MAPPING ORTHOGRAPHIC AND PHONOLOGICAL NEIGHBORHOOD DENSITY EFFECTS IN VISUAL WORD RECOGNITION IN TWO DISTINCT ORTHOGRAPHIES

A Dissertation

by

HSIN-CHIN CHEN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

May 2007

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ABSTRACT

Mapping Orthographic and Phonological Neighborhood Density Effects in
Visual Word Recognition in Two Distinct Orthographies. (May 2007)
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A central issue in word recognition is how readers retrieve and select the right representation among others in the mental lexicon. Recently, it has been claimed that recognition of individual words is influenced by the degree to which the words possess unique vs. shared letters or sounds relative to other words, that is, whether the words have few or several neighbors. Research on so-called neighborhood density effects advances understanding of the organization and operation of the mental lexicon. Orthographic neighborhood effects have been claimed to be facilitative, but recent studies of visual word recognition have led to a revised understanding of the nature of the orthographic neighborhood density effect.

Through a reexamination of orthographic and phonological neighborhood density effects, the specific objective of the present research is to understand how orthographic and phonological representations interact across two different writing systems, i.e., English (an alphabetic orthography) and Chinese (a morphosyllabic orthography). The phenomena were studied using a joint behavioral (lexical decision) and neural imaging approach (near infrared spectroscopy, or NIRS).

Orthographic and phonological (more, specifically, homophone) neighborhood density were manipulated in three lexical decision experiments with English and three with Chinese readers. After different sources of facilitative inter-lexicon connections were controlled, orthographic and phonological neighborhood density effects were found to be inhibitory in both writing systems. Inhibitory neighborhood density effects were also confirmed in two NIRS experiments of English and Chinese.

The present research provided a better control of lexical characteristics than was the case in previous research on neighborhood effects and found a clear and consistent pattern of neighborhood density effects. This research supports interactive-activation models of word recognition rather than parallel-distributed models, given the evidence for lateral inhibition indexed by inhibitory neighborhood density effects. As such, the present study furthers the understanding of the organization and operation of the mental lexicon.

DEDICATION

To the memory of my grandpa, Huan-Sung Chien, and my grandma, Ke Chien-Li.

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INTRODUCTION

During the last three decades, visual word recognition has been one of the most extensively studied topics in psycholinguistics. One aspect of this research has recently attracted a lot of attention on the part of investigators: the claim that recognition of individual words is influenced by the degree to which the words possess unique vs. shared letters or sounds relative to other words, that is, whether the words have few or several neighbors (Andrews, 1997; Yates, Locker & Simpson, 2004). These effects, which are called orthographic or phonological neighborhood density effects, provide a window into the organization and operation of the mental lexicon. However, since the classic work on this topic by Andrews (1989), more problems have been raised rather than solved with respect to the nature and implications of neighborhood effects.

Through a reexamination of orthographic and phonological neighborhood density effect, the objective of the present research is to understand how orthographic and phonological representations interact across two different writing systems, i.e., English (an alphabetic orthography) and Chinese (a morphosyllabic orthography), and what neighborhood effects mean for current models of visual word recognition. The phenomena will be studied using a joint behavioral (lexical decision) and neural imaging (near infrared spectroscopy, or NIRS) approach. The proposed research is the first in the literature to manipulate both orthographic and phonological neighborhood density effects, to relate them to writing system effects, and to examine these effects at both the behavioral and neurobehavioral levels.

This dissertation follows the style of *Journal of Experimental Psychology: Learning, Memory, and Cognition*.

Early Studies of Orthographic Neighborhood Effects

Visual word recognition is a fundamental process in reading. Reading is a highly complex activity consisting of at least five different component processes: word identification, parsing, semantic-syntactic analysis, text comprehension, and integration (Perfetti, 1999). Word identification, which is the process to select the correct, context-appropriate meaning, is particularly important at the early stages of language understanding. Visual word recognition may be defined as the process of retrieving word characteristics (including orthographic, phonological, and semantic information) on the basis of the input letter string (Dijkstra, 2005). It is important to understand visual word recognition because such research enhances our understanding of the limits and the plasticity of human cognitive and linguistic systems. Further, to understand what and how readers process words is especially important for educational purposes.

A central issue in word recognition is how readers retrieve and select the right representation among others in the mental lexicon. To understand the mechanism underlying lexical retrieval and selection, it is not enough to study the processing of a single word by itself, since word recognition often relies on recognizing how individual words are related to other words. Neighborhood effects have been suggested to be the key to understanding the mechanism underlying lexical access (Andrews, 1992).

The measure of *orthographic neighborhood* density[1] was first proposed by Landauer and Streeter (1973). Coltheart, et al. (1977) defined it as the number of words

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[1] The effect of neighborhood *density* was originally called neighborhood *size* effect (Coltheart, Davelaar, Jonasson, & Besner, 1977). However, after 30 years of research, the terms *neighborhood size* and *neighborhood density* were used interchangeably. However, the effect of homophone *density*, which I examined in Chinese experiments, was never replaced by homophone *size*. For the purpose of coherence and readability, I use the term *density*, instead of *size*, in the present study.

that can be generated by replacing one letter from a target word in the same letter position. By this definition, *gap*, *cup,* and *cat* are all orthographic neighbors of the target word, *cap*. In their original work, Coltheart et al. (1977) found no difference in lexical decision between words with a higher orthographic neighborhood density vs. those with a lower orthographic neighborhood density. Perhaps due to this null finding, studies of the orthographic neighborhood density did not attract the attention of researchers until Andrews's (1989) work.

In a joint manipulation of word frequency and orthographic neighborhood density, Andrews (1989) found that words with high orthographic neighborhood density were responded to faster than those with low orthographic neighborhood density on both lexical decision and naming tasks. However, this facilitatory effect was found for low frequency words only. Since Coltheart et al. (1977) only controlled but did not manipulate word frequency, their failure to find an effect of orthographic neighborhood density might have been due to this reason.

Grainger and Segui (1990) argued that Andrews's (1989) stimuli did not control for bigram frequency. However, Andrews (1992) found that bigram frequency did not affect response time on either lexical decision or naming; even when bigram frequencies were carefully controlled, orthographic neighborhood density still showed a facilitative effect for low frequency words on both lexical decision and naming tasks. Andrews (1992) suggested that processing low frequency words is benefited by having many orthographic neighbors.

A facilitative effect of orthographic neighborhood density has not, however, been replicated. Grainger, O'Regen, Jacobs, and Segui (1989) found no significant difference on a lexical decision task between words with no orthographic neighbors and those with many. Instead, Grainger et al. (1989) reported an inhibitory orthographic neighborhood frequency effect: the decision time for a word with at least one orthographic neighbor carrying a higher frequency was slower than that for a word with no higher frequency orthographic neighbor. For example, the words *knee* and *myth* have a compatible frequency, however, *knee* is predicted to be recognized more slowly than *myth* because *knee* has a higher frequency neighbor, *knew*, but the neighbors of *myth*, i.e., *math* and *moth*, all carry relatively lower frequencies. The inhibitory nature of the orthographic neighborhood frequency effect suggests that orthographic neighbors can have negative influences on each other. This seriously challenges the facilitative account of the orthographic neighborhood density.

Studies on orthographic neighborhood density or orthographic neighborhood frequency effects are important on a theoretical level as both kinds of effects provide a detailed test of different word recognition models. At this juncture I will briefly review the major word recognition models and then describe how studies of orthographic neighborhood density and orthographic neighborhood frequency effects matter in testing these models.

Orthographic Neighborhood Effects and Word Recognition Models

Orthographic neighborhood effects are of theoretical significance because they allow a test of competing claims of word recognition models. Generally, there are three groups of word recognition models: serial models, interactive activation models, and parallel distributed processing (PDP) models.

Serial Models. In a serial model, whether it is the search model of Forster (1976), or the activation-verification model of Paap, Newsome, McDonald, and Schvaneveldt (1982), word recognition involves a serial match process between sensory input and attributes of a set of candidates stored in the memory system. In serial models, an increase in the orthographic neighborhood density also means an increase of the search set. For this reason, serial models predict an *inhibitory* effect of orthographic neighborhood *density*. According to serial models, a word is verified by its relative position in a set of candidates. High frequency candidates will be matched earlier than low frequency candidates. Serial models, thus, also predict an *inhibitory* orthographic neighborhood *frequency* effect. A word with a higher frequency neighbor will be slower to verify than a word with a lower frequency neighbor because the target word has to wait for the higher frequency neighbor to be verified.

Interactive Activation Models. Interactive activation (IA) models, such as the IA model of McClelland and Rumelhart (1981), the Dual Route Cascaded Model of Coltheart, Curtis, Atkins, and Haller (1993) and Coltheart, Rastle, Perry, Langdon, and Ziegler (2001), or the Bimodal Interactive Activation model by Grainger and Ferrand (1994) all assume that no serial verification mechanisms are needed. According to interactive models, sensory input activates a set of related representations in parallel. Among these representations, the first one whose activation level exceeds the identification threshold will be selected as the target word. The most important assumption of the interactive activation model is *intra-level lateral inhibition*. Because of this lateral inhibition, orthographic neighbors are expected to interfere with each other. For this reason, interaction activation models predict an *inhibitory* orthographic neighborhood *density* effect because the higher the orthographic neighborhood density the more lateral inhibition a target word should receive. The resting level activation of a representation is positively related to the frequency of a word. The higher the word frequency the higher the resting level activation would be. A word with a higher frequency orthographic neighbor also receives stronger lateral inhibition due to the higher resting level activation of its orthographic neighbor. For this reason, interactive activation models also predict an *inhibitory* orthographic neighborhood *frequency* effect.

Parallel Distributed Processing Models. Different predictions are made by PDP models (e.g., Seidenberg & McClelland, 1989). Representations in orthographic, phonological, and semantic lexicons in PDP models are fully interconnected. No explicit lateral inhibition mechanisms or localized word representations are found in PDP models. Instead, words are said to be represented by a set of activation patterns. A word with many orthographic neighbors is benefited by the similar activation pattern of its similarly spelled neighbors. The related connections are strengthened by a set of orthographic neighbors through training sessions. Thus, PDP models predict a *facilitatory* orthographic neighborhood *density* effect. A similar mechanism is also invoked to explain the orthographic neighborhood frequency effect. In PDP models, high frequency words would have a more accurate activation pattern because of more training opportunity. A word with a higher frequency orthographic neighbor benefits by the strengthened activation pattern of its neighbor. For this reason, PDP models also predict a *facilitative* orthographic neighborhood *frequency* effect.

The differing predictions arising from the different word recognition models have generated fierce debate about the nature of orthographic neighborhood density and orthographic neighborhood frequency effects. The consensus from the first decade of studies on this issue seems to be that orthographic neighborhood density effect tends to show a facilitative effect and orthographic neighborhood frequency tends to show an inhibitory influence. However, newer studies, as well as studies involving phonological neighborhood effects in visual word recognition, have called this generalization into question. In the next section, I will discuss orthographic neighborhood effect findings that have emerged since the work of Andrew (1989) and Grainger et al. (1989). Then, I will discuss findings related to the phonological neighborhood density effect.

The Debate About Orthographic Neighborhood Effects

The facilitative orthographic neighborhood density effect found by Andrews (1989, 1992) seriously challenges the serial model and the interactive activation model of word recognition. Both models predict inhibitory, instead of facilitative, orthographic neighborhood density effects. However, Grainger et al.’s (1989) study suggested an inhibitory orthographic neighborhood frequency effect while no orthographic neighborhood density effect was found. In contrast to Andrew’s (1989, 1992) work, Grainger et al.’s (1989) work is consistent with the serial model and the interactive activation model. These contradictory results have led to a series of studies examining the direction of both the orthographic neighborhood density and orthographic frequency effects.

To reconcile Andrews's (1989, 1992) and Grainger et al.'s (1989) studies, Sears, Hino, and Lupker (1995) systematically examined the influence of orthographic neighborhood density and orthographic neighborhood frequency. Orthographic neighborhood density and orthographic neighborhood frequency tend to covary in that words with higher orthographic neighborhood density also tend to have higher frequency orthographic neighbors. In both the lexical decision and naming task, Sears et al. (1995) found that orthographic neighborhood density clearly showed facilitative effects for low frequency words. However, orthographic neighborhood frequency only revealed a slight facilitative effect in naming but not in lexical decision. The results of Sears et al. (1995) support PDP models but do not favor serial models or interactive activation models. Similar results were also obtained by Forster and Shen (1996). Instead of selecting two groups of words with higher and lower orthographic neighborhood density, Forster and Shen systematically selected words ranging from zero to 5 neighbors, and noted a trend for a facilitative effect for orthographic neighborhood density in the lexical decision task. When also manipulating orthographic neighborhood frequency, Forster and Shen (1996) still obtained a facilitative orthographic neighborhood density effect but no clear inhibitory orthographic neighborhood frequency was found.

All of the studies discussed so far that have found a facilitative orthographic neighborhood density effect were conducted in English. Grainger et al.'s (1989) study, which did not find such an effect, was conducted in French. It is possible that the difference in input language may have contributed to the different findings obtained. Grainger and Jacobs (1996) tested the orthographic neighborhood frequency effect in French lexical decision and generally found no orthographic neighborhood density effects. When manipulating orthographic neighborhood frequency in the same experiment, Grainger and Jacobs (1996) obtained a facilitative orthographic neighborhood density effect for words with higher frequency neighbors only. A similar result was obtained by Carreiras, Perea, and Grainger's (1997) study with Spanish. Although no orthographic neighborhood density effect was found in a Spanish lexical decision task, a facilitative orthographic neighborhood density effect was obtained for Spanish words with higher frequency neighbors.

Language properties may influence the particular nature of the orthographic neighborhood density effect. Andrews (1997) suggested that body/rime structure might be responsible for the different results found in different language. In one-syllable words, body structure is defined by combining the onset plus the vowel, whereas the rime structure is defined by combining the vowel and the coda. For example, the body structure of the word *fine* is the letter cluster *ine*, whereas the rime is its phonology. French and Spanish words are more consistent in orthography to phonology mapping compared to English. For this reason, it is not necessary to develop orthography to phonology mapping units in these languages higher than the grapheme to phoneme level. By contrast, body structure may be especially important in reading English (Treiman, Mullennix, Bijeljac-Babic, & Richmond-Welty, 1995). Andrews (1997), in fact, argued that body structures developed from the inconsistency of orthography to phonology mapping in English might be responsible for the facilitative orthographic neighborhood density effect observed. Because body structure is less important in French and Spanish, studies with these languages tend to find either a null or a slight facilitative effect for orthographic neighborhood density. Based on replicable findings in English studies, Andrews (1997) concluded that the effect of orthographic neighborhood density is facilitative, instead of inhibitory, at least for low frequency words.

Although earlier work by Sears et al. (1995) and Forster and Shen (1996) failed to obtain clear orthographic neighborhood frequency effects, the story is more consistent in more recent work. When controlling for orthographic neighborhood density, word frequency, and orthographic neighborhood frequency, Huntsman and Lima (1996) found that words with higher frequency neighbors were responded to slower than those with fewer higher frequency neighbors in the lexical decision task. When orthographic neighborhood density and word frequency were controlled, Perea and Pollatsek (1998) obtained slower lexical decision for English words with at least one higher frequency neighbor compared to those without. When tested in a sentence context with the eye-tracker, more regressions and longer fixation time were found for words with at least one higher frequency neighbor. The same result was also obtained in another eye-tracking study with English words (Pollatsek, Perea, & Binder, 1999).

Why did Perea and Pollatsek (1998) find an inhibitory orthographic neighborhood frequency effect while Sears et al. (1995) and Forster and Shen (1996) did not? Perea and Rosa (2000) argued that the success of Perea and Pollatsek (1998) in obtaining an inhibitory orthographic neighborhood frequency effect was that they chose stimuli with higher frequency neighbors differing in a middle letter from the target words. This strategy increased the ambiguity among target words and their neighbors and thus increased the inhibitory effect of orthographic neighborhood frequency. However, Sears, Campbell, and Lupker (2006) argued that the stimuli selected by Perea and Pollatsek (1998) are very infrequently encountered. Applying a new set of stimuli, Sears et al. (2006) did not obtain any orthographic neighborhood frequency effect in either a lexical decision task or in eye tracking.

In other languages, inhibitory orthographic neighborhood frequency effects have repeatedly been obtained. Grainger and Segui (1990) found that French words with at least one higher frequency neighbor were responded to slower than those without such a neighbor in the lexical decision task; the inhibitory orthographic neighborhood frequency effect was obtained for both low and high frequency words. After bigram frequencies were controlled, Grainger (1990) obtained the same results in Dutch as were reported by Grainger and Segui (1990) for French. Inhibitory orthographic neighborhood frequency effects were also obtained in the Spanish lexical decision task (Carreiras et al., 1997). However, the effect of orthographic neighborhood frequency was found to be facilitatory in the naming task of Grainger's (1990) study. Similar naming results were also found in Sears et al.'s (1995) study with English. Grainger (1990) argued that the facilitatory orthographic neighborhood frequency effect found in naming was due to the compensation from the connection of orthographic and phonological systems. Because naming requires information from the phonological system, phonological assembly processes may override the inhibitory orthographic neighborhood frequency effect in the orthographic system.

Studies using a priming paradigm in which a target word is preceded by an orthographic similar prime word further strengthen the findings of inhibitory orthographic neighborhood frequency effects. When a prime word was presented for 60 ms, the lexical decision of a French target word was interfered with by a prime which was a higher frequency neighbor to the target compared to that in which the prime word was unrelated to the target word (Segui & Grainger, 1990). Similar results were obtained by Grainger, O'Regan, Jacobs, and Segui (1992) also for French. Grainger et al. (1992) found that higher frequency neighbor primes slowed down lexical decision compared to unrelated primes especially when the prime and the target differed in the fourth position letter.

In summary, orthographic neighborhood density appears to show a facilitative effect for English but a null effect or a slightly facilitative effect for French and Spanish words. However, clear inhibitory orthographic neighborhood frequency effects have been found in French, Dutch, and Spanish but no clear evidence has been found for English. Whereas facilitative orthographic neighborhood density effects support PDP models, inhibitory orthographic neighborhood frequency effects support interactive activation models. It looks like studies with English favor PDP models but French and Spanish studies support interactive activation models.

Serial models are ruled out because of the finding that the frequency effect remains after controlling the number of higher frequency neighbors. In serial models, a target is verified within a set of similar candidates (i.e., orthographic neighbors). Because a high frequency neighbor will be verified earlier than the target, the verification of the target will be postponed. However, if the number of higher frequency neighbors is the same, no response difference should be obtained for high and low frequency words. This is because the verification sequence for these two words, i.e., high and low frequency words with the same number of higher frequency neighbors, is the same. However, Grainger and Segui (1990) still obtained a frequency effect for these two kinds of stimuli in a lexical decision task. Interactive activation models can explain this frequency effect because the resting level activation of a word representation is positive related to the word frequency. For this reason, even when the number of higher frequency neighbors is controlled, the higher resting level activation of the high frequency words makes it faster than that for low frequency words in lexical decision task.

In English, how can one reconcile the contradictory findings of a facilitative orthographic neighborhood density effect but an inhibitory or null orthographic neighborhood frequency effect? Andrews (1997) suggested that the inhibitory effect of lateral connections in the interactive activation models could be compensated for by the facilitative bi-directional connections between word representations and their sublexical representations. Larger orthographic neighborhood density provides stronger excitatory interconnections between word and letter representations. For example, before the input *cap* can be recognized, its letter representations *c*, *a*, and *p* also activate its orthographic neighbors *gap*, *cup*, and *cat*. Local representations of these neighbors *gap*, *cup*, and *cat*, in turn, will send feedback to and strengthen their letter representations including *c*, *a*, *p*, which are also letter representations of the input *cap*. The strengthened representations of *c, a*, *p* will in turn send stronger feedback forward to the word representation *cap*. Before *cap* is finally recognized, cycles of feedback and feedforward will keep going and will be strengthened between word and sublexical levels. The more neighbors a word has, the more word and sublexical representations will participate in the facilitative cycles. More importantly, the increasing of the activation is in a manner similar to geometric progression. For example, if the word representation *cap* sends 3 units of activation to each of its 3 letter representations in the first cycle, its neighbors should deliver 2 units of activation as well due to their sharing of 2 letter units. Each letter representations, in total, will receive 7 units of feedback from word representations, with 3 units from the target word *cap* and 2 units from 2 overlapped neighbors (e.g., *c* representation will receive 3 units from *cap*, 2 units from *cup* and *cat*, but 0 unit from *gap*). These letter representations will send 21 units of feedback to the word representation *cap*, with 7 units of activation from each of its letter representations, *c*, *a*, and *p*. In this manner, the word representation *cap* will continue receiving 147 units of activation in the second cycle, and so on and so forth. Compared to words with few neighbors, words with many neighbors benefit from this kind of accumulation via bi-directional connections between word and sublexical levels. The procedures discussed here that increase activation exponentially after cycles will henceforth be called *activation enhancement.*

On the other hand, Andrews (1997) also suggested that PDP models can explain the inhibitory orthographic neighborhood frequency effect by competition from stronger and similar activation pattern generated by higher frequency neighbors. Grainger and Jacobs (1996) also claimed that their bimodal interactive activation model could account for the facilitative orthographic neighborhood density effect by adding a mechanism that is sensitive to overall lexical activity: the larger the orthographic neighborhood density the higher the overall lexical activity.

The emergence of the phonological neighborhood density effect in visual word recognition provides yet another explanation. In the next section, I will discuss studies of the phonological neighborhood density effect.

Phonological Neighborhood Density Effect

The phonological neighborhood density effect is not new in auditory word recognition but was not systematically studied until the work of Yates et al. (2004). Similar to the definition of orthographic neighborhood density, phonological neighborhood density is defined by the number of words that can be generated by replacing one phoneme in the same position of the phoneme structure (Yates, 2005). After controlling word frequency, orthographic neighborhood density, average frequency of orthographic neighbors, and average frequency of phonological neighbors, Yates et al. (2004) obtained a clear phonological neighborhood density effect on the lexical decision task. More importantly, the effect was facilitative, just like the orthographic neighborhood density effect observed by Andrews (1997). With another set of stimuli, Yates (2005) again obtained a facilitative phonological neighborhood density effect on lexical decision, naming, and semantic categorization tasks.

A similar mechanism should presumably work for both orthographic and phonological lexicons. Interactive activation models suggest lateral inhibitory connections also work for a set of phonological neighbors. The facilitation found for phonological neighborhood density is contributed by excitatory interconnections between whole word phonology representations and sublexical phoneme representations. The bimodal interactive activation model would suggest that a mechanism that is sensitive to the overall activation level is what is responsible for the facilitative phonological neighborhood density effect.

In many alphabetic scripts, such as English, orthographic neighbors also tend to be phonological neighbors. This fact makes it difficult to determine the nature of visual vs. phonological neighborhood influences in word recognition for such languages. Yates et al. (2004) suggested, for example, that the earlier finding of a facilitative orthographic neighborhood density effect might be the result of a confounding from a facilitative phonological neighborhood density. To examine this possibility more closely, I calculated the phonological neighborhood density for stimuli used in previous studies that found facilitative orthographic neighborhood density effects. As shown in Table 1, across stimuli with high and low orthographic neighborhood density there was a significant difference not only in orthographic neighborhood density but also in phonological neighborhood density, with the exception of the stimuli used in Andrews's (1992) study.

For studies that did not separate their stimuli into distinct groups based on orthographic neighborhood density, I calculated the correlation between orthographic

Table 1.

Summary of Empirical Studies Examining the Orthographic Neighborhood Density Effect Part I.

Study	Task	OND Effect	Average Stimuli OND [a]		t^b	Average Stimuli PND [a]		t^c
			High OND	Low OND		High PND	Low PND	
Andrews (1989) Exp.1,2,3 HF	Exp.1,2: LDT Exp.3: Naming	Facilitation	13.13	3.33	<.001	20.07	10.73	<.001
Andrews (1989) Exp.1,2,3 LF	Exp.1,2: LDT Exp.3: Naming	Facilitation	13.47	3.73	<.001	22.33	12.40	<.001
Andrews (1992) Exp.1,2 HF	Exp.1: LDT Exp.2: Naming	Facilitation	12.25	4.08	<.001	20.08	14.58	=.05
Andrews (1992) Exp.1,2 LF	Exp.1: LDT Exp.2: Naming	Facilitation	12.42	4.25	<.001	17.27	14.92	n.s.
Sears et al. (1995) Exp.1,2	Exp.1: LDT Exp.2: Naming	Facilitation	9.67	3.75	<.001	17.92	11.54	<.001
Sears et al. (1995) Exp.3 HF	LDT; Naming	Facilitation	12.93	3.40	<.001	20.20	11.60	<.01
Sears et al. (1995) Exp.3 LF	LDT; Naming	Facilitation	13.93	3.13	<.001	22.47	12.33	<.001
Sears et al. (1995) Exp.5	LDT	Facilitation	9.29	3.29	<.001	17.07	12.18	<.05
Sears et al. (1995) Exp.6	LDT	Facilitation	6.07	1.73	<.001	14.03	7.37	<.001

Note. [a] Based on Balota et al. (in press) and Vaden and Hickok (2005). [b] This column listed the *p* value of the t-test on the averaged stimuli OND between the High OND and Low OND groups. [c] This column listed the *p* value of the t-test on the averaged stimuli PND between the High PND and Low PND groups. HF = high frequency. LF = low frequency. LDT = lexical decision task. OND = orthographic neighborhood density. PND = phonological neighborhood density.

Table 2.

Summary of Empirical Studies Examining the Orthographic Neighborhood Density Effect Part II.

Study	Task	OND Effect	Average Stimuli OND [a]	Average Stimuli PND [a]	r [b]	p [c]
Sears et al. (1995) Exp.4	LDT; Naming	Facilitation	OND = 0 : 0.14	PND = 0 : 5.64	.593	<.001
			OND = Few : 3.12	PND = Few : 11.50		
			OND = Many : 9.62	PND = Many : 17.93		
Forster & Shen (1996) Exp.1 HON	LDT	Facilitation	OND = 0 : 0.11	PND = 0 : 4.28	.509	<.001
			OND = 1 : 1.33	PND = 1 : 5.88		
			OND = 2 : 2.44	PND = 2 : 7.89		
			OND = 3 : 4.11	PND = 3 : 10.00		
			OND = 4 : 4.72	PND = 4 : 8.94		
			OND = 5 : 6.33	PND = 5 : 14.50		
Forster & Shen (1996) Exp.1 No HON	LDT	Facilitation	OND = 0 : 0.27	PND = 0 : 3.20	.552	<.001
			OND = 1 : 1.23	PND = 1 : 4.53		
			OND = 2 : 2.40	PND = 2 : 7.54		
			OND = 3/4 : 4.73	PND = 3/4 : 9.33		

Note. [a] Based on Balota et al. (in press) and Vaden and Hickok (2005). [b] This column listed the correlation between the average stimuli OND and the average stimuli PND. [c] This column listed the *p* value for the correlation between average stimuli OND and average stimuli PND. HON = have at least one orthographic neighbor with a higher frequency. LDT = lexical decision task. OND = orthographic neighborhood density. PND = phonological neighborhood density.

neighborhood density and phonological neighborhood density. The results of the analyses, as shown in Table 2, suggest that an increase in orthographic neighborhood density is accompanied by an increase in phonological neighborhood density. Since Yates et al.'s (2004) and Yates's (2005) studies controlled the orthographic neighborhood density of their stimuli, the facilitative phonological neighborhood density effect cannot be attributed to a confound of orthographic neighborhood density. Conversely, because previous studies on orthographic neighborhood density have not controlled phonological neighborhood density of their stimuli, we do not know if orthographic neighborhood density would still reveal a facilitative effect once phonological neighborhood density is controlled.

A recent study by Mulatti, Reynolds, and Besner (2006) that did control phonological neighborhood density has challenged the facilitative effect of orthographic neighborhood density. Using a naming task, Mulatti et al. (2006) found that no orthographic neighborhood density effects were obtained when controlling phonological neighborhood density, whereas a facilitative effect of phonological neighborhood density was still found after controlling orthographic neighborhood density. This study calls into question the facilitative orthographic neighborhood density effect found for previous studies that did not control phonological neighborhood density. However, it could be argued that the task used by Mulatti et al. (2006) is a phonologically-demanding task and thus not an appropriate tool for examining orthographic neighborhood density effects. It is still an open question whether a similar result would be obtained when using a lexical decision task.

Cross-Code Consistency Account

Another challenge to the claim of facilitative effects of orthographic and phonological neighborhood density comes from the cross-code consistency view. Cross-code consistency refers to the degree of consistency in mapping between orthographic and phonological representations (Grainger, Muneaux, Farioli, & Ziegler, 2005). To examine the relationship between orthographic neighborhood density and phonological neighborhood density in visual word recognition, Grainger et al. (2005) first systematically manipulated both the orthographic neighborhood density and the phonological neighborhood density. In a lexical decision task with French, Grainger et al. (2005) found that the effect of phonological neighborhood density was facilitative for words with high orthographic neighborhood density but was inhibitory for words with low orthographic neighborhood density. That is, words with high orthographic and phonological neighborhood density or words with low orthographic and phonological neighborhood density were responded to faster compared to words that were high in one type of neighborhood density but low in the other.

No previous models can clearly explain what was found by Grainger et al. (2005). In the interactive activation model, an explanation based on excitatory connections between word and letter representations or one based on adding a mechanism that is sensitive to overall lexical activation both predict an additive effect of orthographic neighborhood density and phonological neighborhood density. That is, words with both high orthographic neighborhood density and phonological neighborhood density achieve the highest activation and words with low orthographic and phonological neighborhood density achieve the lowest activation.

To explain the interaction found for orthographic neighborhood density and phonological neighborhood density, Grainger et al. (2005) added one more mechanism to their bimodal interactive activation model. They proposed a central interface for orthography-to-phonology and phonology-to-orthography conversion, which bi-directionally interacts with the orthographic whole word system, the orthographic sublexical input system, the phonological whole word system, and the phonological sublexical input system.

With this updated bimodal interactive activation model, words with high orthographic and high phonological neighborhood density and words with low orthographic and low phonological neighborhood density tend to have more consistent orthographic to phonological representations compared to words that are high in one type of neighborhood density but low in the other. The higher the cross-code consistency the faster the response time would be. With this explanation, when words have a large orthographic neighborhood density, the greater the phonological neighborhood density the word carries, the more consistent the cross-code mapping and the faster the response. This results in a facilitative phonological neighborhood density effect. Conversely, when words have a low orthographic neighborhood density, the higher the phonological neighborhood density a word carries, the less consistent the cross-code mapping and thus the slower the response. This results in an inhibitory phonological neighborhood density effect.

Cross-code consistency can also explain the facilitative effect of phonological neighborhood density found by Yates et al. (2004) and Yates (2005). In these two studies, the orthographic neighborhood density which is controlled for in the stimuli tested fits into the higher level of Grainger et al.'s (2005) study. Because increasing the phonological neighborhood density also increases the cross-code consistency, a facilitative phonological neighborhood density effect is predicted and this is what was found in Yates et al. (2004) and Yates (2005).

The Neural Basis of Neighborhood Density Effects

Recent progress in techniques of brain imaging and recording brain activities has made it possible for researchers to examine the neural correlates of how neighborhood density modulates visual word recognition. In an electrophysiological study, Holcomb, Grainger, and O'Rourke (2002) recorded event-related brain potentials (ERPs) while subjects made lexical decision judgments. Holcomb et al. found that words with higher orthographic neighborhood density generated larger N400s than those with lower orthographic neighborhood density. The facilitative effect of orthographic neighborhood density in ERPs fits with behavioral observations that words with high orthographic neighborhood density tend to be responded to faster than those with low orthographic neighborhood density.

Whereas orthographic neighborhood density effects have mainly been studied using ERPs, phonological neighborhood density has been mainly studied using magnetoencephalography (MEG). MEG measures the magnetic fields induced by nerve cells. Within different components, the M350 response component is suggested to be sensitive to phonological neighborhood density (Pylkkänen & Marantz, 2003; Pylkkänen, Stringfellow, & Marantz, 2002). Pylkkänen et al. (2002) found that words with high phonological neighborhood density decreased M350 latencies compared to the latencies of words with low phonological neighborhood density. This facilitative effect of phonological neighborhood density in M350 fits with behavioral observations that words with high phonological neighborhood density tend to be responded to faster than those with low phonological neighborhood density. However, Pylkkänen et al.'s (2002) finding was not replicated in a subsequent study by Stockall, Stringfellow, and Marantz's (2004), in which a null effect of phonological neighborhood density was obtained.

In the same line with the ERPs and MEG studies, neighborhood density should be expected to show a facilitative effect when using hemodynamic measures. However, an fMRI study conducted by Binder et al. (2003) found the opposite. On a lexical decision task, stronger activation in the left angular gyrus, the dorsal prefrontal cortex, and the middle temporal cortex was found for words with no orthographic neighbors compared to those with many orthographic neighbors. The Binder et al.'s (2003) finding contradicts previous behavioral data discussed in the earlier sections, as well as the ERP and MEG findings. However, Binder et al. (2003) also obtained a slightly inhibitory orthographic neighborhood density effect in their behavioral data measured during hemodynamic recoding in their participants, although a facilitative orthographic neighborhood density effect was obtained where the participant who separately tested behaviorally. It is possible that the imaging setting biased participants' responses and made them deviant from the situation in normal reading.

The Present Study

Recent studies on phonological neighborhood density and cross-code consistency challenge traditional findings of a facilitative orthographic neighborhood density effect. Nevertheless, an important caveat has to be addressed. As can be seen from Table 1 and Table 2, there is a high positive correlation between orthographic neighborhood density and phonological neighborhood density in stimuli used in previous studies. Based on the cross-code account suggested by Grainger et al. (2005), stimuli with a high orthographic and phonological neighborhood density and those with a low orthographic and phonological neighborhood density should both be considered as exhibiting high cross-code consistency. The prediction, thus, is that no orthographic neighborhood density effect should be found. Unfortunately, facilitative effects of orthographic neighborhood density are repeatedly found.

However, the facilitative effects of orthographic neighborhood density have been found predominantly for English. For more transparent scripts, such as French and Spanish, the effect of orthographic neighborhood density tends to be null or only slightly facilitative. Since Grainger et al.'s (2005) results were based on French stimuli, the null effect of orthographic neighborhood density predicted by the cross-code consistency account is supported. Following this rationale, I suspect that the Grainger et al.'s (2005) findings, which strongly support the cross-code consistency account, would not be found in English. The underlying organization and operation may not be the same across different types of writing systems.

The motivation for research on effects of orthographic neighborhood density, phonological neighborhood density, and cross-code consistency is to examine the predictions generated from different visual word recognition models. However, due to the inconsistency of study results, it is very difficult to evaluate which model is better fitted to the data obtained. *The goal of the present study is to understand the nature of the connections between orthographic and phonological lexicons in studying orthographic neighborhood density and the phonological neighborhood density concurrently*. Only if we can obtain a clearer result for both orthographic neighborhood density and phonological neighborhood density effects can we have the confidence to evaluate the different visual recognition models. For my dissertation, a total of 8 experiments were conducted, as summarized in Table 3. These included 6 behavioral and 2 brain hemodynamic experiments.

Table 3.

Summary of Eight Experiments in the Present Study.

Study	Measure	Script	OND Manipulation	PND or HD Manipulation[a]	Objective
Experiment 1	Behavior	English	High vs. Low	High vs. Low	Test the cross-code account in English
Experiment 2	Behavior	English	High vs. Low	Very Few	Examine the nature of the OND effect with out the influence from the PND
Experiment 3	Behavior	English	Zero	High vs. Low	Examine the nature of the PND effect with out the influence from the OND
Experiment 4	Behavior	Chinese	High vs. Low	High vs. Low	Test the cross-code account in Chinese
Experiment 5	Behavior	Chinese	High vs. Low	Zero	Examine the nature of the OND effect with out the influence from the HD
Experiment 6	Behavior	Chinese	Zero	High vs. Low	Examine the nature of the HD effect with out the influence from the OND
Experiment 7	NIRS	English	Zero	High vs. Low	Explore English PND effect in BA39/40
Experiment 8	NIRS	Chinese	Zero	High vs. Low	Explore Chinese HD effect in BA9

Note. [a] Due to different orthography-to-phonology mapping in English and Chinese, PND is manipulated when English is tested, whereas HD is manipulated when Chinese is tested. OND = orthographic neighborhood density. PND = phonological neighborhood density. HD = homophone density.

OVERVIEW AND RATIONALE UNDERLYING THE PRESENT EXPERIMENTS

Behavioral Experiments in English

The first set of experiments sought to clarify the nature of orthographic and phonological neighborhood density effects in English using standard behavioral measures such as lexical decision. To fully test the cross-code consistency account in English, a design that mimics Grainger et al.'s (2005) study was conducted. Experiment 1 systematically manipulated both orthographic neighborhood density and phonological neighborhood density in a 2 (orthographic neighborhood density: high vs. low) by 2 (phonological neighborhood density: high vs. low) within-subjects factorial. Experiment 1 also tested the reliability of the orthographic neighborhood density effect. If the effect of orthographic neighborhood density is independent of phonological neighborhood density Experiment 1 should obtain a clear orthographic neighborhood density effect, in addition to a phonological neighborhood density effect.

Experiment 2 sought to improve on the design of Mulatti et al. (2006). Whereas Mulatti et al. had obtained a null effect of orthographic neighborhood density using a naming task, Experiment 2 examined the orthographic neighborhood density effect using a lexical decision task, which is considered a more appropriate task than naming to study orthographic effects. A second problematic aspect of the Mulatti et al.'s (2006) study was the way phonological neighborhood density was controlled. The average phonological neighborhood density for stimuli used in Mulatti et al.'s (2006) study was 6.47 and 6.63 for low and high orthographic neighborhood density words respectively. Based on PDP and the mechanism of overall lexical activity in Grainger and Jacobs's

(1996) bimodal interactive activation model, phonological neighbors of the target word would still lead to a increase in global activation in the orthographic lexicon through interconnections between orthographic and phonological lexicons.

Another problem for Mulatti et al.'s (2006) study is that orthographic neighbors also tend to be phonological neighbors. As such, four sources of facilitative bi-directional connections could create *activation enhancement* to the target word: 1) connections between word and sublexical levels in the orthographic lexicon; 2) connections between word and sublexical levels in the phonological lexicon; 3) connections between word levels of orthographic and phonological lexicons; and 4) connections between sublexical levels of orthographic and phonological lexicons. As an example, the word *scrap* has 2 orthographic neighbors, *strap* and *scram*, and 4 phonological neighbors, *strap, scram*, *scrape,* and *scratch*. The word *proof* has no orthographic neighbors but has 4 phonological neighbors, *prof*, *prude*, *prune*, and *prove*. The influences in the phonological lexicon can be assumed to be equivalent for *scrap* and *proof* due to the same number of phonological neighbors. How about activation in the orthographic lexicon? Based on the same procedure I described earlier, if one supposes that the word representation *scrap* sends 5 units of activation to each of its 5 letter representations in the first cycle, its two neighbors, *strap* and *scram*, should deliver 4 units of activation as well due to their sharing of 4 letter units. Each letter representation, in total, will receive 13 units of feedback from word representations, with 5 units from the target word *scrap* and 4 units from overlapping neighbors. These letter representations will send 57 units of feedback to the word representation *scrap*, with 13 units of activation from letter representations, *s*, *r*, and *a*, and 9 units of activation from letter representations, *c* and *p*. In this manner, the word representation *cap* will continue receiving 669 units of activation in the second cycle, and so on and so forth. As to the word representation for *proof*, its letter representations will only send 25 and 125 units of feedback in the first and the second cycles.

However, it is incorrect to assume that controlling phonological neighborhood density also controls the influences from the phonological lexicon. In the case of *scrap*, the *activation enhancement* in phonological lexicon can affect enhancement processes in the orthographic lexicon through inter-connections of *scrap* and its two dual role neighbors, *strap* and *scram*. Because *strap* and *scram* are both orthographic and phonological neighbors of *scrap*, their facilitative bi-directional connections between their word representations in the orthographic and phonological lexicons can work just like the *activation enhancement* between word and sublexical levels in orthographic lexicon. Similar *activation enhancement* can also happen between letter representations between orthographic and phonological lexicons for these dual role neighbors. The word *proof* cannot benefit additionally from sources like this because it has no orthographic neighbors.

To understand more clearly the nature of orthographic neighborhood density without the influence of phonological neighborhood density, the best way would be to investigate words without any phonological neighbors. In this way, one could significantly reduce the *activation enhancement* through connections between word representations of orthographic and phonological lexicons. In Experiment 2, I reexamined the orthographic neighborhood density effect with words that had very low phonological neighborhood density. Although the ideal design would be one that reduces the phonological neighborhood density to zero, few English words have zero phonological neighbors. By reducing and controlling the number of phonological neighbors, the influence from the phonological lexicon can be reduced and a clearer orthographic neighborhood density effect can be examined.

Studies have suggested that the orthographic neighborhood density effect tends to be present only in low frequency words (Andrews, 1992). Mulatti et al.'s (2006) failure to obtain an orthographic neighborhood density effect may also be due to the fact that the stimuli in their study had high frequencies (mean > 100). In Experiment 2, I selected stimuli with low frequency to see if an orthographic neighborhood density effect can be obtained.

Using the same rationale, to understand the nature of the phonological neighborhood density without any influence from orthographic neighborhood density, the best way would be to investigate words without any orthographic neighbors. Although the studies of Yates et al. (2004), Yates (2005), and Mulatti et al. (2006) all controlled orthographic neighborhood density, orthographic neighbors of target words in these studies should still increase the global activation in the phonological lexicon through interconnections between orthographic and phonological lexicons.

In Experiment 3, I examined the phonological neighborhood density effect for words without any orthographic neighbors. Unlike the case with phonological neighborhood density, words with zero orthographic neighborhood density do exist in

English. For example, the word *urge* has no orthographic neighbors but has many phonological neighbors, such as *edge*, *age*, *earl*, *earn*, and *earth*. By reducing the number of orthographic neighbors to zero, phonological neighborhood density can be examined without any influence of orthographic density.

PDP models predict facilitative effects of orthographic and phonological neighborhood density in Experiments 2 and 3. An additive effect of facilitative orthographic neighborhood density and phonological neighborhood density is also predicted in Exp.1. For traditional IA models, inhibitory effects of orthographic and phonological neighborhood density are predicted in Exp.2 and Exp.3. An additive effect of inhibitory orthographic neighborhood density and phonological neighborhood density is also predicted in Exp.1. The BIA model with mechanisms sensitive to global lexical activation and cross-code consistency (Grainger and Jacobs, 1996; Grainger et al., 2005) predicts facilitative effects of orthographic and phonological neighborhood density in Exp.2 and Exp.3. More importantly, an interaction of orthographic neighborhood density and phonological neighborhood density that is similar to the results of Grainger et al. (2005) is predicted in Exp.1. As to the suggestion by Andrews (1997) of compensation through facilitative bi-directional connections, an additive effect of facilitative orthographic neighborhood density and phonological neighborhood density is also predicted in Exp.1. However, reduced or even inhibitory effects of orthographic and phonological neighborhood density in Exp.2 and Exp.3 are expected.

Behavioral Experiments in Chinese

The next set of experiments sought to clarify the relative contribution of orthographic and phonological influences on neighborhood density effects by testing native readers of Chinese. Although one can find words in English that are high in orthographic neighborhood density but low in phonological neighborhood density, in many cases this is not possible. For example, the word *urge*, which has many phonological neighbors such as *edge*, *age*, *earl*, *earn*, and *earth*, has no orthographic neighbors, following the standard definition of orthographic and phonological neighbors, where the target words and its neighbors still share a large portion of letters and phonemes. This fact makes it difficult to tease apart the specific contribution of visual vs. phonological neighborhood influence in word recognition in English.

By contrast, in other languages, such as Chinese, one can easily find a group of orthographic neighbors without any phonological relationship and a group of phonologically related words without any visual similarity. For this reason, a comparison between English and Chinese provides a good opportunity to examine how the orthography-phonology correspondence of a writing system influences the organization within and between orthographic and phonological lexicons. One difference to note between English and Chinese is that because there are no units in Chinese characters that correspond to phonemes, there are strictly speaking no phonological neighbors in the same sense as one talks of them in alphabetic languages. Instead, only whole word phonology can be calculated in Chinese. Fortunately, Chinese has many homophones. For this reason, homophone density was used as a proxy for phonological neighborhood density in the Chinese studies. Another important difference is in the definition of orthographic neighbors across the two languages. Since there are no sublexical structures corresponding to letters in Chinese, another orthographic structure, i.e., radicals, was used in the present experiments as a way of manipulating orthographic neighbors. Chinese orthographic neighbors were thus defined in terms of characters that share all but one radical.

For characters with a frequency higher than one count in the database of Wu and Liu (1988), 93% of Chinese characters are clearly combined by one semantic radical and one phonetic radical. Feldman and Siok (1999) found a facilitative semantic radical neighborhood density effect in a primed Chinese lexical decision task, however, it is difficult to know if this facilitative effect is due to orthographic or semantic overlap. For Chinese characters, semantic radicals tend to have fewer strokes than phonetic radicals. Based on my calculation of characters with a frequency higher than one count in Wu and Liu’s (1988) database, 4585 Chinese characters are combined by 326 semantic radicals with an average of 18 orthographic neighbors and 1186 phonetic radicals with an average of 7 orthographic neighbors. Because the present study focused on the organization and operation within and between orthographic and phonological lexicons, I manipulated orthographic neighborhood density effect for phonetic radicals but held that for semantic radicals constant. Thus, for the purposes of the present research, when referring to Chinese orthographic neighborhood density what I mean is density based on an overlap in phonetic radicals (not semantic radicals).

Two advantages for studying Chinese should be pointed out. First, Chinese orthographic neighbors studied in the present study only share one sublexical unit, the phonetic radical, unlike English orthographic neighbors, which share many letters, Chinese orthographic neighbors thus have a subjectively reduced effect of facilitative bi-directional connections between word and sublexical levels within the orthographic lexicon. Second, since no sublexical units like phonemes in English are represented in the Chinese phonological lexicon, forces from facilitative bi-directional connections between word and sublexical levels within the phonological lexicon can be ruled out completely for Chinese. These advantages makes Chinese a valuable tool to examine the design of intra-level lateral inhibition in IA models.

To test the cross-code consistency account in Chinese, a design that resembles that of Grainger et al.’s (2005) study was also examined. In Experiment 4, a systematic manipulation of orthographic neighborhood density and homophone density was conducted using a 2 (orthographic neighborhood density: high vs. low) by 2 (homophone density: high vs. low) within-subjects factorial. Experiment 4 is especially important for testing the cross-code account suggested by Grainger et al. (2005).

In Experiment 5, I examined the orthographic neighborhood density effect with Chinese characters without any homophone mates. By reducing the number of homophone mates to zero, a clearer orthographic neighborhood density effect in Chinese can be examined. In Experiment 6, I examined the homophone density effect for Chinese characters without any orthographic neighbors. By reducing the number of orthographic neighbors to zero, a clearer homophone density effect can be examined.

One advantage of studying the homophone density effect in Chinese is that homophone mates can be selected without any contamination from visual similarity of the homophones, thereby avoiding any interconnections between homophone mates within the orthographic lexicon. Further, because no phoneme units are represented for Chinese orthography, homophone mates share only a single whole word phonological representation in the phonological lexicon. Since no visual similarity and no sublexical phonemic units can be found in Chinese orthography, any density effect found must therefore occur at the whole word level. For this reason, Experiment 6 is especially important in testing the overall lexical activation account of a facilitative neighborhood density effect (Grainger & Jacobs, 1996). The explanation of facilitative bidirectional connections between word representations and their sublexical representations may not work here (Andrews, 1997). Ziegler, Tan, Perry, & Montant (2000) reported facilitative homophone density effects in Chinese lexical decision and naming which supports the overall lexical activation account. However, Zhou and Marslen-Wilson (1999) did not obtain a clear homophone density effect in Chinese naming. Nevertheless, Zhou and Marslen-Wilson’s (1999) and Ziegler et al.’s (2000) studies did not control orthographic neighborhood density or orthographic neighborhood frequency. Even more, homophone density manipulated in Ziegler et al. (2000) covaried with phonological frequency. We, thus, do not know if the facilitative homophone density effect can still be found for our Experiment 6 which excluded any stimuli with any orthographic neighbors. The better manipulation in the present research will provide a clearer test of the nature of a homophone density effect in Chinese.

PDP models predict facilitative effects of both orthographic neighborhood and homophone density in Exp. 5 and Exp. 6. An additive effect of facilitative orthographic neighborhood density and homophone density is also predicted in Exp. 4.

For traditional IA models, an inhibitory effect of orthographic neighborhood density is predicted in Exp.5 due to intra-level lateral inhibition. However, a null effect of homophone density is expected in Exp.6 because stimuli selected shared only one phonology representation and no connections within the orthographic lexicon. An inhibitory orthographic neighborhood density and a null homophone density are thus also predicted in Exp.4.

The BIA model with mechanisms sensitive to global lexical activation and cross-code consistency (Grainger & Jacobs, 1996; Grainger et al., 2005) predicts facilitative effects of orthographic neighborhood and homophone density in Exp.5 and Exp.6. More importantly, an interaction of orthographic neighborhood density and homophone density that is similar to the results of Grainger et al. (2005) is predicted in Exp.4.

As to the suggestion of a compensation through facilitative bi-directional connections by Andrews (1997), a reduced or even inhibitory effect of orthographic neighborhood density in Exp.5 is expected. A null effect of homophone density should be obtained in Exp.6 for two reasons: 1) no sublexical units like phonemes are represented in the Chinese phonological lexicon and thus the forces from facilitative bi-directional connections between word and sublexical representations in phonological lexicon like in English can be reduced to zero; 2) the stimuli in Exp.6 were selected purposely so that they have no orthographic neighbors and thus no connections between homophones at either lexical or sublexical levels within orthographic lexicon should be found. This should also reduce the forces from facilitative bi-directional connections between word and sublexical representations in the orthographic lexicon like in English to zero. For the same reason, an inhibitory orthographic neighborhood density effect with a null effect of homophone density was expected in Exp.4.

NIRS Experiments

The remaining experiments explored neural correlates of neighborhood density effects using the hemodynamic measure of near infrared spectroscopy (NIRS). Because research on neighborhood density effects is comparatively new, very few neural imaging studies have specifically examined this variable. However, hemodynamic changes in the brain can potentially provide further evidence supporting a facilitative or inhibitory account for the neighborhood density effect.

Electrophysiological recording methods like EEG or ERP provide good temporal resolution but are poor in spatial resolution, whereas hemodynamic measures like fMRI support detailed spatial resolution but are more limited in their temporal resolution. However, the NIRS technique, an optical imaging method, provides both good temporal resolution (in the millisecond scale) and reasonable spatial resolution (see Strangman, Boas, & Sutton, 2002, for discussion). NIRS measures the changes in the concentration of oxy-hemoglobin and deoxy-hemoglobin in the brain regions of interest by shining near-infrared light (650-950nm) into the scalp and applying its absorbing and scattering characteristics. Based on NIRS measures, the amplitudes and latencies of the blood flow change can be analyzed.

In the present study, two exploratory NIRS experiments are conducted to test neighborhood density effects in English and Chinese. Two wavelengths, 690nm and 830nm, were selected for testing; the former is more sensitive to the deoxy-hemoglobin and the latter is more sensitive to the oxy-hemoglobin. When a brain area engages in a mental operation, an increase in the concentration of the oxy-hemoglobin and a decrease in the concentration of the deoxy-hemoglobin should be observed (see Strangman et al., 2002, for a review).

Because the NIRS system is not able to monitor blood flow change in the whole brain, the need to identify the brain region of interest (ROI) before measuring is important. Since fMRI studies for orthographic processing had shown less consistent results than those for phonological processing, I studied NIRS for phonological processing instead of orthographic processing. In two meta-analyses of fMRI studies (Bolger, Perfetti, & Schneider, 2005; Tan, Laird, Li, & Fox, 2005), the left middle frontal gyrus (Brodmann’s Area 9), which is involved in addressed phonology, was found to be specifically related to Chinese processing, whereas the left temporoparietal region (Brodmann’s Area 39/40), which is involved in assembled phonology, was found to be especially important for reading alphabetic writing systems like English.

In Experiment 7, I applied NIRS to measure blood flow change in Brodmann Area 39/40 using the English stimuli selected from Experiment 3 in order to see if I could find the neural basis for phonological neighborhood density in English found by Yates et al. (2004) and Yates (2005). Different patterns of blood flow changes for words with high vs. low phonological neighborhood density were expected in Exp.7.

Specifically, words with high phonological neighborhood density were predicted to induce greater blood flow changes, which may be due to stronger inhibitory or facilitative connections, than those with low phonological neighborhood density.

In Experiment 8, I used NIRS to measure blood flow change in Brodmann's Area 9 with Chinese stimuli selected from Experiment 6 to test homophone density effect found by Ziegler et al. (2000). Different patterns of blood flow changes for words with high vs. low homophone density were also expected in Exp.8. Specifically, words with high homophone density were predicted to induce larger blood flow changes, which may be due to stronger inhibitory or facilitative connections, than those with low homophone density.

EXPERIMENT 1: CROSS-CODE CONSISTENCY EFFECT IN ENGLISH

Method

Participants. Twenty-six college students from a large southwestern U.S. university participated in the experiment. All were fluent readers of English with normal or corrected-to-normal vision.

Design and Materials. The design was a 2 (Orthographic neighborhood density: high vs. low) x 2 (Phonological neighborhood density: high vs. low) within subjects factorial, with a total of 4 conditions. Eighty 4 to 7-letter monosyllabic, single-morpheme English words were selected as the stimuli. They were subdivided into four categories as follows: 20 words with high orthographic density (defined as greater than or equal to 7) and high phonological neighborhood density (defined as greater than or equal to 15), 20 words with high orthographic but low phonological neighborhood density (lower than or equal to 8), 20 words with low orthographic density (lower than or equal to 4) but high phonological neighborhood density, and 20 words with low orthographic and low phonological neighborhood density. In addition there were 80 nonwords. The four sets of stimuli were matched in number of letters, number of phonemes, bigram frequency, mean frequency of orthographic neighbors, and mean frequency of phonological neighbors. Studies have suggested that the orthographic neighborhood density effect tends to be obtained for low frequency words (Andrews, 1989, 1992). For this reason, only low frequency words (< 35) were selected. All values of linguistic characteristics were determined by consulting the English lexicon project (Balota, et al., in press) and the Irvine Phonotactic Online Dictionary (IPhOD) (Vaden &

Hickok, 2005). See Table 4 for a summary of stimulus characteristics and Appendix A for the actual stimuli.

Apparatus and Procedure. Participants, tested individually, first saw a fixation signal (a cross) for 1000 ms, followed by a stimulus presented at the center of the screen. The stimulus was displayed until the participant made a speeded lexical decision

Table 4

Characteristics of the Stimuli Used in Experiment 1 (Mean Values)

	High OND		Low OND	
Characteristic	High PND	Low PND	High PND	Low PND
Letters	4.35	4.10	4.75	4.55
Phonemes	3.65	4.00	3.60	3.90
Frequency	10.85	10.60	11.20	10.70
OND	9.05	9.00	2.55	2.75
PND	21.20	6.40	21.15	6.30
BF	2232.80	1716.45	2289.10	2002.20
Mean Frequency of ON	6.88	6.95	6.88	6.61
Mean Frequency of PN	16.11	15.44	16.30	15.81

Note. OND = orthographic neighborhood density; BF = bigram frequency; ON = orthographic neighbors; PN = phonological neighbors; PND = phonological neighborhood density.

response. Response time (RT) was recorded from the onset of stimulus presentation until the participant pressed a button. Participants received 10 practice trials at the beginning of the experiment. A rest was given after every 40 trials. The experiment was administered on personal computers using an E-Prime software package (Schneider, Eschman, & Zuccolotto, 2002).

Results and Discussion

Data from 3 items were excluded in analyses due to their low accuracy (<40%). In calculating the mean RTs of correct responses for each condition for each participant, those trials with RTs less than 200 ms or higher than 1800 ms were discarded. These cutoffs led to the rejection of 1.68% of the observations. Table 5 shows the accuracy calculated from the entire set of trials, and re-computed means for correct RTs for each experimental condition.

The data were analyzed in a 2x2 repeated measures analysis of variance (ANOVA) that resulted from the factorial combination of Orthographic Neighborhood Density (high vs. low), and Phonological Neighborhood Density (high vs. low). The data were analyzed by subjects (F_1) and by items (F_2). Although we provide the accuracy and the by-item analyses as well, discussion of the results will focus primarily on the by-subject RT analyses.

The results of the ANOVA indicated a significant main effect for Orthographic Neighborhood Density in RT, $F_1(1,25) = 14.21$, $p < .01$, $F_2(1,73) = 3.53$, $p = .06$, but not in accuracy, $F_1(1,25) < 1$, $F_2(1,73) = < 1$, indicating a facilitative orthographic neighborhood density effect. In addition, a significant main effect for Phonological

Neighborhood Density was obtained in RT, $F_1(1,25) = 15.25$, $p < .01$, $F_2(1,73) = 4.24$, $p < .05$, and in accuracy when analyzed by subject, $F_1(1,25) = 4.90$, $p < .05$, $F_2(1,73) < 1$, indicating a facilitative phonological neighborhood density effect. No interactions of Orthographic Neighborhood Density and Phonological Neighborhood Density were found in RT, $F_1(1,25) = 2.24$, p =.14, $F_2(1,73) <1$, or in accuracy, $F_1(1,25) < 1$, $F_2(1,73) < 1$.

Table 5

Mean Reaction Time (ms) and Accuracy (%) in Experiment 1

		High OND	Low OND	OND Effect
High PND	RT	680.30 (17.27)	705.14 (21.18)	-24.84 (10.67)
	Accuracy	94.44 (0.87)	93.93 (1.00)	-0.51 (1.18)
Low PND	RT	708.29 (17.62)	753.81 (22.70)	-45.52 (12.49)
	Accuracy	92.12 (1.15)	91.92 (1.27)	-0.20 (1.70)
PND Effect	RT	-27.99 (9.74)	-48.67 (13.91)	
	Accuracy	-2.32 (1.29)	-2.01 (1.53)	

Note. OND = orthographic neighborhood density; PND = phonological neighborhood density. The OND effect refers to the difference in performance on the high vs. low OND condition. The PND effect refers to the difference in performance on the high vs. low PND condition. A positive value indicates a facilitative effect and a negative value an inhibitory effect. Standard errors are reported in parentheses.

The results indicate that despite a design that was modeled after Grainger et al.'s (2005) study, their results were not replicated; thus, no support was found for Grainger et al.'s cross-code account. Although Yates (2005) and Mulatti et al. (2006) have questioned the reliability of the orthographic neighborhood density effect, the present study obtained a clear effect of orthographic neighborhood density using a better manipulation than was the case in the previous studies in this literature. The present results suggest that the orthographic neighborhood density effect is reliable and independent of the effect of phonological neighborhood density.

Whereas no support was found for traditional IA models, the findings from the present experiment can be accounted for both by PDP models and by Andrews's (1997) suggestion of compensation from facilitative bi-directional connections. Although the global activation account in the BIA model can explain the current data, the specific suggestion by Grainger et al. (2005) of a mechanism that calculates cross-code consistency was not supported.

EXPERIMENT 2: ORTHOGRAPHIC NEIGHBORHOOD DENSITY EFFECT IN ENGLISH

Method

Participants. Twenty participants were selected, based on similar criteria as were used in Exp.1.

Design and Materials. The experimental design was a one factor (Orthographic Neighborhood Density: high vs. low) within-subjects design.

The same criteria for stimulus selection as in Exp.1 were used except that only English words with few phonological neighbors were selected. To keep phonological neighborhood density as low as possible, only English words with fewer than 4 phonological neighbors were selected. Stimuli included 20 words with high orthographic neighborhood density (greater than 5) and 20 words with low orthographic neighborhood density (lower than 5).

In addition, 40 nonwords were selected and intermixed with the experimental trials. Each participant received a different randomized sequence from a list consisting of 80 trials that included 20 words with high orthographic neighborhood density, 20 words with low orthographic neighborhood density, and 40 nonwords. See Table 6 for a summary of stimulus characteristics and Appendix A for the actual stimuli.

Apparatus and Procedure. The apparatus and the procedure in Exp.2 were the same as in Exp.1.

Results and Discussion

Data from 2 items were excluded from the analyses due to their low accuracy (<40%). In calculating the mean RTs of correct responses per condition for each participant, those trials with RTs less than 200 ms or higher than 1800 ms were discarded. These cutoffs led to the rejection of 2.17% of the observations. Table 7 shows the accuracy, calculated from the entire set of trials, and the re-computed means for correct RTs for each experimental condition.

Table 6

Characteristics of the Stimuli Used in Experiment 2 (Mean Values)

Characteristic	High OND	Low OND
Letters	4.40	4.65
Phonemes	4.25	4.40
Frequency	10.00	9.75
OND	7.15	2.20
PND	3.25	3.20
BF	1655.20	1631.80
Mean Frequency of ON	6.32	6.47
Mean Frequency of PN	23.12	23.30

Note. OND = orthographic neighborhood density; BF = bigram frequency; ON = orthographic neighbors; PN = phonological neighbors; PND = phonological neighborhood density.

The data were analyzed in a one-way repeated measures analysis of variance (ANOVA) with the factor of Orthographic Neighborhood Density (high vs. low). The data were analyzed by subjects (F_1) and by items (F_2). Although the discussion in the present study is based mainly on the by-subject RT analyses, the accuracy and by-item RT analyses are also provided for readers' interest.

The results of the ANOVA indicated a significant main effect for Orthographic Neighborhood Density in RT when analyzed by subject, $F_1(1,19) = 11.59$, $p < .01$, $F_2(1,36) = 2.67$, $p = .11$, indicating an inhibitory orthographic neighborhood density effect. There was no effect of orthographic density in the accuracy analysis, $F_1(1,19) = 2.58$, $p = .12$, $F_2(1,36) < 1$.

After improving on the design of Mulatti et al. (2006) by selecting stimuli with very few phonological neighbors, evidence was found in the present study for a clear

Table 7

Mean Reaction Time (ms) and Accuracy (%) in Experiment 2

	High OND	Low OND	OND Effect
RT	780.88 (28.15)	740.49 (25.96)	40.39 (11.87)
Accuracy	88.89 (1.71)	91.25 (1.20)	2.36 (1.47)

Note. OND = orthographic neighborhood density. The OND effect refers to the difference in performance on the high vs. low OND condition. A positive value indicates a facilitative effect and a negative value an inhibitory effect. Standard errors are reported in parentheses.

inhibitory orthographic neighborhood density effect in lexical decision RT. Although Mulatti et al.’s (2006) study controlled phonological neighborhood density, their stimuli still had phonological neighborhood densities high enough to induce *activation enhancement* through connections between word levels of orthographic and phonological lexicons by dual role neighbors. The assumption in Mulatti et al.’s (2006) study that controlling phonological neighborhood density also controls the influence from the phonological lexicon turns out not to be correct.

Another possible reason for the failure by Mulatti et al. (2006) to obtain an orthographic neighborhood density effect was their use of high frequency stimuli. When stimuli with low frequencies are selected, as in the present experiment, there was no facilitative orthographic neighborhood density effect.

The finding of an inhibitory orthographic neighborhood density effect supports the idea of inter-level lateral inhibition central to IA models. Conversely, PDP models fail to explain the present results. The idea of a mechanism sensitive to global activation by (Grainger & Jacobs, 1996) did not receive support because stimuli with a higher orthographic neighborhood density were not recognized faster. .

Andrews’s (1997) suggestion of a compensation from facilitative bi-directional connections can successfully explain the results in both Exp.1 and Exp.2. When words have several phonological neighbors, they are influenced by four sources of facilitative bi-directional connections: 1) connections between word and sublexical levels in the orthographic lexicon; 2) connections between word and sublexical levels in the phonological lexicon; 3) connections between word levels of the orthographic and phonological lexicons; and 4) connections between sublexical levels of the orthographic and phonological lexicons. These four sources of influence quickly accumulate resulting in strong activations of the target word. Following Andrews, one may argue that these forces were so strong that they compensated for the inhibitory forces from intra-level lateral connections and resulted in a net facilitative effect, as obtained in Exp.1. However, when forces from facilitative bi-directional connections are limited to the orthographic lexicon only, forces from intra-level lateral inhibition may override the facilitative forces from bi-directional connections and cause a net inhibitory effect, as found in Exp.2.

EXPERIMENT 3: PHONOLOGICAL NEIGHBORHOOD DENSITY EFFECT IN ENGLISH

Method

Participants. Twenty-four participants were selected, based on similar criteria as used in Exp.1.

Design and Materials. The experimental design was a one factor (Phonological Neighborhood Density: high vs. low) within-subjects design.

Table 8

Characteristics of the Stimuli Used in Experiment 3 (Mean Values)

Characteristic	High OND	Low OND
Letters	5.50	5.90
Phonemes	3.80	4.50
Frequency	11.05	11.20
OND	0.00	0.00
PND	14.75	2.80
BF	2381.65	2311.90
Mean Frequency of ON	0.00	0.00
Mean Frequency of PN	17.76	17.55

Note. OND = orthographic neighborhood density; BF = bigram frequency; ON = orthographic neighbors; PN = phonological neighbors; PND = phonological neighborhood density.

The same criteria for stimulus selection as in Exp.1 were used except that stimuli were English words without any orthographic neighbors. They included 20 words with higher phonological neighborhood density (greater than 6) and 20 words with lower phonological neighborhood density (lower than 6).

In addition, 40 nonwords were selected and intermixed with the experimental trials. Each participant received a different randomized sequence from a list consisting of 80 trials that included 20 words with higher phonological neighborhood density, 20 words with lower phonological neighborhood density, and 40 nonwords. See Table 8 for a summary of stimulus characteristics and Appendix A for the actual stimuli.

Apparatus and Procedure. The apparatus and procedure in Exp.3 were the same as in Exp.1.

Results and Discussion

In calculating the mean RTs of correct responses for each condition for each participant, those trials with RTs less than 200 ms or higher than 1800 ms were discarded. These cutoffs led to the rejection of 2.29% of the observations. Table 9 shows the accuracy, calculated from the entire set of trials, and re-computed means for correct RTs for each experimental condition.

The data were analyzed in a one-way repeated measures analysis of variance (ANOVA) with the factor Phonological Neighborhood Density (high vs. low). The data were analyzed by subjects (F_1) and by items (F_2). Although the discussion in the present study is mainly based on the by-subject RT analyses, we provide accuracy and by-item RT analyses for readers' interest.

The results of the ANOVA indicated a significant main effect for Phonological Neighborhood Density in RT when analyzed by subjects, $F_1(1,23) = 8.60$, $p < .01$, $F_2(1,38) = 2.76$, $p = .10$, and in accuracy, $F_1(1,23) = 39.91$, $p < .001$, $F_2(1,36) = 4.01$, $p < .05$, indicating an inhibitory phonological neighborhood density effect.

Thus, as in Exp.2 where an inhibitory orthographic neighborhood density effect was obtained, in Exp. 3 an inhibitory phonological neighborhood density effect was found. Although Yates (2005) and Mulatti et al. (2006) controlled orthographic neighborhood density, their stimuli still had orthographic neighborhood densities high enough to induce *activation enhancement* through connections between word levels of orthographic and phonological lexicons by dual role neighbors.

PDP models again fail to explain the present results. The idea of a mechanism

Table 9

Mean Reaction Time (ms) and Accuracy (%) in Experiment 3

	High PND	Low PND	PND Effect
RT	723.69 (19.86)	694.35 (19.80)	29.34 (10.00)
Accuracy	87.71 (1.56)	97.08 (0.85)	9.37 (1.48)

Note. PND = phonological neighborhood density. The PND effect refers to the difference in performance on the high vs. low PND condition. A positive value indicates a facilitative effect and a negative value an inhibitory effect. Standard errors are reported in parentheses.

sensitive to global activation by Grainger and Jacobs, 1996) did not obtain support as well because higher phonological neighborhood density did not accelerate the speed of recognizing words. Andrews's (1997) suggestion of compensation from facilitative bi-directional connections does successfully explain the results of the present experiment as well as those from Exp.1 and Exp.2. When forces from facilitative bi-directional connections are limited to the phonological lexicon, forces from intra-level lateral inhibition can override the facilitative effect of bi-directional connections, resulting in a net inhibitory effect.

EXPERIMENT 4: CROSS-CODE CONSISTENCY EFFECT IN CHINESE

Method

Participants. Twenty Taiwanese graduate students from a large southwestern U.S. university participated in the experiment. All were fluent readers of Chinese with normal or corrected-to-normal vision.

Design and Materials. The design was a 2 (Orthographic neighborhood density: high vs. low) x 2 (Homophone density: high vs. low) within subjects factorial, with a total of 4 conditions.

Sixty-four Chinese characters were selected as the stimuli. Subdivided into four categories, they included 16 words with high orthographic neighborhood density (greater or equal to 10) and homophone density (greater or equal to 9), 16 words with high orthographic neighborhood density but low homophone density (lower or equal to 5), 16 words with low orthographic neighborhood density (lower or equal to 4) but high homophone density, and 16 words with low orthographic neighborhood density and homophone density. These four sets of stimuli were matched on number of strokes, mean frequency of orthographic neighbors, and mean frequency of homophone mates. For the same reason as in Exp.1, only low frequency characters were selected. All values of linguistic characteristics were calculated from the database created by Wu and Liu (1988) and Wu (2003).

In addition, 64 filler characters and 128 pseudo-characters were selected and intermixed with the experimental trials. Pseudo-characters were created by combining two radicals that never co-occur in real characters but follow legal Chinese combination rules. Each participant received a different randomized sequence from a list consisting of 256 trials containing 16 characters with high orthographic neighborhood and homophone density, 16 characters with high orthographic neighborhood density but low homophone density, 16 characters with low orthographic neighborhood density (< or equal to 4) but high homophone density, 16 characters with low orthographic neighborhood density and low homophone density, 64 filler characters, and 128 pseudo-characters. See Table 10 for a summary of stimulus characteristics and Appendix B for the actual stimuli.

Table 10

Characteristics of the Stimuli Used in Experiment 4 (Mean Values)

	High OND		Low OND	
Characteristic	High HD	Low HD	High HD	Low HD
Strokes	12.81	12.56	12.81	12.75
Frequency	19.94	20.00	19.63	19.88
OND	11.50	11.69	2.06	2.19
HD	16.88	3.00	16.56	3.25
Mean Frequency of ON	75.83	74.88	71.82	72.36
Mean Frequency of HM	95.31	94.20	93.97	95.62

Note. OND = orthographic neighborhood density; HD = homophone density; ON = orthographic neighbors; HM = homophone mates.

Apparatus and Procedure. The apparatus and procedure in Exp.4 were the same as in Exp.1.

Results and Discussion

In calculating the mean RTs of correct responses for each condition for each participant, those trials with RTs less than 200 ms or higher than 1800 ms were discarded. These cutoffs led to the rejection of 0.70% of the observations. Table 11 shows the accuracy, calculated from the entire set of trials, and re-computed means for correct RTs for each experimental condition.

The data were analyzed in a 2x2 repeated measures analysis of variance (ANOVA) that resulted from the factorial combination of Orthographic Neighborhood Density (high vs. low), and Homophone Density (high vs. low). The data were analyzed by subjects (F_1) and by items (F_2). Although the discussion in the present study is mainly based on the by-subject RT analyses, we provide accuracy and by-item analyses for readers' interest.

The results of the ANOVA indicated a significant main effect for Orthographic Neighborhood Density in RT, $F_1(1,19) = 18.66$, $p < .001$, $F_2(1,60) = 2.75$, $p = .09$, and in accuracy when analyzed by subject, $F_1(1,19) = 6.45$, $p = .05$, $F_2(1,60) = 1.66$, $p = .20$, indicating an inhibitory orthographic neighborhood density effect. In addition, a significant main effect for Homophone Density was obtained in RT, $F_1(1,19) = 11.49$, $p < .01$, $F_2(1,60) = 2.94$, $p = .09$, and in accuracy by subject, $F_1(1,19) = 4.13$, $p = .05$, $F_2(1,60) = < 1$, indicating an inhibitory phonological neighborhood density effect. No interaction of Orthographic Neighborhood Density and Homophone Neighborhood

Density was found in RT, $F_1(1,19) < 1$, $F_2(1,60) < 1$, or in accuracy, $F_1(1,19) < 1$, $F_2(1,60) < 1$.

With a design that mimics Grainger et al.'s (2005) study, we did not replicate their results and thus did not support their cross-code account. As noted earlier, although Yates (2005) and Mulatti et al. (2006) have questioned the reliability of the orthographic neighborhood density effect, the present study obtained a clear effect of orthographic

Table 11

Mean Reaction Time (ms) and Accuracy (%) in Experiment 4

		High OND	Low OND	OND Effect
High HD	RT	694.63 (29.68)	659.40 (30.74)	35.23 (9.15)
	Accuracy	88.44 (2.32)	92.19 (1.63)	3.75 (1.60)
Low HD	RT	653.79 (25.64)	631.42 (27.38)	22.37 (11.88)
	Accuracy	91.25 (1.89)	94.06 (1.54)	2.81 (1.78)
HD Effect	RT	40.84 (13.92)	27.98 (12.17)	
	Accuracy	2.81 (1.66)	1.87 (1.51)	

Note. OND = orthographic neighborhood density; HD = homophone density. The OND effect refers to the difference in performance on the high vs. low OND condition. The HD effect refers to the difference in performance on the high vs. low HD condition. A positive value indicates a facilitative effect and a negative value an inhibitory effect. Standard errors are reported in parentheses.

neighborhood density using a better manipulation, but the effect was inhibitory. The present results suggest, therefore, that the orthographic neighborhood density effect in Chinese is reliable and independent of the effect of homophone density.

PDP models and the global activation account of the BIA model (Grainger & Jacobs, 1996) fail to explain the additive effect of inhibitory orthographic neighborhood and homophone density. Both traditional IA models and the suggestion of compensation through facilitative bi-directional connections (Andrews, 1997) successfully predict an inhibitory effect of orthographic neighborhood density but fail in predicting the inhibitory homophone density effect in the present experiment. As such, no current visual word recognition model can successfully explain the full range of the present findings.

EXPERIMENT 5: ORTHOGRAPHIC NEIGHBORHOOD DENSITY EFFECT IN CHINESE

Method

Participants. Eighteen participants were selected, based on similar criteria as in Exp.4.

Design and Materials. The experimental design was a one factor (Orthographic neighborhood density: high vs. low) within-subjects design.

The same criteria for stimulus selection were used as in Exp.4 except that only Chinese characters with no homophone mates were selected. Stimuli included 14 characters with high orthographic neighborhood density (greater or equal to 5), 14

Table 12

Characteristics of the Stimuli Used in Experiment 5 (Mean Values)

Characteristic	High OND	Low OND
Strokes	13.21	13.43
Frequency	23.04	24.29
OND	8.71	2.43
HD	0.00	0.00
Mean Frequency of ON	54.20	47.58
Mean Frequency of HM	0.00	0.00

Note. OND = orthographic neighborhood density; HD = homophone density; ON = orthographic neighbors; HM = homophone mates.

characters with low orthographic neighborhood density (lower or equal to 4), 28 filler characters, and 56 pseudo-characters.

Each participant received a different randomized sequence from a list consisting of 112 trials containing 14 characters with higher orthographic neighborhood density, 14 characters with lower orthographic neighborhood density, 28 filler characters, and 56 pseudo-characters. See Table 12 for a summary of stimulus characteristics and Appendix B for the actual stimuli.

Apparatus and Procedure. The apparatus and the procedure in Exp.5 were the same as in Exp.1.

Results and Discussion

In calculating the mean RTs of correct responses for each condition for each participant, those trials with RTs less than 200 ms or higher than 1800 ms were

Table 13

Mean Reaction Time (ms) and Accuracy (%) in Experiment 5

	High OND	Low OND	OND Effect
RT	594.53 (12.30)	565.97 (11.25)	28.56 (6.65)
Accuracy	91.27 (1.69)	91.67 (1.85)	0.40 (1.96)

Note. OND = orthographic neighborhood density. The OND effect refers to the difference in performance on the high vs. low OND condition. A positive value indicates a facilitative effect and a negative value an inhibitory effect. Standard errors are reported in parentheses.

discarded. These cutoffs led to the rejection of 0.20% of the observations. Table 13 shows the accuracy, calculated from the entire set of trials, and re-computed means for correct RTs for each experimental condition.

The data were analyzed in a one-way repeated measures analysis of variance (ANOVA) with the factor of Orthographic Neighborhood Density (high vs. low). The data were analyzed by subjects (F_1) and by items (F_2). Although the discussion in the present study was mainly based on the by-subject RT analyses, we provide accuracy analyses and by-item RT analyses for readers' interest.

The results of the ANOVA indicated a significant main effect for Orthographic Neighborhood Density in RT when analyzed by subject, $F_1(1,17) = 18.43$, $p < .001$, $F_2(1,26) = 3.11$, $p = .08$, but not in accuracy, $F_1(1,17) < 1$, $F_2(1,26) = < 1$, indicating an inhibitory orthographic neighborhood density effect.

The present experiment obtained a clear inhibitory orthographic neighborhood density effect in Chinese as was the case in Exp.2 in English. The finding of an inhibitory orthographic neighborhood density effect supports the idea of inter-level lateral inhibition in IA models. Conversely, PDP models and the global activation account (Grainger & Jacobs, 1996) fail to explain the present results.

Andrews's (1997) suggestions of compensations from facilitative bi-directional connections can also successfully explain the present results. Because the stimuli selected purposely excluded characters sharing any homophone mates, the influence of *activation enhancement* from the phonological lexicon can be reduced significantly. In addition, the *activation enhancement* from facilitative bi-directional connections between word and sublexical levels within orthographic lexicon is also reduced because orthographic neighbors in Chinese shared only one sublexical unit, i.e., radicals. As such, it appears that forces from intra-level lateral inhibitions can outperform forces from *activation enhancement* in Exp.5 and result in an inhibitory orthographic neighborhood density effect.

EXPERIMENT 6: HOMOPHONE DENSITY EFFECT IN CHINESE

Method

Participants. Eighteen participants were selected, based on similar criteria as in Exp.4.

Design and Materials. The experimental design was a one factor (Homophone density: high vs. low) within-subjects design.

The same criteria for stimulus selection were used as in Exp.4 except that only Chinese characters with no orthographic neighbors were selected. Stimuli included 20

Table 14

Characteristics of the Stimuli Used in Experiment 6 (Mean Values)

Characteristic	High HD	Low HD
Strokes	13.60	13.55
Frequency	14.80	14.55
OND	0.00	0.00
HD	14.30	2.80
Mean Frequency of ON	0.00	0.00
Mean Frequency of HM	101.42	103.75

Note. OND = orthographic neighborhood density; HD = homophone density; ON = orthographic neighbors; HM = homophone mates.

characters with high homophone density (greater or equal to 7), 20 characters with low homophone density (lower or equal to 4), 40 filler characters, and 80 pseudo-characters. See Table 14 for a summary of stimulus characteristics and Appendix B for the actual stimuli.

Apparatus and Procedure. The apparatus and procedure in Exp.6 will be the same as in Exp.1.

Results and Discussion

In calculating the mean RTs of correct responses for each condition for each participant, those trials with RTs less than 200 ms or higher than 1800 ms were discarded. These cutoffs led to the rejection of 0.14% of the observations. Table 15 shows the accuracy, calculated from the entire set of trials, and re-computed means for correct RTs for each experimental condition.

Table 15

Mean Reaction Time (ms) and Accuracy (%) in Experiment 6

	High HD	Low HD	HD Effect
RT	613.48 (19.72)	583.63 (16.18)	29.85 (9.20)
Accuracy	89.72 (2.41)	87.78 (1.73)	-1.94 (2.36)

Note. HD = homophone density. The HD effect refers to the difference in performance on the high vs. low HD condition. A positive value indicates a facilitative effect and a negative value an inhibitory effect. Standard errors are reported in parentheses.

The data were analyzed in a one-way repeated measures analysis of variance (ANOVA) with the factor of Homophone Density (high vs. low). The data were analyzed by subjects (F_1) and by items (F_2). Although the discussion in the present study was mainly based on the by-subject RT analyses, we provide accuracy and by-item RT analyses for readers' interest.

The results of the ANOVA indicated a significant main effect for Homophone Density in RT when analyzed by subject, $F_1(1,17) = 10.52$, $p < .01$, $F_2(1,38) = 3.29$, $p = .07$, but not in accuracy, $F_1(1,17) < 1$, $F_2(1,38) < 1$, indicating an inhibitory homophone density effect.

Results in Exp.6 replicated the null effect of homophone density in Exp.4. PDP and global activation account suggested by Grainger and Jacobs (1996) failed to explain the inhibitory homophone density effects. Both traditional IA models and the suggestions of the compensation through facilitative bi-directional connections (Andrews, 1997) also failed in predicting the inhibitory homophone density effect in the present experiment. As such, no current visual word recognition models can successfully explain the present findings.

EXPERIMENT 7: NIRS STUDY ON PHONOLOGICAL NEIGHBORHOOD DENSITY EFFECT IN ENGLISH

Method

Participants. Nine college students from a large southwestern U.S. university were participate in the experiment. All were fluent readers of English with normal or corrected-to-normal vision.

Design and the Materials. The design was a 2 (Phonological neighborhood density: high vs. low) x 2 (Hemisphere: left vs. right) within subjects factorial, with a total of 4 conditions.

Sixteen words with higher phonological neighborhood density, 16 words with lower phonological neighborhood density, and 32 nonwords were selected from Exp.2. Each participant received a different randomized sequence from a list consisting of these 64 stimuli. See Table 16 for a summary of stimulus characteristics and Appendix A for the actual stimuli.

Apparatus. The apparatus for the behavioral measurement was the same as in Exp.2. The NIRS signals are collected by an electronic control box serving both as the source of the near-infrared laser light and as the receiver of the detected near-infrared laser light. A cap is designed with one laser emitter that scatters the near-infrared light into the scalp and two laser detectors that receive the returned near-infrared light located separately over Brodmann Area 39/40 of each hemisphere. Each emitter contains two light sources with a wavelength of 690nm and 830nm respectively. Another laptop is programmed to control and record the signals received by the electronic control box.

Procedure. The task was a Go/No Go version of the lexical decision task. For each trial, participants, tested individually, first saw a fixation signal (cross) presented at the center of the screen. Participants were to press a button after seeing the fixation signal. This was followed by one stimulus presented at the center of the screen. Participants were to make a speeded lexical decision response and press the button only if they thought the stimulus was an English word. This was followed by a blank. If participants did not think the stimulus was an English word and did not press the button, the stimulus

Table 16

Characteristics of the Stimuli Used in Experiment 7 (Mean Values)

Characteristic	High OND	Low OND
Letters	5.63	5.88
Phonemes	4.00	4.38
Frequency	10.06	10.75
OND	0.00	0.00
PND	13.44	3.13
BF	2498.25	2409.44
Mean Frequency of ON	0.00	0.00
Mean Frequency of PN	17.63	18.06

Note. OND = orthographic neighborhood density; BF = bigram frequency; ON = orthographic neighbors; PN = phonological neighbors; PND = phonological neighborhood density.

disappeared after 2 seconds and was followed by a blank. RT was recorded from the onset of stimulus presentation until the participant pressed a button. A blank was randomly presented for 12, 14,16, or 18 seconds before the next trial. The variation of the presentation time of the cross was to keep participants' attention and avoided possible guessing. Participants received at least 10 practice trials until they got used to the procedure before the experiment.

The experiment was administered on personal computers using an E-Prime software package (Schneider et al., 2002). A cap with one laser emitter and two detectors located on the region corresponding to Brodmann's Area 39/40 of each hemisphere was placed on the participant's head to record blood flow change during the lexical decision task.

Results and Discussion

Behavioral Data. In calculating the mean RTs of correct responses for each condition for each participant, those trials with RTs less than 200 ms or higher than 1800 ms were discarded. These cutoffs led to the rejection of 0.26% of the observations. Table 17 shows the accuracy, calculated from the entire set of trials, and re-computed means for correct RTs for each experimental condition.

The data were analyzed in a one-way repeated measures analysis of variance (ANOVA) with the factor of Phonological Neighborhood Density (high vs. low). The data were analyzed by subjects (F_1) and by items (F_2). Although the discussion in the present study was mainly based on the by-subject RT analyses, analyses of accuracy data and by-item RT data are provided for readers' interest.

The results of the ANOVA did not yield a significant main effect for Phonological Neighborhood Density in RT, $F_1(1,8) = 1.80$, $p = .21$, $F_2(1,28) = 1.21$, $p = .28$, or in accuracy, $F_1(1,8) < 1$, $F_2(1,28) < 1$, although there was a trend of an inhibitory phonological neighborhood density effect (37ms).

NIRS Data. The NIRS data from 4 detectors (2 over each hemisphere) were digitally recorded at 200Hz. The data were then converted into optical density units that were digitized and low-pass-filtered at 1Hz and high-pass-filtered at 0.02 Hz to reduce the noise of systemic physiology. The filtered data were then converted to reflect the concentration of both the oxy-hemoglobin and deoxy-hemoglobin; these served as the data used for advanced analysis. The converted data were analyzed in 17-second epochs including 2 seconds before and 15 seconds after the onset of the stimuli. Data conversion was conducted using HomER software (Huppert & Boas, 2005).

Table 17

Mean Reaction Time (ms) and Accuracy (%) in Experiment 7

	High PND	Low PND	PND Effect
RT	801.05 (47.14)	764.14 (53.55)	36.91 (27.52)
Accuracy	92.36 (2.50)	92.86 (2.92)	0.50 (1.54)

Note. PND = phonological neighborhood density. The PND effect refers to the difference in performance on the high vs. low PND condition. A positive value indicates a facilitative effect and a negative value an inhibitory effect. Standard errors are reported in parentheses.

NIRS data were first down sampled to 2 Hz. Data from the two detectors per hemisphere were then averaged in further analyses. Two separate 2 (Phonological neighborhood density: high vs. low) x 2 (Hemisphere: left vs. right) within-subjects ANOVAs were conducted, one for the latency and the other for the peak amplitude data of blood flow changes. The concentration of oxy-hemoglobin was treated as the dependent variable. Table 18 shows the amplitudes and latencies of the peaks of the blood flow changes for each experimental condition.

Amplitude Analysis. The results of the ANOVA on the amplitudes at the peak of blood flow change showed a marginal significant main effect for Phonological Neighborhood Density, *F*(1,8) = 4.81, *p* = .06, indicating a larger amplitude for words with high phonological neighborhood density, compared to those with low phonological

Table 18

Mean Amplitudes (μ Molar) and Latencies (seconds) for Peaks of Blood Flow Changes in Experiment 7

		High PND	Low PND
Left Hemisphere	Amplitude	6.22 (1.35)	5.33 (1.15)
	Latency	5.83 (0.87)	6.17 (1.21)
Right Hemisphere	Amplitude	5.74 (1.22)	3.27 (0.90)
	Latency	6.44 (0.92)	4.17 (0.90)

Note. PND = phonological neighborhood density. Standard errors are reported in parentheses.

neighborhood density. In addition, a significant main effect for Hemisphere was $F(1,8) = 6.53$, $p < .05$, indicating a larger amplitude for the left hemisphere, compared to the right hemisphere. No interaction of Phonological Neighborhood Density and Hemisphere was found, $F(1,8) = 3.41$, $p = .10$. Further simple effect analyses showed that the phonological neighborhood density effect was only present in the *right* hemisphere, $F(1,16) = 7.91$, $p < .05$ (for the *left* hemisphere, $F(1,16) = 1.05$, $p = .32$), in the direction of a larger amplitude for words with high phonological neighborhood density.

Latency Analysis. The results of the ANOVA on the latencies at the peak of blood flow change yielded neither a main effect for Phonological Neighborhood Density, $F(1,8) = 1.22$, $p = .30$, nor for Hemisphere, $F(1,8) = 2.44$, $p = .15$. No interaction of Phonological Neighborhood Density and Hemisphere was found, $F(1,8) = 3.11$, $p = .11$. Further simple effect analyses showed that phonological neighborhood density effect was only marginally significant in the *right* hemisphere, $F(1,16) = 3.92$, $p = .06$, and not significant in *left* hemisphere, $F(1,16) < 1$; there was a slower peak for words with high phonological neighborhood density in the right hemisphere.

Comparison to Baseline. Blood flow changes in oxy-hemoglobin, deoxy-hemoglobin, and total hemoglobin during English lexical decision were also analyzed for both hemispheres. Figure 1 (a) depicts the results for words with *high* phonological neighborhood density and 1 (b) those with *low* phonological neighborhood density in the *left* hemisphere. Figure 2 (a) depicts the results for words with *high* phonological neighborhood density and 2 (b) presents those with *low* phonological neighborhood density in the *right* hemisphere.

Compared to the baseline, which was defined by the mean blood flow changes starting from 2 seconds before the onset until the presentation of the stimuli, blood flow changes in oxy-hemoglobin were significantly elevated both in the *left* hemisphere, $t(29) = 6.71$, $p < .001$, and in the *right* hemisphere, $t(29) = 9.24$, $p < .001$, for words with *high* phonological neighborhood density. As to words with *low* phonological neighborhood density, blood flow changes in oxy-hemoglobin were raised significantly only in the *left* hemisphere, $t(29) = 7.09$, $p < .001$; *right* hemisphere, $t(29) = -0.70$, $p = .49$.

Although discussion in the present study is mainly based on the results of oxy-hemoglobin, I also provide the analyses for blood flow changes in both deoxy-hemoglobin and total hemoglobin for readers' interest. For words with *high* phonological neighborhood density, blood flow changes in deoxy-hemoglobin were significantly decreased in the *left* hemisphere, $t(29) = -7.80$, $p < .001$; there was no difference in the *right* hemisphere, $t(29) = -1.01$, $p = .32$. As to words with *low* phonological neighborhood density, blood flow changes in deoxy-hemoglobin decreased significantly in the *left* hemisphere, $t(29) = -6.67$, $p < .001$, but increased in the *right* hemisphere, $t(29) = 3.38$, $p < .01$. As to blood flow changes in total hemoglobin, it was increased both in the *left* hemisphere, $t(29) = 4.87$, $p < .001$, and in the *right* hemisphere, $t(29) = 8.63$, $p < .001$, for words with *high* phonological neighborhood density. Finally, for words with *low* phonological neighborhood density, blood flow changes in total hemoglobin were neither raised significantly in the *left* hemisphere, $t(29) < 1$, or in the *right* hemisphere, $t(29) < 1$.

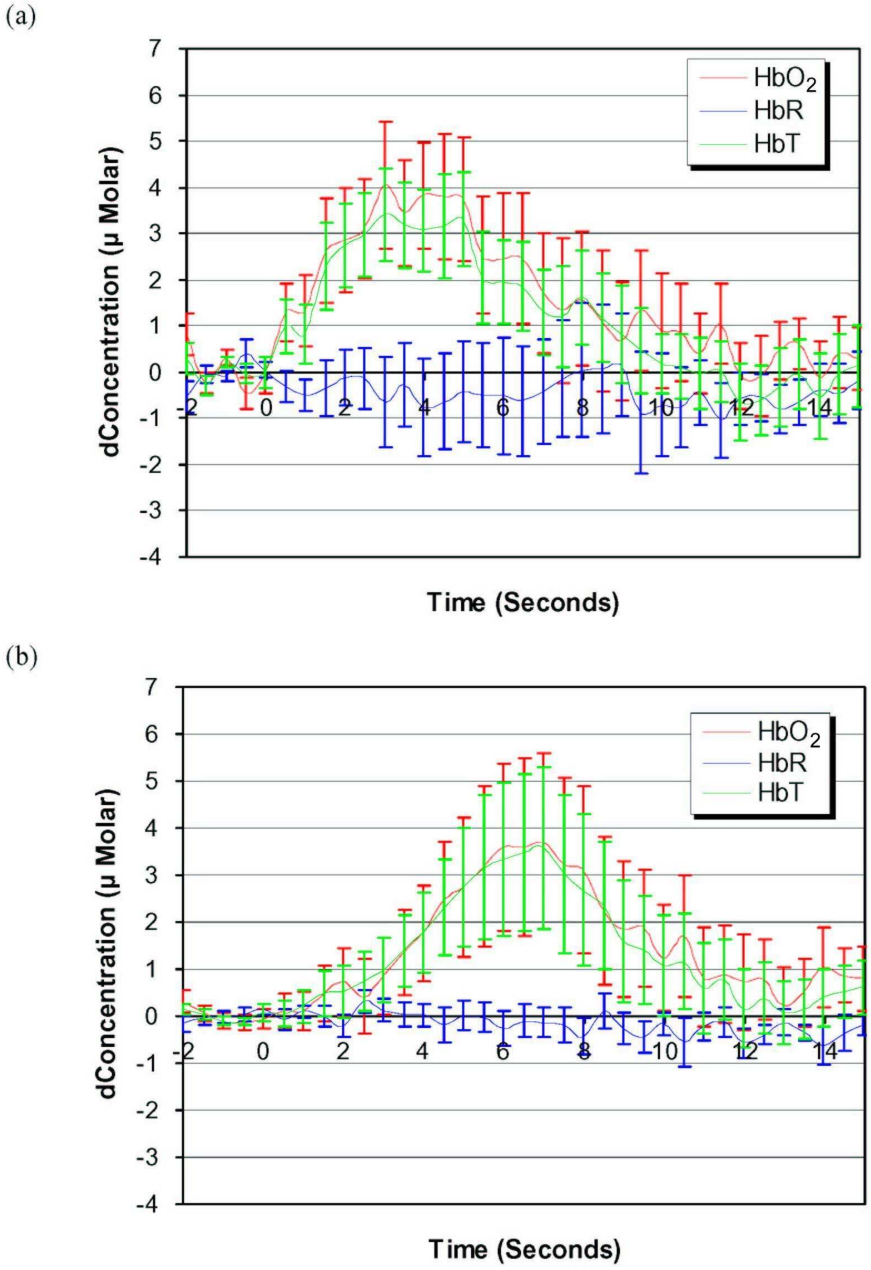


Figure 1. Blood flow change in BA 39/40 of (a) left hemisphere and (b) right hemisphere during English lexical decision on ***high*** phonological neighborhood density words. HbO_2 = oxy-hemoglobin; HbR = deoxy-hemoglobin; HbT = total hemoglobin.

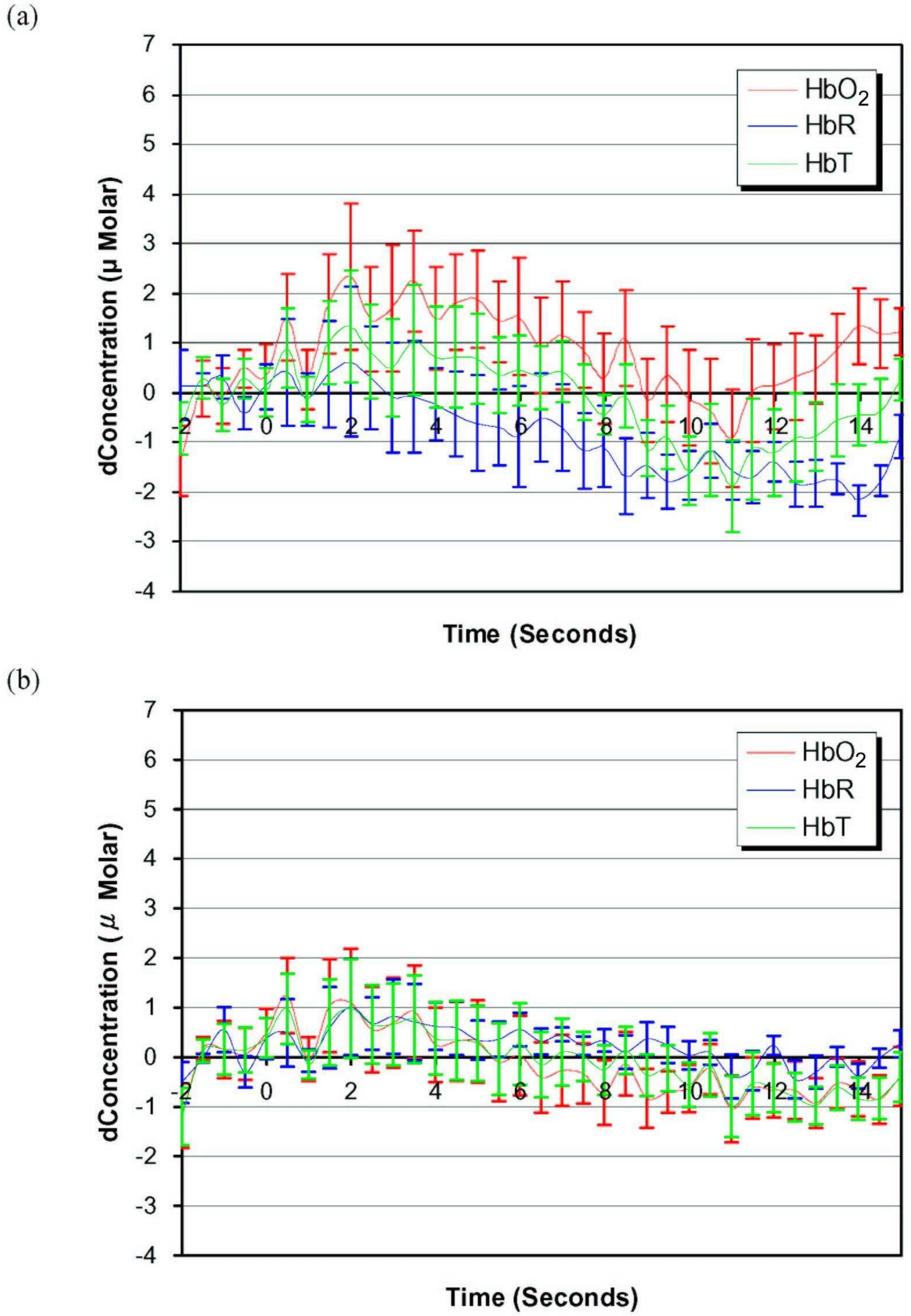
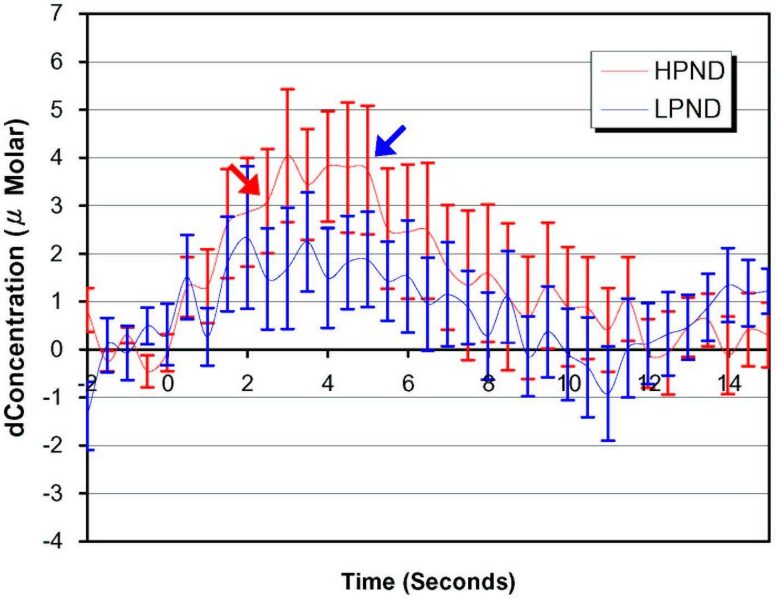


Figure 2. Blood flow change in BA 39/40 of (a) left hemisphere and (b) right hemisphere during English lexical decision on ***low*** phonological neighborhood density words. HbO_2 = oxy-hemoglobin; HbR = deoxy-hemoglobin; HbT = total hemoglobin.

Phonological Neighborhood Density Effect. Figure 3 compared blood flow changes in oxy-hemoglobin for words with *high* vs. *low* phonological neighborhood density for (a) the *left* hemisphere and (b) the *right* hemisphere. Blood flow changes in oxy-hemoglobin for words with *high* phonological neighborhood density were significantly larger than those with *low* phonological neighborhood density both in the *left* hemisphere, $t(29) = 3.12$, $p < .01$, and in the *right* hemisphere, $t(29) = 10.27$, $p < .001$. When taking into account the time course in the *left* hemisphere, blood flow changes for words with *high* phonological neighborhood density started to be significantly larger than that for words with *low* phonological neighborhood density by 2.5 seconds, $t(8) = 2.40$, $p < .05$, until 5 seconds, $t(8) = 2.53$, $p < .05$, after stimulus onset. By contrast, in the *right* hemisphere, blood flow changes for words with *high* phonological neighborhood density started to be significantly larger than that for words with *low* phonological neighborhood density from 2 seconds, $t(8) = 2.69$, $p < .05$, until 14.5 seconds, $t(8) = 2.76$, $p < .05$, after stimulus onset.

Although the behavioral results in the present experiment did not reveal a significant effect of phonological neighborhood density, this may due to the considerably low number of participants. The effect size for the phonological neighborhood density effect, $\omega^2 = .04$, is close to a medium effect. For this reason, the phonological neighborhood density effect in the present study may likely reach a significant criterion after increasing the number of participants.

(a)



(b)

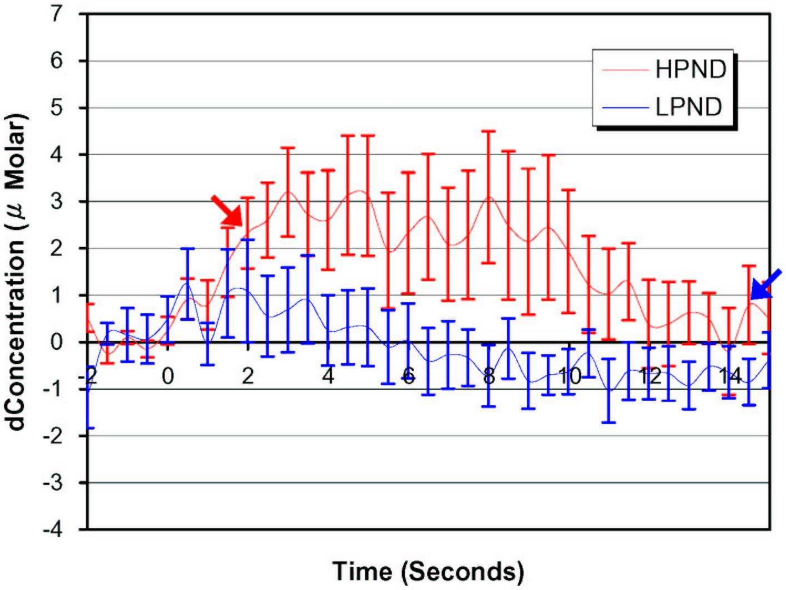


Figure 3. Comparison of blood flow change in BA 39/40 of (a) left hemisphere and (b) right hemisphere on the concentration of oxy-hemoglobin during English lexical decision on high vs. low phonological neighborhood density words. Red and blue arrows denote the start and the end in which blood flow change shows significant difference between two conditions.

The NIRS data provide neural evidence for a phonological density effect. Words with high phonological neighborhood density generated stronger blood flow changes in BA 39/40, which is suggested to be an important area for phonological processing in alphabetic writing systems like English. Due to the limitation of the technique, it is hard to tell if these stronger blood flow changes should be interpreted as being due to more inhibition or facilitation. However, based on the trend of an inhibitory effect in the behavioral data, the stronger blood flow changes for words with high phonological neighborhood density are more likely contributed by stronger inhibition from intra-level lateral connections.

Interestingly, the NIRS data suggest that a phonological neighborhood density effect was more evidenced in the right hemisphere than in the left hemisphere. This right hemisphere advantage of *phonological* neighborhood density is in line with other findings of a right hemisphere advantage for *orthographic* neighborhood density using repetitive transcranial magnetic stimulation (Lavidor & Walsh, 2003) and divided visual field presentation paradigms (Lavidor, Hayes, Shillcock, & Ellis, 2004). However, the finding of a right hemisphere advantage for density effects in the phonological processing domain has not previously been reported.

EXPERIMENT 8: NIRS STUDY ON HOMOPHONE DENSITY EFFECT IN CHINESE

Method

Participants. Eleven Taiwanese graduate students from a large southwestern U.S. university participated in the experiment. All were fluent readers of Chinese with normal or corrected-to-normal vision.

Design and Materials. The design was a 2 (Homophone density: high vs. low) x 2 (Hemisphere: left vs. right) within subjects factorial, with a total of 4 conditions.

Twelve Chinese characters with higher homophone density, 12 Chinese characters with lower homophone density, and 24 pseudo-characters were selected from Exp.5.

Table 19

Characteristics of the Stimuli Used in Experiment 8 (Mean Values)

Characteristic	High HD	Low HD
Strokes	13.25	13.92
Frequency	17.25	16.67
OND	0.00	0.00
HD	16.75	3.08
Mean Frequency of ON	0.00	0.00
Mean Frequency of HM	96.76	93.70

Note. OND = orthographic neighborhood density; HD = homophone density; ON = orthographic neighbors; HM = homophone mates.

Each participant received a different randomized sequence from a list consisting of these 48 stimuli. See Table 19 for a summary of stimulus characteristics and Appendix B for the actual stimuli.

Apparatus and Procedure. The apparatus and procedure was the same as in Exp.7 except that the brain area monitored was Brodmann Area 9.

Results and Discussion

Behavioral Data. Data from 2 items were excluded in the analyses due to low accuracy. In calculating the mean RTs of correct responses for each condition for each participant, those trials with RTs less than 200 ms or higher than 1800 ms were discarded. These cutoffs led to the rejection of 0.91% of the observations. Table 20 shows the accuracy, calculated from the entire set of trials, and re-computed means for correct RTs for each experimental condition.

Table 20

Mean Reaction Time (ms) and Accuracy (%) in Experiment 8

	High HD	Low HD	HD Effect
RT	849.14 (60.95)	808.01 (58.67)	41.13 (19.18)
Accuracy	90.15 (2.47)	95.46 (2.07)	5.31 (2.05)

Note. HD = homophone density. The HD effect refers to the difference in performance on the high vs. low HD condition. A positive value indicates a facilitative effect and a negative value an inhibitory effect. Standard errors are reported in parentheses.

The data were analyzed in a one-way repeated measures analysis of variance (ANOVA) with the factor of Homophone Density (high vs. low). The data were analyzed by subjects (F_1) and by items (F_2). Although the discussion here will focus on the by-subject RT analyses, findings from the accuracy and by-item RT analyses are also provided.

The results of the ANOVA indicated a significant main effect for Homophone Density in RT when analyzed by subject, $F_1(1,10) = 4.60$, $p = .05$, $F_2(1,20) = 1.38$, $p = .25$, and in accuracy when analyzed by subject, $F_1(1,10) = 6.72$, $p < .05$, $F_2(1,10) < 1$, indicating an inhibitory homophone density effect.

NIRS Data. The same procedures for NIRS data analyses were applied as were used in the previous experiment. Two separate 2 (Homophone density: high vs. low) x 2 (Hemisphere: left vs. right) within-subjects ANOVAs were conducted for both the latency and the amplitude of the peaks of the blood flow changes. The concentration of oxy-hemoglobin was treated as the dependent variable. Table 21 shows the amplitudes and latencies of the peaks of the blood flow changes for each experimental condition.

Amplitude Analysis. The results of the ANOVA on the amplitudes at the peak of blood flow change neighbor showed no effect for Homophone Density, $F(1,10) = 1.96$, $p = .19$, or for Hemisphere, $F(1,10) < 1$. No interaction of Homophone Density and Hemisphere was found, $F(1,10) <1$. Further simple effect analyses showed that the homophone density effect was not present either in the right hemisphere, $F(1,20) = 2.51$, $p = .13$, or in the left hemisphere, $F(1,20) <1$, although there was a trend for a stronger homophone density effect in the right hemisphere.

Latency Analysis. The results of the ANOVA on the latencies at the peak of blood flow change neither obtained a significant main effect for Homophone Density, $F(1,10) < 1$, nor a significant main effect for Hemisphere, $F(1,10) = 2.07$, $p = .18$. No interaction of Homophone Density and Hemisphere was found, $F(1,10) < 1$. The homophone effect was neither obtained in the right hemisphere, $F(1,20) < 1$, nor in the left hemisphere, $F(1,20) = 1.47$, $p = .24$.

Comparison to Baseline. Blood flow changes in oxy-hemoglobin, deoxy-hemoglobin, and total hemoglobin during English lexical decision were also analyzed for both hemispheres. Figure 4 (a) depicts the results for characters with *high* homophone density and Fig. 4 (b) presents those with *low* homophone density in the *left* hemisphere. Figure 5 (a) depicts the results for characters with *high* homophone

Table 21

Mean Amplitudes (μ Molar) and Latencies (seconds) for Peaks of Blood Flow Changes in Experiment 8

		High HD	Low HD
Left Hemisphere	Amplitude	4.92 (2.23)	3.75 (1.43)
	Latency	6.18 (0.92)	5.14 (0.61)
Right Hemisphere	Amplitude	5.19 (1.75)	3.08 (0.75)
	Latency	6.68 (0.79)	6.32 (0.68)

Note. HD = homophone density. Standard errors are reported in parentheses.

density and Fig. 5 (b) presents those with *low* homophone density in the *right* hemisphere.

Compared to the baseline, which was defined by the mean blood flow changes starting from 2 seconds before the onset until the presentation of the stimuli, blood flow change in oxy-hemoglobin was significantly raised both in the *left* hemisphere, $t(29) = 4.62$, $p < .001$, and in the *right* hemisphere, $t(29) = 7.41$, $p < .001$, for characters with *high* homophone density. As to characters with *low* homophone density, blood flow change in oxy-hemoglobin was raised significantly in the *left* hemisphere, $t(29) = 2.46$, $p < .05$, but not in the *right* hemisphere, $t(29) < 1$.

Although discussion in the present study is mainly based on the results of oxy-hemoglobin, I also provide the analyses for blood flow changes in both deoxy-hemoglobin and total hemoglobin for readers' interest. For characters with *high* homophone density, blood flow change in deoxy-hemoglobin was significantly decreased in the *left* hemisphere, $t(29) = -4.79$, $p < .001$, and in the *right* hemisphere, $t(29) = -4.20$, $p < .001$. As to characters with *low* homophone density, blood flow change in deoxy-hemoglobin was decreased significantly in the *left* hemisphere, $t(29) = -2.46$, $p < .05$, but not in the *right* hemisphere, $t(29) < 1$. As to blood flow changes in total hemoglobin, it was raised both in the *left* hemisphere, $t(29) = 4.19$, $p < .001$, and in the *right* hemisphere, $t(29) = 6.52$, $p < .001$, for characters with *high* homophone density. As to characters with *low* homophone density, blood flow change in total hemoglobin was raised significantly only in the left hemisphere, $t(29) = 2.23$, $p < .05$, not in the right hemisphere, $t(29) < 1$.

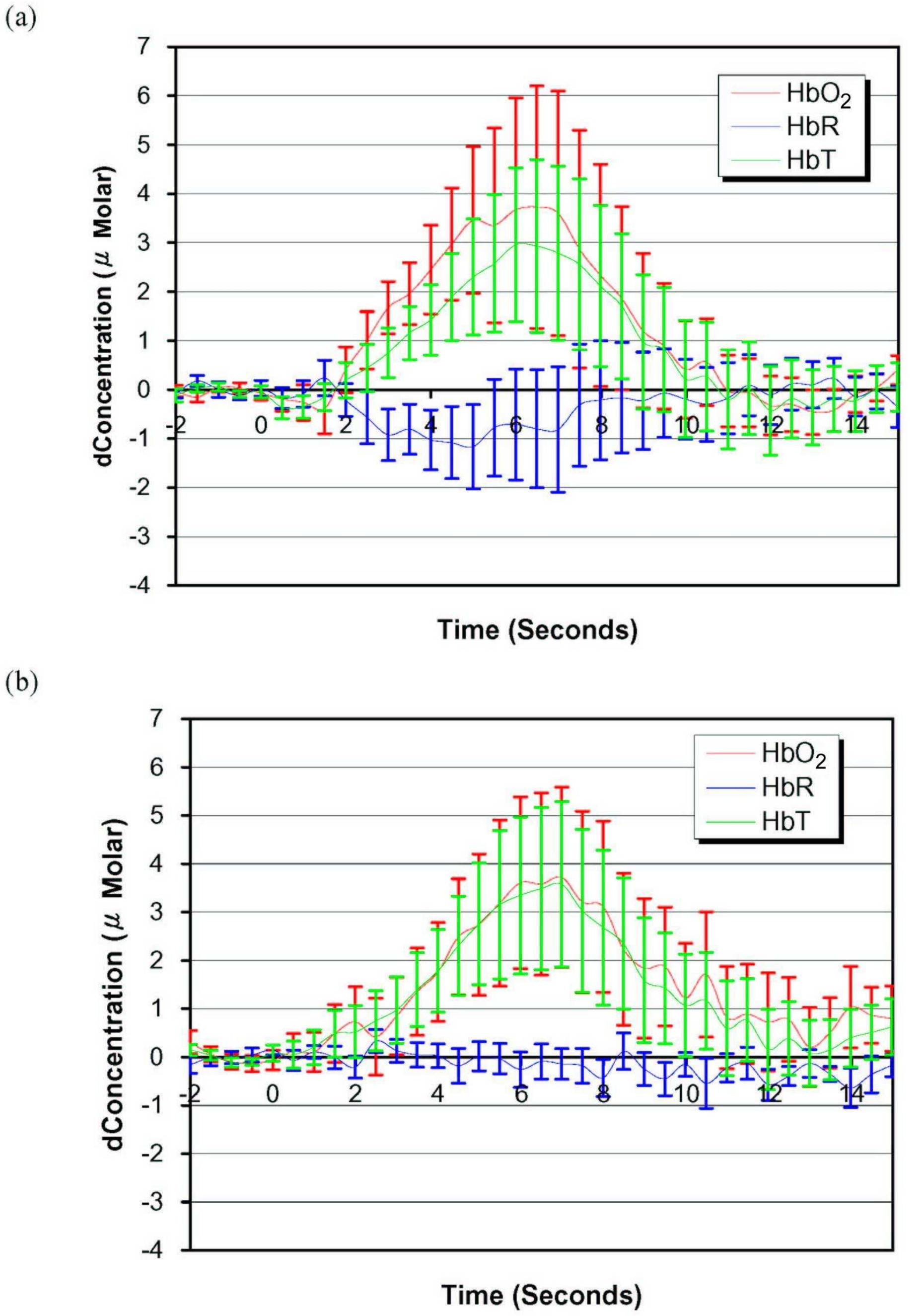


Figure 4. Blood flow change in BA 9 of (a) left hemisphere and (b) right hemisphere during Chinese lexical decision on ***high*** homophone density characters. HbO_2 = oxy-hemoglobin; HbR = deoxy-hemoglobin; HbT = total hemoglobin.

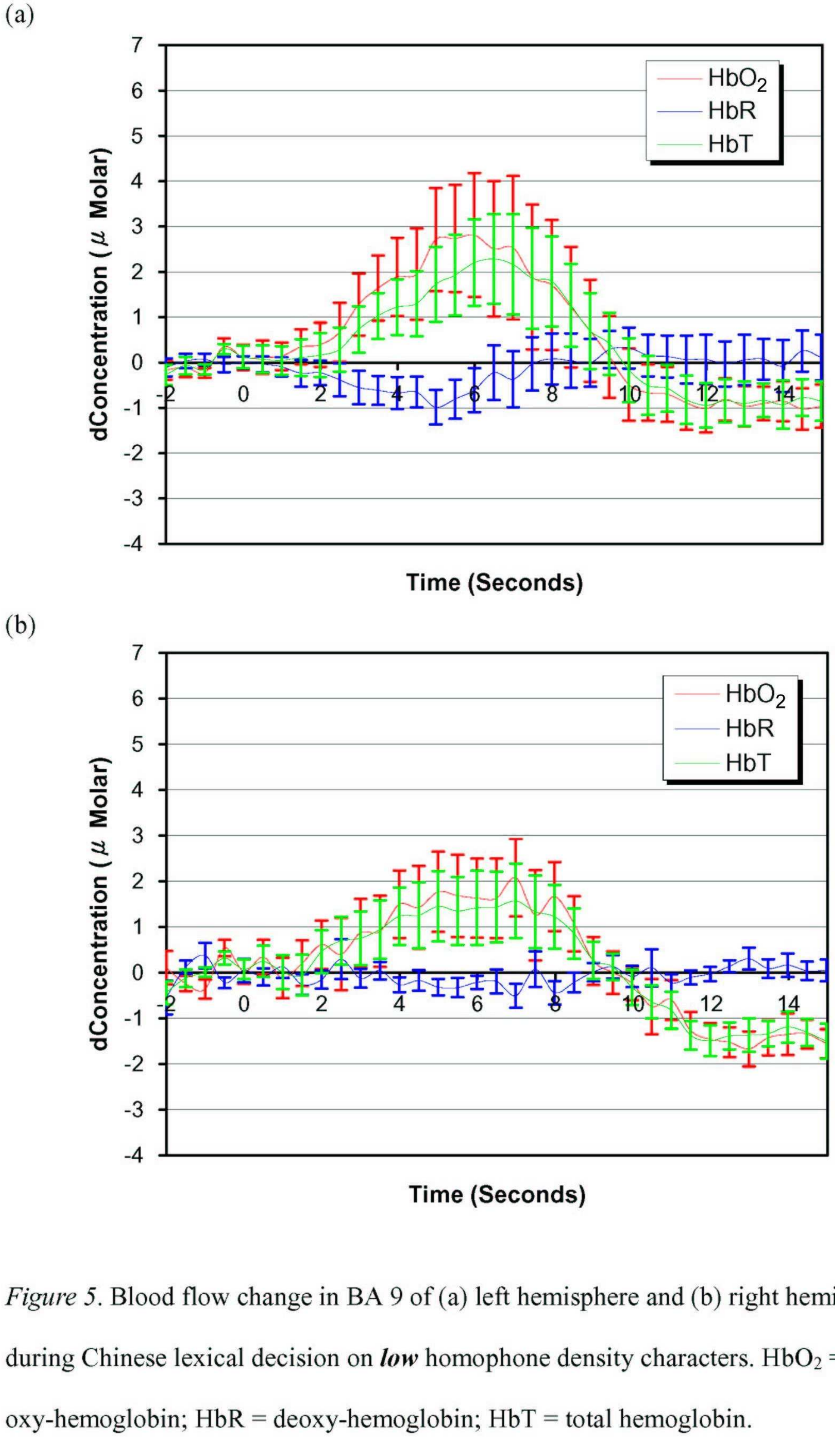


Figure 5. Blood flow change in BA 9 of (a) left hemisphere and (b) right hemisphere during Chinese lexical decision on ***low*** homophone density characters. HbO_2 = oxy-hemoglobin; HbR = deoxy-hemoglobin; HbT = total hemoglobin.

Homophone Density Effect. Figure 6 shows the blood flow changes in oxy-hemoglobin for characters with *high* vs. *low* homophone density in (a) the *left* hemisphere and (b) the *right* hemisphere. Blood flow change in oxy-hemoglobin for characters with *high* homophone density was significantly larger than that for words with *low* homophone density both in the *left* hemisphere, $t(29) = 7.29$, $p < .001$, and in the *right* hemisphere, $t(29) = 8.83$, $p < .001$. When taking into account the time course in the *left* hemisphere, blood flow change for characters with *high* homophone density was initially significantly larger than that for words with *low* homophone density from 14 seconds, $t(10) = 2.37$, $p < .05$, until 15 seconds, $t(10) = 3.64$, $p < .01$, after stimulus onset. By contrast, in the *right* hemisphere, blood flow change for characters with *high* homophone density started to be significantly larger than that for words with *low* homophone density at 10.5 seconds, $t(10) = 2.24$, $p < .05$, until 15 seconds, $t(10) = 3.27$, $p < .01$, after stimulus onset.

The NIRS data provide neural evidence for the homophone density effect in Chinese. Words with high homophone density generated stronger blood flow changes in BA 9, which is suggested to be an important area for phonology processing in morphosyllabic writing systems like Chinese. Based on my knowledge, this is the first report of neural evidence for a homophone density effect. Unlike Exp.7, the NIRS data did not show a hemisphere difference in Chinese homophone density, although there was a trend for a right hemisphere advantage.

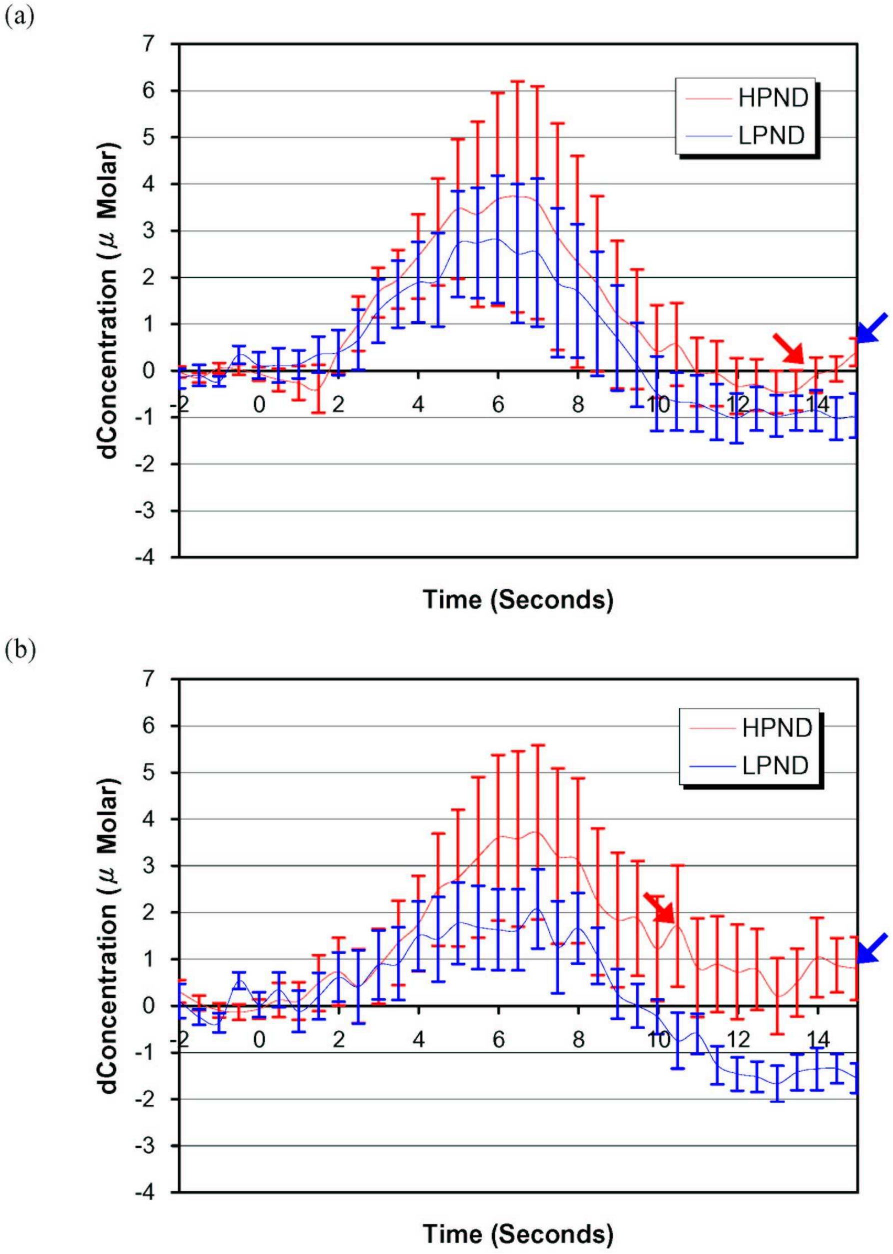


Figure 6. Comparison of blood flow change in BA 9 of (a) left hemisphere and (b) right hemisphere on the concentration of oxy-hemoglobin during Chinese lexical decision on high vs. low homophone density characters. Red and blue arrows denote the start and the end in which blood flow changes show significant difference between two conditions.

GENERAL DISCUSSION

To fully understand the processes involved in lexical retrieval and selection, it is necessary to study how orthographically and phonologically similar words interact to affect word recognition. After decades of research, however, the nature of orthographic and phonological neighborhood density effects and their interaction is still being debated. Neighborhood density effects in principle allow a test of different models of word recognition. However, the inconsistencies in the literature thus far as to the nature of these effects as well as their interpretation have made it difficult to confidently draw conclusions. In the present study, I systematically manipulated both orthographic and phonological neighborhood effects in both English and Chinese to clarify the direction of these effects. Exploiting the fact that phonemes are not present in Chinese characters, my research design allowed a test of the mechanism of bi-directional facilitative connections between whole-word and sublexical levels and that of overall lexical activation proposed by different word recognition models. Besides behavioral data, the present study also sought hemodynamic evidences for effects of phonological neighborhood (in English) and homophone density (in Chinese), using the NIRS technique. Through a joint behavioral and neurobehavioral examination of both orthographic and phonological neighborhood density effects, our understanding of the nature of the mechanism and operation of the orthographic and phonological lexicons can be advanced.

The Nature of Neighborhood Density Effects

The nature of neighborhood density effects was not clear from previous studies due to inconsistent results across studies. Whereas facilitative orthographic neighborhood density effects were mainly found in English lexical decision task, inhibitory orthographic neighborhood density effects were obtained in French and Spanish studies. Studies by Yates et al. (2004), Yates (2005), and Mulatti et al. (2006) questioned the facilitative effect of orthographic neighborhood density because a facilitative effect of phonological neighborhood density was found in both lexical decision and naming after controlling orthographic neighborhood density, however, an orthographic neighborhood density effect was not obtained in naming when controlling phonological neighborhood density. Nevertheless, Grainger et al.'s (2005) finding of a cross-code effect also challenged the facilitative effect of orthographic neighborhood density and suggested instead that the direction of orthographic neighborhood density effect may depend on phonological neighborhood density.

Yates et al. (2004), Yates (2005), Grainger et al. (2005), and Mulatti et al. (2006) examined neighborhood density effects by seeking to control one type of neighborhood density effect in order to test the other type of neighborhood density effect. The rationale underlying this strategy was that controlling one type of neighborhood density can limit the influence from the related language component. For example, controlling phonological neighborhood density can eliminate effects attributable to the phonological system. As such, any orthographic neighborhood density effect found may be attributed to the orthographic system only. However, the present research argues that this assumption is incorrect due to a multi-system activation enhancement effect.

The different systems related to visual word recognition are connected in a highly interactive manner. Even if one controls phonological neighborhood density across two groups of words with different orthographic neighborhood density, phonological neighborhood density can still have an influence. As discussed earlier, although *scrap* and *proof* initially have the same levels of activation in the phonological system (due to their having the same number of phonological neighbors), *scrap* actually receives more *activation enhancement* from the phonological system by virtue of its having dual-role neighbors, *strap* and *scram*. For this reason, if we want to examine the effect of each type of neighborhood density in isolation, we should reduce the other kind of neighborhood density to zero or as close to that as possible.

To achieve this goal, I systematically tested neighborhood density effects by aiming for successively more control across each subsequent experiment. Experiment 1 manipulated both orthographic neighborhood density and phonological neighborhood density in English. In Experiment 2, orthographic neighborhood density was examined using English words with very low phonological neighborhood density. In Experiment 3, orthographic neighborhood density was reduced to zero and I tested the effect of phonological neighborhood density in English. Exps. 4-6, conducted with Chinese, enabled a clearer look at neighborhood effects than that possible using English alone, given that there is no phoneme level of representation in Chinese. In Experiment 4, I tested orthographic neighborhood density and homophone density in Chinese.

Experiment 5 examined orthographic neighborhood density with Chinese characters having no homophones. In Experiment 6, the homophone density effect with Chinese characters was tested further using characters having no orthographic neighbors. Because Chinese homophones share only a whole phonology representation in the phonological lexicon and only those stimuli were selected that had no overlap in orthographic structures (i.e., radicals), Experiment 6 provided the cleanest environment in which to test the neighborhood density effect.

Experiments 1 to 6, which reduced noise step by step, allow a much clearer examination of the nature of neighborhood effects than previously possible. In Experiment 1, an additive effect of facilitative orthographic neighborhood density and phonological neighborhood density was obtained, suggesting that the cross-code account proposed by Grainger et al. (2005) is not tenable. The present finding replicates earlier results of facilitative orthographic neighborhood density (Andrews, 1989, 1992; Forster & Shen, 1996; Sears et al., 1995) and further demonstrates that this effect is independent of phonological neighborhood density.

Although Experiment 1 confirmed both facilitative effects of orthographic neighborhood density and phonological neighborhood density, no evidence of intra-level lateral inhibitions suggested by traditional IA models was obtained. I reasoned that this is because our mental lexicon is highly interactively connected. To recognize a word, at least four sources of forces are at work: 1) connections between word and sublexical levels in the orthographic lexicon; 2) connections between word and sublexical levels in the phonological lexicon; 3) connections between word levels of orthographic and phonological lexicons; and 4) connections between sublexical levels of orthographic and phonological lexicons. The combination of all of these four forces can create a cumulative enhanced activation in recognizing words. After reducing forces from the phonological lexicon by selecting words with only a few phonological neighbors, an inhibitory orthographic neighborhood density effect was obtained in Experiment 2.

The finding of an inhibitory effect of orthographic neighborhood density is consistent with what was found by Bowers, Davis, and Hanley (2005). Bowers et al. (2005) created novel words (e.g., BANARA) which were orthographic neighbors of real words (e.g., BANANA) that have no real orthographic neighborhood neighbors. This novel learning experience was found to interfere with participants' performance on real words (e.g., BANANA) in a semantic category judgment task. Because these target words have no orthographic neighbors, few benefits can be obtained from facilitative bi-directional connections between any lexicons. The inhibitory effect from intra-level lateral inhibitions was thus obtained. Both Experiment 2 and Bowers et al.'s (2005) results point to the validity of intra-level lateral inhibition as described in traditional IA models.

The explanation for the results in Experiment 1 and 2 should also apply in Experiment 3. After reducing orthographic neighborhood density to zero, Experiment 3 obtained a clear inhibitory phonological neighborhood density effect, suggesting that intra-level lateral inhibition also works for the phonological lexicon. The reason why Yates et al. (2004), Yates (2005), and Mulatti et al. (2006) may have obtained a facilitative phonological neighborhood density effect is that their stimuli had too many orthographic neighbors. Facilitative bi-directional connections between different sorts of lexicons create facilitation that is strong enough to override the inhibition induced by intra-level lateral inhibition.

The claim of intra-level lateral inhibition was further confirmed in the Chinese studies. The Chinese writing system has two important advantages for studying neighborhood density effects. First, Chinese orthographic neighbors share only one sublexical unit, i.e., the phonetic radical. There are fewer such units than is the case for sublexical units (letters) in English. Second, no sublexical units like phonemes exist in the Chinese phonological lexicon. For these reasons, one would expect not only that forces from facilitative bi-directional connections between word and sublexical levels within the Chinese orthographic lexicon would be much weaker than in English, but also that those within the Chinese phonological lexicon can be ruled out completely. As we can see, both orthographic neighborhood density and homophone density consistently showed inhibitory effects in Experiments 4 through 6, indicating inhibitory effects generated by intra-level lateral connections.

A broader implication of the present research is that asking whether neighborhood density effect is facilitative or inhibitory is a simplification of the phenomenon. Because at least four highly connected lexical systems participate in visual word recognition, the amount of units from all sources should be taken into account. The more the overall units, whether they are orthographic/phonological or word/sublexical representations, participate in recognizing a word the more facilitative forces from all sources of bi-directional connections would be produced. If facilitative forces from bi-directional connections outperform inhibitory forces from intra-level lateral connections, a facilitative neighborhood density effect will be obtained. However, if inhibitory forces from intra-level lateral connections outperform facilitative forces from bi-directional connections, an inhibitory neighborhood density effect should be found. This may be the reason why previous studies obtained inconsistent results.

What remains to be discussed is the inhibitory homophone density effects found in Chinese. Because the issue of sublexical phonemic units is not relevant for the Chinese homophone stimuli selected in Experiment 6, any density effect obtained must reflect whole word level effects. Also, because homophone mates of the stimuli did not share any visual similarity, no intra-level lateral inhibition should be expected in Experiment 6. Why then was an inhibitory homophone density effect still obtained? One possible explanation lies in competition processes independent of connections among representations. In traditional IA models, a representation must be activated higher than a specific threshold to reach the status of recognition. Competition happens when a representation achieves a high activation level close to the target word. In PDP models, an activation pattern related to a specific word also needs to achieve a stable status to reach the status of recognition. Competition happens when an activation pattern is close to the target activation pattern. The inhibitory homophone density may reflect this competition after facilitative forces from bi-directional connections and inhibitory forces from intra-level lateral connections are cancelled out. Future experiments will need to test this explanation.

Visual Word Recognition Models

The present experiments also contribute to testing different models. In previous studies, PDP models appeared to be better fitted to account for both facilitative effects of orthographic neighborhood density and phonological neighborhood density obtained in English research because similar activation patterns of neighbors can facilitate the processing of target words. Conversely, traditional IA models failed to account for facilitative neighborhood density effects because intra-level lateral inhibition should cause inhibitory neighborhood density effects.

To overcome the failure in explaining facilitative neighborhood density effects, several modifications of IA models have been suggested. Grainger and Jacobs (1996) suggested that this problem can be solved simply by adding one mechanism sensitive to global lexical activation into their BIA model. Later, Grainger et al. (2005) proposed one more mechanism - calculating cross-code consistency - in their BIA model to account for their finding of a cross-code consistency effect. Using a different strategy, Andrews (1997) suggested that IA models, such as the DRC model, can explain a facilitative neighborhood density effect without adding any new mechanism. Andrews (1997) suggested that simply raising weights for facilitative bi-directional connections and lowering weights for intra-level lateral inhibition can simulate a facilitative orthographic neighborhood density effect with DRC model.

Explanations of PDP models and three modifications were tested in the present experiments. First, the idea of cross-code consistency effect was tested in Exp.1 with English and in Exp.4 with Chinese. However, neither Exp.1 nor Exp.4 obtained any results that could support a mechanism that calculates cross-code consistency. In English, both orthographic neighborhood density and phonological neighborhood density showed facilitative effects when both factors were carefully manipulated in a single experiment. For Chinese, both orthographic neighborhood density and homophone density showed inhibitory effects when both factors were carefully manipulated in a single experiment. No interaction of orthographic and phonological density effects was found in either writing system. However, the present results do not falsify the cross-code consistency effect observed in French because there are different orthography-phonology mappings in French than is the case for English or Chinese. Whereas French is more a letter-phoneme mapping system, English is more a body-rime system, and Chinese is a whole word-whole phonology system. Since Grainger et al.'s (2005) design of a mechanism calculating cross-code consistency is based on letter-phoneme mapping, it is still possible this design could be part of a French word recognition system.

PDP models were not supported in the present experiments. Although they are good at explaining a facilitative effect of orthographic neighborhood density and phonological neighborhood density, they fail to explain inhibitory effects of neighborhood density obtained in Exps.2 to Exp.6. PDP models have no intra-level lateral inhibition mechanism nor any local representations. A word is represented by a specific activation pattern. For this reason, neighbors or homophone mates should generate activation patterns that mimic the activation pattern of the target word. These similar activation patterns should then facilitate the processing of the target word because they accelerate the activation pattern of the target word into a stable status. However, orthographic neighborhood density effects were found to be inhibitory in English (Exp.2) and in Chinese (Exp.5). English phonological neighborhood density (Exp.3) and Chinese homophone density (Exp.6) were also found to be inhibitory. As such, both orthographic and phonological density effects were found to be inhibitory in both writing systems tested.

The suggestion of a mechanism sensitive to global lexical activation was not supported in the present experiments as well. Based on Grainger and Jacobs (1996), the more the number of representations in lexical systems participating in word recognition the stronger the global lexical activation that should be generated; this, in turn, will produce clearer facilitative effects. However, in spite of what was obtained in Exp.1, the results of Exp.2 through Exp.6 all obtained inhibitory density effects. Exp.6 was especially a good setting for testing the idea of a mechanism sensitive to global lexical activation. Chinese stimuli selected in Exp.6 share only one phonology in phonological system and share no visual units in orthographic system. For this reason, no connections should be expected between representations within whole word system or between whole word and sublexical systems. As such, all forces from facilitative bi-directional connections can be cleaned up. If there is a mechanism sensitive to global lexical activation that can outperform intra-level lateral inhibitions, a clear facilitative density effect should still be obtained. However, homophone density effect turned out to be inhibitory. The present experiments, thus, seriously question the proposal by Grainger and Jacobs (1996).

Andrews’s (1997) proposal that facilitative bi-directional connections can counteract the effects of intra-level lateral inhibitions for words with many neighbors works very well in the present experiments. Based on her suggestion, words with few neighbors should present inhibitory density effects reflecting intra-level lateral inhibitions; however, words with many neighbors should show a facilitative density effect because forces from facilitative bi-directional connections can outperform intra-level lateral inhibitions. This is what I obtained in the present experiments. In Exp.1, when stimuli selected all had many orthographic and phonological neighbors, both orthographic and phonological neighborhood density showed facilitative effects. However, when stimuli were selected so that either they had very few phonological neighbors or had no orthographic neighbors, inhibitory density effects were found in Exp.2 and Exp.3. In the Chinese experiments, forces from facilitative bi-directional connections were expected to be lower compared to that in English because no sublexical phonological system should be present and orthographic neighbors at most share only one sublexical unit, i.e., the radical. We did obtain inhibitory effects of orthographic neighborhood density in both Exp.4 and Exp.5. However, in Exp.6, after forces from intra-level lateral inhibitions and facilitative bi-directional connections were all reduced, an inhibitory homophone density effect was still obtained. One might argue that Andrews’s (1997) suggestion does not work here, but as explained earlier, this might simply reflect competition processes during visual word recognition. Compared to the other explanations, Andrews’s (1997) suggestion is still the most successful.

Neural Basis of Neighborhood Density Effects

Recent progress in techniques of brain imaging and recording brain activities has made it possible for researchers to begin to examine the neural correlates of how neighborhood density modulates visual word recognition. Whereas Holcomb et al.'s (2002) ERP study obtained a facilitative effect of orthographic neighborhood density and Pylkkänen et al.'s (2002) MEG study suggested a facilitative effect of phonological neighborhood density, Binder et al.'s (2003) fMRI study found inhibitory orthographic neighborhood density effects in both of their fMRI and behavioral data. Because none of these studies carefully manipulated or controlled both orthographic and phonological neighborhood density effects, the interpretation of these data is in question.

With a better English stimulus set that controlled orthographic neighborhood density (by reducing it to zero), Exp.7 obtained only a trend of an inhibitory effect of phonological neighborhood density in behavioral measures (37 ms). Because the effect size for this effect is close to a medium effect ($\omega^2 = .04$), the inhibitory effect of phonological neighborhood density may likely reach the significant criterion as in Exp.2 after increasing the number of participants. At the same time, the present NIRS data provide neural evidence for density effects by showing that words with high phonological neighborhood density generate stronger blood flow changes in BA 39/40, which is an area suggested to be important in phonological processing in English. A similar pattern was found in Exp.8 with Chinese stimuli. Like what was found in Exp.6, an inhibitory homophone density effect was obtained in the behavioral data of Exp.8. Nevertheless, NIRS data indicated that words with high homophone density generate stronger blood flow changes in BA 9, which is an area suggested to be important for phonological processing in Chinese. Both Exp.7 and Exp.8 thus provide support for a neural basis for phonological density effects.

Studies by Lavidor and Walsh (2003) and Lavidor et al. (2004) suggested a right hemisphere advantage for density effects of *orthographic* neighborhood using rTMS and divided visual field presentation paradigms. Interestingly, NIRS data in Exp.7 also obtained a right hemisphere advantage for English *phonological* neighborhood density, suggesting a special role of the right hemisphere in neighborhood density effects. Future studies are needed to answer why the right hemisphere appears to play a more important role in neighborhood density effects compared to the left hemisphere. Although Exp.8 did not obtain hemisphere differences for homophone density in Chinese, a trend for a right hemisphere advantage still emerged.

Several possible explanations may be explored for the observed right hemisphere advantage observed for density effects. Ellis (2004) argued that feedback from the word level to the sublexical level, which is necessary for revealing density effects, is only present in the right hemisphere. However, word recognition processes in the left hemisphere occur rapidly and in parallel and thus require no need for feedback between word and sublexicals. Chiarello (2002) proposed that the left hemisphere rapidly encodes words into deep level codes, whereas the right hemisphere maintains a surface encoding (e.g., letters), even when deep codes are available. Because density effects would need processes that involve early codes (e.g., sublexical representations in lexicons), this could account for a greater right hemisphere sensitivity in density effects.

However, these explanations are mainly based on orthographic neighborhood density effect. More studies on phonological effects are needed to confirm their ability to explain the right hemisphere advantage observed in effects of phonological neighborhood density and homophone density.

Caveats and Future Studies

Due to the stringent requirements of the present research for stimulus matching on a variety of dimensions to rule out confounds, we were severely limited in the range of stimuli we could use. As a result, the generalizability of the findings may be restricted to the stimulus set we used. Future studies using regression models applied to a larger number of stimuli are thus needed to confirm and increase the generalizability of the present study. Although I discussed and tested different visual word recognition models in the present study, simulation data directly driven from these models are still needed.

Future research should also be directed a better testing and understanding the nature of blood flow changes in relation to facilitation vs. inhibition effects. In its current stage, the brain imaging technique used in the present study, did not provide a basis for establishing if the stronger blood flow changes noted reflected inhibition or facilitation. Studies on effects of phonological neighborhood density and homophone density using other techniques, e.g., ERPs and MEG, are suggested to confirm the pattern of findings obtained in the present study. Finally, given that the participants in the Chinese experiments were also familiar with English, some of their neural activity may reflect their knowledge of this other language (see Vaid, in press, for an overview of neuroimaging findings with bilinguals). In future research it will be important to disentangle the influence of multiple language experience on phenomena such as density effects being tested in individual languages.

CONCLUSION

Intra-level lateral inhibition has been studied and confirmed in many fields such as perception and attention. The present research suggests that this phenomenon is also present in visual word recognition. After different sources of facilitative inter-lexicon connections were reduced step by step, both orthographic and phonological neighborhood density effects were found to be inhibitory in both English and Chinese lexical decision. Inhibitory neighborhood density effects were also confirmed in two NIRS experiments of both English and Chinese. The present data better support interactive-activation models rather than parallel-distributed models by evidence of lateral inhibition. The suggestions of mechanisms sensitive to global lexical activation or cross-code consistency were not supported in the present experiments as well. However, asking whether neighborhood density effect is facilitative or inhibitory is a simplification of the phenomenon. The more the overall units, whether they are word/sublexical or orthographic/phonological representations, participate in recognizing a word the more facilitative forces from all sources of bi-directional connections would be produced. If facilitative forces from bi-directional connections outperform inhibitory forces from intra-level lateral connections, a facilitative neighborhood density effect will be obtained. If inhibitory forces from intra-level lateral connections outperform facilitative forces from bi-directional connections, an inhibitory neighborhood density effect should be found. As such, the present study furthers our understanding of the organization and operation of the mental lexicon.

REFERENCES

Andrews, S. (1989). Frequency and neighborhood effects on lexical lexical access: Activation or search? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15*, 802-814.

Andrews, S. (1992). Frequency and neighborhood effects in lexical access: Lexical similarity or orthographic redundancy? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18*, 234-254.

Andrews, S. (1997). The effect of orthographic similarity on lexical retrieval: Resolving neighborhood conflicts. *Psychonomic Bulletin & Review, 4*, 439-461.

Balota, D. A., Yap, M. J., Cortese, M. J., Hutchison, K. A., Kessler, B., Loftis, B., Neely, J. H., Nelson, D. L., Simpson, G. B., & Treiman, R. (in press). The English Lexicon Project. *Behavior Research Methods*.

Binder, J. R., McKiernan, K. A., Parsons, M. E., Westbury, C. F., Possing, E. T., Kaufman, J. N., & Buchanan, L. (2003). Neural correlates of lexical access during visual word recognition. *Journal of Cognitive Neuroscience, 15*, 372-393.

Bolger, D. J., Perfetti, C. A., & Schneider, W. (2005). A cross-cultural effect on the brain revisited: Universal structures plus writing system variation. *Journal of Human Brain Mapping, 25*, 83-91.

Bowers, J. S., Davis, C. J., & Hanley, D. A. (2005). Interfering neighbours: The impact of novel word learning on the identification of visually similar words. *Cognition, 97*, B45-B54.

Carreiras, M., Perea, M., & Grainger, J. (1997). Effects of orthographic neighborhood in visual word recognition: Cross-task comparisons. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 23,* 857-871.

Chiarello, C. (2002). Parallel systems for processing language: Hemispheric complementarity in the normal brain. In M. T. Banich, & M. Mack (Eds.), *Mind, brain and language: Multidisciplinary perspectives*. Mahwah, NJ: Erlbaum.

Coltheart, M., Curtis, B., Atkins, P., & Haller, M. (1993). Models of reading aloud: Dual-route and parallel-distributed-processing approaches. *Psychological Review, 100*, 589-608.

Coltheart, M., Davelaar, E., Jonasson, J. T., & Besner, D. (1977). Access to the internal lexicon. In S. Dornic (Ed.), *Attention and performance VI* (pp. 535-555). New York: Academic Press.

Coltheart, M., Rastle, K., Perry, C., Langdon, R., & Ziegler, J. (2001). DRC: A dual route cascaded model of visual word recognition and reading aloud. *Psychological Review, 108*, 204-256.

Dijkstra, T. (2005). Bilingual visual word recognition and lexical access. In J. Kroll & A. M. B. De Groot (Eds.), *Handbook of bilingualism: Psycholinguistic approaches* (pp. 179-201). Oxford, UK: Oxford University Press.

Ellis, A. W. (2004) Length, formats, neighbours, hemispheres, and the processing of words presented laterally or at fixation. *Brain and Language, 88*, 355-366.

Feldman, L. B., & Siok, W. W. T. (1999). Semantic radicals contribute to the visual identification of Chinese characters. *Journal of Memory and Language, 40*, 559-576.

Forster, K. I. (1976). Accessing the mental lexicon. In R. Wales & E. Walker (Eds.), *New approaches to language mechanisms* (pp. 257-287). Amsterdam: North-Holland.

Forster, K. I., & Shen, D. (1996). No enemies in the neighborhood: Absence of inhibitory effects in lexical decision and semantic categorization. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 22*, 696-713.

Grainger, J. (1990). Word frequency and neighborhood frequency effects in lexical decision and naming. *Journal of Memory and Language, 29*, 228-244.

Grainger, J., & Ferrand, L. (1994). Phonology and orthography in visual word recognition: Effects of masked homophone primes. *Journal of Memory and Language, 33*, 218-233.

Grainger, J., & Jacobs, A. M. (1996). Orthographic processing in visual word recognition: A multiple read-out model. *Psychological Review, 103,* 518-565.

Grainger, J., Muneaux, M., Farioli, F., & Ziegler, J. C. (2005). Effects of phonological and orthographic neighbourhood density interact in visual word recognition. *The Quarterly Journal of Experimental Psychology, 58A,* 981-998.

Grainger, J., O'Regan, J. K., Jacobs, A. M., & Segui, J. (1989). On the role of competing word units in visual word recognition: The neighborhood frequency effect. *Perception and Psychophysics, 45,* 189-195.

Grainger, J., O'Regan, J. K., Jacobs, A. M., & Segui, J. (1992). Neighborhood frequency effects and letter visibility in visual word recognition. *Perception and Psychophysics, 51*, 49-56.

Grainger, J., & Segui, J. (1990). Neighborhood frequency effects in visual word recognition. *Perception & Psychophysics, 47*, 191-198.

Holcomb, P. J., Grainger, J., & O'Rourke, T. (2002). An electrophysiological study of the effects of orthographic neighborhood size on printed word perception. *Journal of Cognitive Neuroscience, 14*, 938-950.

Huntsman, L. A., & Lima, S. D. (1996). Orthographic neighborhood structure and lexical access. *Journal of Psycholinguistic Research, 25,* 417-429.

Huppert, T., & Boas, D. A. (2005). *HomER: Hemodynamic Evoked Response NIRS data analysis GUI.* Available from the Photon Migration Imaging Lab, Martinos Center for Biomedical Imaging, http://www.nmr.mgh.harvard.edu/PMI/.

Landauer, T. K., & Streeter, L. A. (1973). Structural differences between common and rare words: Failure or equivalence assumptions for theories of word recognition. *Journal of Verbal Learning and Verbal Behavior, 12,* 119-131.

Lavidor, M., Hayes, A., Shillcock, R., & Ellis, A. W. (2004). Evaluating a split processing model of visual word recognition: Effects of orthographic neighborhood size. *Brain and Language, 88*, 312-320.

Lavidor, M., & Walsh, V. (2003). A magnetic stimulation examination of orthographic neighborhood effects in visual word recognition. *Journal of Cognitive Neuroscience, 15,* 354-363.

McClelland, J. L., & Rumelhart, D. E. (1981). An interactive activation model of context effects in letter perception: I. An account of basic findings. *Psychological Review, 88,* 375-407.

Mulatti, C., Reynolds, M. G., & Besner, D. (2006). Neighborhood effects in reading aloud: New findings and new challenges for computational models. *Journal of Experimental Psychology: Human Perception and Performance, 32*, 799-810.

Paap, K. R., Newsome, S. L., McDonald, J. E., & Schvaneveldt, R. W. (1982). An activation-verification model for letter and word recognition: The word superiority effect. *Psychological Review, 89*, 573-594.

Perea, M., & Pollatsek, A. (1998). The effects of neighborhood frequency in reading and lexical decision. *Journal of Experimental Psychology: Perception & Performance, 24,* 767-779.

Perea, M., & Rosa, E. (2000). The effects of orthographic neighborhood in reading and laboratory word identification tasks: A review. *Psicológica, 21*, 327-340.

Perfetti, C. A. (1999). Comprehending written language: A blueprint of the reader. In C. Brown & P. Hagoort (Eds.), *The neurocognition of language* (pp. 167-208). Oxford, UK: Oxford University Press.

Pollatsek, A., Perea, M., & Binder, K. (1999). The effects of “neighborhood size” in reading and lexical decision. *Journal of Experimental Psychology: Perception and Performance, 25*, 1142-1158.

Pylkkänen, L., & Marantz, A. (2003). Tracking the time course of word recognition with MEG. *TRENDS in Cognitive Sciences*, *7,* 187-189.

Pylkkänen, L., Stringfellow, A., & Marantz, A. (2002). Neuromagnetic evidence for the timing of lexical activation: An MEG component sensitive to phonotactic probability but not to neighborhood density. *Brain and Language, 81*, 666-678.

Schneider, W., Eschman, A., & Zuccolotto, A. (2002). *E-Prime user's guide*. Pittsburgh, PA: Psychology Software Tools.

Sears, C. R., Hino, Y., & Campbell, C. R. (2006). Is there a neighborhood frequency effects in English? Evidence from reading and lexical decision. *Journal of Experimental Psychology: Perception and Performance, 32*, 1040-1062.

Sears, C. R., Hino, Y., & Lupker, S. J. (1995). Neighborhood size and neighborhood frequency effects in word recognition. *Journal of Experimental Psychology: Perception and Performance, 21*, 876-900.

Segui, J., & Grainger, J. (1990). Priming word recognition with orthographic neighbors: The effects of relative prime-target frequency. *Journal of Experimental Psychology: Perception and Performance, 16*, 65-76.

Seidenberg, M. S., & McClelland, J. L. (1989). A distributed, developmental model of word recognition and naming. *Psychological Review, 96*, 523-568.

Stockall, L., Stringfellow, A., & Marantz, A. (2004). The precise time course of lexical activation: MEG measurements of the effects of frequency, probability, and density in lexical decision. *Brain and Language, 90*, 88-94.

Strangman, G., Boas, D. A., & Sutton, J. P. (2002). Non-invasive neuroimaging using near-infrared light. *Biological Psychiatry, 52*, 679-693.

Tan, L. H., Laird, A., Li, K., & Fox, P. T. (2005). Neuroanatomical correlates of phonological processing of Chinese characters and alphabetic words: A meta-analysis. *Human Brain Mapping, 25*, 83-91.

Treiman, M., Mullennix, J., Bijeljac-Babic, R., & Richmond-Welty, E. D. (1995). The special role of rimes in description, use, and acquisition of English orthography. *Journal of Experimental Psychology: General, 124,* 107-136.

Vaden, K. I. & Hickok, G. S. (2005). *Irvine Phonotactic Online Dictionary*. [Data file]. Available from the Laboratory for Cognitive Brain Research, http://lcbr.ss.uci.edu.

Vaid, J. (in press). Neural substrates of language processing in bilinguals: Imagi(ni)ng the possibilities. In Srinivasan, N., Pandey, J., & Gupta, A.K. (Eds.), *Advances in Cognitive Science.* New Delhi: Sage Press.

Wu, J. T. (2003). *The role of radical in character recognition and naming (I)*. National Science Council Technical Report: NSC 91-2413-H002-012. [In Chinese]

Wu, J. T., & Liu, I. M. (1988). A data base system about the psychological features of Chinese characters and words. In I. M. Liu, H. C. Chen, and M. J. Chen (Eds.), *Cognitive aspects of the Chinese language* (Pp. 171-186). Hong Kong: Asian Research Service.

Yates, M. (2005). Phonological neighbors speed visual word recognition: Evidence from multiple tasks. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 31*, 1385-1397.

Yates, M., Locker, L., & Simpson, G. B. (2004). The influence of phonological neighborhood on visual word recognition. *Psychonomic Bulletin & Review, 11,* 452-457.

Zhou, X., & Marslen-Wilson, W. (1999). Phonology, orthography, and semantic activation in reading Chinese. *Journal Memory and Language, 41,* 579-606.

Ziegler, J. C., Tan, L. H., Perry, C., & Montant, M. (2000). Phonology matters: The phonological frequency effect in written Chinese. *Psychological Science, 11,* 234-238.

APPENDIX A

ENGLISH STIMULI USED IN EXPERIMENT 1, 2, 3, & 7

Exp.1				Exp.2		Exp.3		Exp.7	
High OND		Low OND		High OND	Low OND				
High PND	Low PND	High PND	Low PND			High PND	Low PND	High PND	Low PND
blow	bulk	brand	crawl	bush	bulb	braille	blimp	braille	blithe
brake	cure	brood	crib	clog	cusp	bronze	blithe	bronze	blouse
brick	cute	bruise	flung	cult	frost	chaise	blouse	chaise	glance
chap	drab	clue	garb	drab	glen	chalk	glance	chrome	glib
clock	drag	cream	glove	jolt	kelp	chrome	glib	froze	hertz
crane	dusk	crude	grub	puke	prep	dirge	hertz	fruit	lounge
craze	flag	float	gulp	pure	pulse	froze	lounge	lapse	prompt
crone	junk	folk	nerve	romp	scrub	fruit	prompt	proud	proof
deck	mule	gene	pulp	scalp	smart	lapse	proof	quake	scourge
jeep	mute	grill	ranch	scarf	smirk	phrase	scourge	shield	scratch
lath	plank	grille	realm	snort	smith	proud	scratch	sleeve	sketch
loud	rusk	lewd	scope	snout	smog	quake	screech	sphere	sluice
milt	slave	pause	shaft	snug	split	shield	sketch	waltz	sparse
poke	slob	prey	smug	soft	stump	sleeve	sluice	whoop	spouse
pond	snag	slope	solve	stint	swath	sphere	sparse	whoosh	swerve
raft	swam	stir	spray	straw	tempt	urge	spleen	writhe	warmth
ramp	swim	thorn	swig	stunk	trunk	waltz	spouse		
spine	trig	weird	thief	stunt	tweed	whoop	swerve		
tilt	verb	wrap	trek	swam	twist	whoosh	twelve		
trim	yarn	wrath	trot	wasp	wolf	writhe	warmth		

Note. OND = orthographic neighborhood density; PND = phonological neighborhood density.

APPENDIX B

CHINESE STIMULI USED IN EXPERIMENT 4, 5, 6, & 8

Exp.4				Exp.5		Exp.6		Exp.8	
High OND		Low OND		High OND	Low OND				
High HD	Low HD	High HD	Low HD			High HD	Low HD	High HD	Low HD
怡	沼	俯	拇	拎	尬	娓	汰	娓	惚
歧	枒	娛	肺	娃	垮	砸	啃	砸	涵
殁	洽	悖	徊	俺	倔	陛	惚	陛	眸
玷	軒	嗅	洶	徐	捧	惦	涵	悸	鈣
郊	祥	堰	俸	租	捨	悸	眸	嫉	摔
畦	脾	媒	啞	掐	棍	嫉	鈣	慄	滬
跤	蛙	絨	唾	傀	賊	慄	嗡	滯	碳
飴	剽	郵	腔	揣	慘	睦	塚	稷	撐
漁	飽	睫	跋	湍	噴	愫	搗	誼	椿
竭	摟	鉛	滲	裸	璀	嫣	嗲	賦	媳
澆	槐	飼	綿	擰	餒	滯	摔	諮	瞬
褐	誨	甄	憒	繞	貓	煽	滬	擱	輾
劑	趨	璃	檜	謬	嚕	嫻	碳		
嶸	骷	膝	糟	釀	囉	稷	撐		
谿	諷	諺	瀑			誼	椿		
臍	擠	蹊	謹			賦	媳		
						穆	燜		
						諮	瞬		
						嚐	輾		
						擱	礎		

Note. OND = orthographic neighborhood density; HD = homophone density.

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Chen, H.-C., & Vaid, J. (2007). Word frequency modulates the basic orthographic syllable structure (BOSS) effect in English polysyllable word recognition. *Language and Cognitive Processes*, *22*, 52-82.

Friedman, M., Chen, H.-C., & Vaid, J. (2006). Proverb preferences across cultures: Dialecticality or poeticality? *Psychonomic Bulletin & Review, 13,* 353-359.

Yamauchi, T., Cooper, L. A., Hilton, H. J., Szerlip, N. J., Chen, H.-C., & Barnhardt, T. M. (2006). Priming for symmetry detection of three-dimensional figures: Central axes of symmetries are assessed separately from local components. *Visual Cognition, 13,* 363-397.

Wu, J. T., & Chen, H.-C. (2003). Chinese orthographic priming in lexical decision and naming tasks. *Chinese Journal of Psychology, 45*, 75-95.

Chen, H.-C., Chien, P. C., Cheng, C. C., & Wu, J. T. (2002). A cognitive approach to mental rotation test on pilot selection. *Chinese Journal of Psychology, 44*, 227-238.

Wu, J. T., & Chen, H.-C. (2000). Evaluating semantic priming and homophonic priming in recognition and naming of Chinese characters. *Chinese Journal of Psychology*, 42, 65-86.