kao and several other related experiments, Kao and his colleagues have further analysed thoroughly a set of commonly used Chinese characters from the psycho-geometric perspective. Gao and **Kao** (chapter 10) report on the preliminary results of this major exercise in analysing the perceptual and orthographic features of nearly 5,000 most commonly used Chinese characters. Their results show that the Pragnanz properties of connectivity, linearity, symmetry and visual balance are important elements in the compositionality of Chinese characters and lend further support to Kao's psycho-geometric theory.

The issue of goodness of form in recognizing Chinese characters is approached in a different way by **Han** (chapter 11). Han explains components as functional units akin to the stroke patterns of Chen (chapter 7) and component combinations as intermediate between components and characters. Frequency pertains to type, token frequency and position frequency, and is based on Han's corpus linguistic research into the frequency database of some 567 components and 7583 component combinations. He shows from latency and error data in his experiments the left-right component combination effects and their interaction with frequency and the general structure of the character as a whole. His interpretation of positional effects of component combinations in facilitating or inhibiting Chinese character recognition will need to be reconciled with the functional approach such as that studied by Feldman and Siok (1999), who emphasized the functional roles of the phonetic and semantic components of characters and not so much the left-right positions. In particular, Han's study will also need to accommodate at least two broad groups of activation models of Chinese character recognition. One is the multi-level hierarchical interactive model such as that of Taft and Zhu (1997), who stress the activation of information of submorphemic components. The other is the Interactive Constituency Model with phonology as a main constituent along with orthographic and semantic components in Chinese word identification (Perfetti, Liu, & Tan, chapter 2; Perfetti & Tan, 1999; Tan & Perfetti, 1999).

Learning Chinese characters and words

In the discussion of relevant cognitive neuroscience literature and the summary of the different chapters on the cognitive and neural bases of interfacing orthographic, phonological and semantic components of

Chinese characters and words, some pertinent applied research questions relate to how readers acquire words accurately, rapidly and with precision. These are the empirical issues of making explicit what beginning readers know from their language to make contact with print; the reading of two Chinese scripts: the traditional or complex script as used in Taiwan and Hong Kong and the simplified script as used in mainland China and Singapore; strategies used by skilled and less skilled young Chinese students in reading Chinese characters and words; and the acquisition and development of vocabulary for pedagogical purposes. These issues are addressed in this volume by the five sets of authors: Leong; Lam; Wang and Guthrie; T'sou, Kwan, and Liu; and Kwan and T'sou.

From a cross-language perspective (see Leong & Joshi, 1997), **Leong** (chapter 12) discusses the central issue of the involvement of phonological and orthographic processes and their interplay in reading the alphabetic English and the morphosyllabic Chinese. Cumulative research findings have shown that sensitivity to speech sounds and their mapping to script is a precursor to learning to read and in preventing reading difficulties (Leong, 1991; Snow, Burns, & Griffin, 1998). In learning to read English, children need to be sensitive to the morpho-phonemic nature of the system, which is represented by phonemes, syllables with their onsets and rimes and other sublexical units. In learning to read the kana script of Japanese, children need to be sensitive to the subsyllabic and timing unit of *morae* (Leong & Tamaoka, 1998). In learning to read Chinese, children need to be sensitive to the internal structure of the syllable with its *onset* (initial in the Chinese syllable) and *rime* (final in the Chinese syllable).

Leong's proposal (Leong, 1997) of paradigmatic analysis emphasizes a network of linguistic connections as a potent approach to learning to read Chinese characters and words. These are the basic psychological issues of what constitutes a word and word boundaries in Chinese (Hoosain, 1992); and the linguistic issues of a word being a free form entailing syntactic relation with other similar units as explicated by the noted linguist Yuen Ren Chao (1968, 1976). The underlying psycholinguistic principle is the unit of processing or the size of speech segment to be recognized as a word and the mapping between the speech unit and print. Leong discusses relevant research studies on segmental and syllabic analysis of Chinese characters and words; and emphasizes explicit, systematic teaching of more precise Chinese word knowledge in schools.

In the modern Chinese writing system in use from 1949, there are in fact two slightly different scripts with the same pronunciation. The traditional script with complex characters is used in Taiwan and Hong

Kong and the simplified script (simplified from, and orthographically very similar to, the traditional script) is used in mainland China, in Singapore and in Chinese courses taught in many universities in the USA. What is the ease or difficulty for Hong Kong learners trained in the traditional script learning these two scripts, and, conversely, for Beijing students trained in the simplified script? These are the psycholinguistic issues explored by **Lam** (chapter 13), who focuses on the context effects of reading these two scripts with the same pronunciation. She first outlines the linguistic principles of character simplification and discusses two studies, one with Hong Kong university students and the other with Beijing university students, on the nature of phonetic and semantic activation in reading character lists and text materials. Using reading time per character and percentage error as her metrics, she found the response time and difficulty of reading the unfamiliar script for the two different groups to be considerably reduced when the characters were embedded in texts. Moreover, her prediction that different types of character simplification would result in different degrees of difficulty in reading was also upheld.

The issue of ease or difficulty in reading Chinese by elementary school students in Taiwan was explored by **Wang and Guthrie** (chapter 14). In three studies they focused on the strategies and cues used by skilled and less skilled fifth grade readers, selected by their teachers, in identifying unknown Chinese characters. The first study used a verbal report protocol from reading aloud a story, in which the students reported how they read the characters and if they knew the meaning and function of the left-right radicals constituting the characters. The different errors of pronunciation of the characters were taken as different reading strategies. From this study and the subsequent two studies, Wang and Guthrie found that skilled and less skilled readers differed in their reading strategies in recognizing and pronouncing unknown characters, and that skilled readers used more linguistic cues, especially phonetic cues. Moreover, their skilled readers were able to differentiate phonetic cues from semantic cues inherent in the orthographic information in the characters. While there may be a caveat in the teacher selection of skilled and unskilled readers, the Wang and Guthrie analysis highlights the need to examine the fine-grained aspects of Chinese character compositionality, as discussed in the chapters by Chen, Chen and Kao, Gao and Kao, Han and others. Furthermore, their statement of greater use of phonetic cues by skilled readers may be better understood in the broader context of the Interactive Constituency Model of reading Chinese, as instantiated with both regular and exception Chinese characters and words at different frequency ranges.

Continuing the theme of learning words and acquiring word knowledge, the two chapters by T'sou and his colleagues should be read within the context of Chinese corpus linguistics. Current studies of corpus linguistics are usually defined in terms of a collection of electronic texts selected according to certain linguistic criteria (Atkins, Clear, & Ostler, 1992). The general idea is to extract linguistic data so as to reflect the behaviour of a language in general at a particular time, such as the well-known Brown corpus of English (Kučera & Francis, 1967). From this extraction linguists can form theoretical hypotheses, verify them and further apply them for computational purposes. Grammatical categories or 'tags' help to provide structure for the linguistic data. The rationale of tagging is 'basically syntactic, with some morphological distributions' (Francis & Kučera, 1982, p. 9).

This raises the question of what constitutes a word in Chinese, as alluded to earlier (Chao, 1968, 1976; Hoosain, 1992). There is also the relationship between word-syntax and sentence-syntax in Chinese compound words. Take as examples the case of reduplication in Chinese compound words (e.g., reduplication of *look/ see*, or of *beautiful*). Leong (1995, 1998) treats these reduplicated compound Chinese words as morphological constraints, and Tang (1994) as syntactic manifestations of aspect and degree intensification. Linguists Di Sciullo and Williams (1987) discussed the different senses or forms of a 'word' in English. There is the morphological form in terms of a set of 'atoms' or morphemes; the syntactic form in terms of syntactic atoms; and the memorized lists of language objects termed *listemes* or 'frozen expressions' (e.g., *red herring*). The fourth sense of the word — the phonological form — is barely discussed by Di Sciullo and Williams. Just as Di Sciullo and Williams (1987) argued for the close relationship between English phrases and sentences, it is reasonable to say that in Chinese there is a parallel between morphological structure and syntactic structure in Chinese compound words, especially in compound verbs, verb phrases and sentences (Tang, 1994).

The above succinct discussion underpins the rationale and methods of the large-scale Chinese corpus linguistics investigation known as Linguistic Variation in Chinese Communities (LIVAC, 1995–1997) conducted in China, Taiwan, Singapore and Hong Kong by T'sou and his team. Chinese newspapers were used as the database because newspaper texts are available on-line and easily lend themselves to computational linguistic analyses, and also because newspapers typically contain all genres of literary styles. Within this broad framework and using words derived from the LIVAC corpus, **T'sou, Kwan and Liu** (chapter 15) studied the passive or receptive and active or productive vocabulary knowledge and general and academic vocabulary in 856 Hong Kong secondary students. They also related these different levels of vocabulary knowledge to student characteristics such as education level, general ability and Chinese language proficiency. T'sou et al. suggested that successful vocabulary learning requires the conditions of need or motivation, frequent encounter in different contexts and active usage. **Kwan and T'sou** (chapter 16) selected 12 typical students out of the subgroup of 90 from the nearly 900 secondary students in T'sou et al. (chapter 15) to further explore their 'decoding' strategies. Kwan and T'sou used the term *decoding* to denote getting meaning from very low frequency and almost unknown multi-character Chinese words and employed the talking aloud protocol as the source of data collection. These naturalistic data throw light on the way that secondary students in Hong Kong grapple with the meaning of difficult and obscure words and provide a window to their lexical development. The two chapters by T'sou and his colleagues have also raised the issue of assessing word meaning and vocabulary knowledge. The typical approach as used by Anglin (1993) and in the literature is to ask for definitions, then usage of words in sentences so as to explain their meanings and also in the multiple-choice format or all these different approaches. However, knowing the meanings of words also involves knowing the situations in which words are used (see Anglin, 1993; Li, chapter 4) and of acquiring different levels of word meanings (Leong, 1998).

One of the ways in vocabulary development that T'sou and his colleagues allude to is the process of collocation. This refers to the phenomenon that lexical items which consistently co-occur and which are semantically transparent (e.g., 'heavy smoker' but not * 'heavy thinker') are learned easier than others. In computational linguistics the notion of collocation can be defined statistically in probabilistic terms of mutual information to determine which words are collocated according to syntactic and semantic criteria (Church & Hanks, 1990; Sinclair, 1991). The mutual information between linguistic elements, expressed as a unidimensional log function in relation to the size of the corpus and of the linguistic window selected, is in some contrast to the high-density two-dimensional self-organizing map in learning word meaning that Li (chapter 4) has explicated.

There is another aspect of word meaning and vocabulary development that is more typical of the Chinese language. There are non-transparent or semantically opaque expressions of idioms or listemes (Di Sciullo & Williams, 1987) that are distinguishable from collocations and that form stumbling blocks to learning Chinese. These frozen expressions, or listemes (e.g., 'to break the axe and sink the boat'), are not easily decipherable without knowing the historical context. There are also familiar phrases, which convey propositional forms (e.g., 'mud Buddha crossing the river' with the implication that not even Buddha can save himself). Study of Chinese vocabulary development should include these two-, three- and four-character words in frozen forms because they figure prominently in text reading and in literacy development. The interrelated issues of word meaning, vocabulary acquisition and development provide rich sources of study in psychology and psycholinguistics.

Making Connections

We began this integrative commentary with the assertion of Simon and Kaplan (1989) that cognitive science is concerned with the study of intelligent behaviour and its computational processes and also with the explication of Sejnowski and Churchland (1989) that knowledge of brain architecture could explain human cognition. The different chapters in this volume have provided theoretical and research perspectives of the cognitive conjunction approach of Price and Friston (1997) in showing the analyses of psychological and psycholinguistic data on the Chinese language system and their interpretation within a cognitive neuroscience framework. Our contributors have shown, from different theoretical and research paradigms, the complex nature of the interfacing of orthographic, phonological and semantic processing of Chinese. We are enjoined by Brown and Hagoort (1999) to take a more integrative approach toward languages in terms of their core characteristics, their different levels and representational systems, their measurements and the use of different psychological, psycholinguistic and neural techniques for their fuller understanding. We are further reminded by Gazzaniga (2000) to understand the mind and the brain as 'cognitive thinking', and by Perfetti et al. (chapter 2) and other contributors how the mind can meet the brain in language processing, which can help to ensure that we are studying challenging and interesting constructs and topics.

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