DIFFERENTIAL INVOLVEMENT OF WORKING MEMORY IN READING LOGOGRAPHIC CHINESE VERSUS ALPHABETIC ENGLISH

By

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To my family

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The purpose of the current study is to examine whether word reading in Chinese and in English to a differential degree involves visuo-spatial working memory and verbal working memory (WM) because of the significant linguistic differences between the scripts. The study used the multiple-component WM Model (Baddeley, 2000; Baddeley & Hitch, 1974) as the theoretical framework. In two experiments, Chinese participants and English participants were asked to quickly read words in two conditions. Word reading was accompanied with a concurrent visuo-spatial WM task (Condition 1) and word reading was accompanied with a concurrent verbal WM task (Condition 2). The results of the two experiments showed that (1) Chinese participants showed a significantly lower accuracy for reading both high and low frequency words in the visuo-spatial WM condition than the verbal WM condition; (2) English participants had a significantly lower accuracy in the verbal WM condition than in the visuo-spatial condition when reading high frequency words; when reading low frequency words, English participants did not show significant differences in reading accuracy between the two WM conditions; (3) participants' reading skills did not have an effect on the involvement of visuo-spatial and verbal WM in reading in either Chinese or English. It

was concluded that reading logographic Chinese and alphabetic English differentially involve visuo-spatial WM and verbal WM, at least when HF words were read; and the linguistic features of different scripts invite differences in underlying cognitive mechanisms, such as the involvement of WM, in reading them. The findings were then discussed in terms of its implications for reading research and reading instructional practice, particularly the instruction for Chinese/English bilingual readers.

CHAPTER 1
INTRODUCTION

Statement of the Problem

Is it possible that a dyslexic in his or her native language can still have normal reading abilities in his or her second language reading? As surprising as it may sound, the answer is probably yes. In a recent study, Wydell and Butterworth (1999) reported a case that supported the potential dissociation between an individual's reading ability in his native language and his second language. It was found that a bilingual teenager, who is a dyslexic in English - his native language, can read logographic Japanese kanji and symbolic kana with an equivalent level to that of Japanese undergraduates. A similar case was also found in Chinese/English bilingual readers (Ho & Fong, 2005). Despite being diagnosed a Chinese dyslexic, a Chinese/English bilingual boy showed excellent performance in English word reading tests (Ho & Fong, 2005). Cases like these raise interesting issues regarding reading across scripts. What factors underlie dramatically different performance of people when they read across scripts? Are there any differences in cognitive mechanisms underlying reading across scripts? If so, which kind of cognitive mechanisms are different? In an attempt to explore these issues, the current study examines a cognitive mechanism that could uniquely influence reading two sharply different scripts- logographic Chinese and alphabetic English. Specifically, the current study investigates whether word reading in Chinese and English involves varying degrees of visuo-spatial working memory (WM) and verbal WM because of the distinctive features of the two scripts.

The constructs of visuo-spatial WM and verbal WM in the current study are conceptualized under the framework of Baddeley's Working Memory Model (Baddeley,

2000; Baddeley & Hitch, 1974). According to this model, WM is a memory system that provides temporary and simultaneous storage and manipulation of information (Baddelay, 1992). Structurally, WM consists of the central executive, the phonological loop, the visuo-spatial sketchpad, and the episodic buffer. The central executive is a domain-general system functioning as a coordinator and regulator of attentional resources within WM. The phonological loop and visuo-spatial sketchpad are two domain-specific slave systems of the central executive. These two slave systems are responsible for temporarily storing and manipulating verbal and visuo-spatial information, respectively (Baddeley & Hitch, 1974). The episodic buffer is mainly in charge of integrating the information in the two slave systems and the information between the two slave systems and long-term memory (Baddeley, 2000). In the current study, visuo-spatial WM is defined as the system consisting of the visuo-spatial sketchpad and central executive, which jointly implement the function of temporarily manipulating and storing visuo-spatial information in cognitive activities (Logie & Marchetti, 1991). Verbal WM refers to the system consisting of the phonological loop and central executive, which together are responsible for the temporary retention and manipulation of verbal or phonological information (Kondo & Osaka, 2004).

This study investigates individual differences in the use of WM between reading Chinese and English *at the word reading level* for several reasons. As an important component of integrated reading behaviors (Perfetti & Hogaboam, 1975), word reading is the first and indispensible step of reading behaviors by which readers decipher written linguistic symbols in order to ultimately get the meanings of texts. It has been suggested that word reading or word decoding shares a limited capacity mechanism or WM

resources with higher-level reading processes, such as inference-making and the construction of situation models (Lundquist, 2004; Perfetti & Hogaboam, 1975). Because of the sharing of a common cognitive resource pool, lower-level word reading process has to compete with higher-level reading processes for limited WM resources during reading activities. This means that if there are any individual differences in the use of WM at the word reading level, this difference at the lower-level reading processes would further influence higher-level reading processes or other reading behaviors of readers. Considering there is still limited research that investigates the potential individual differences at the lower-level word reading caused by reading different scripts, the current study filled the gap and examined the potentially different involvement of WM in word reading in Chinese versus English.

An important fact emerging from the current literature is that existing word reading studies were largely regarded reading alphabetic scripts, mainly in English. In comparison, there is still limited research examining how word reading in a non-alphabetic script is achieved. Word reading research solely focusing on examining alphabetic scripts has its limitations. For a long time, such word reading studies tended to focus on the issues of how *phonology* plays its role in word recognition (Perfetti, Liu, & Tan, 2005) and how *verbal WM* is thus involved in reading processes. In contrast, limited efforts have been made to explore how visual processing of words is achieved during word recognition. Considering the linguistic characteristics of alphabetic writing systems, the situation seems to be understandable. For alphabetic writing systems, the association between written words and spoken sounds exist at the phoneme-letter level (Perfetti, Liu, Fiez, Nelson, Bolger, & Tan, 2007), which makes it possible that

alphabetic readers can rapidly transform individual letters into corresponding phonemes and then assemble the activated phonemes into the sound of the words (i.e., assembled phonology). In the reading literature, it has been proposed that assembled phonology occurs before the lexical presentations of English words were accessed (Lukatela & Turvey, 1994) and it plays a predominant role in the recognition of English words by mediating the final activation of semantic meanings (Frost, 1998). In contrast to the predominant phonological processing, the visual processing of English words seems to play a secondary role in confirming the activated representations of words at the later stage of word recognition (Van Ordon, 1987).

In contrast to alphabetic scripts, non-alphabetic scripts are typically not sound-based. Taking logographic Chinese as an example, rather than consisting of abstract letters, logographic Chinese characters consist of individual strokes and meaning radicals (i.e., certain patterns of strokes that have semantic meanings) and most Chinese characters have arbitrarily assigned pronunciations. In addition, the associations between spoken sounds and written Chinese words exist at the word level, rather than at the phoneme level. These linguistic characteristics make pre-lexical assembled phonology impossible in reading Chinese (Perfetti et al., 2007). Instead, the phonological activation of Chinese words depends on an earlier and fully specified activation of orthographic representations of words (Perfetti et al., 2005). Furthermore, the orthography of Chinese characters is quite differentiated among characters and is less confounded with the phonology. This allows a better manipulation and examination of visual-orthographic processing of words in a study, which is often difficulty in English

word reading studies. In this sense, it can be said that studying non-alphabetic scripts can offer unique information on word reading processes.

Corresponding to the aforementioned linguistic analysis of alphabetic and non-alphabetic scripts, brain-imaging research has shown that several neural areas are distinctively associated with reading non-alphabetic scripts, such as Chinese and Japanese Kanji, and alphabetic scripts, such as English (Tan, Laird, Li, & Fox, 2005; Bolger, Perfetti, & Schneider, 2005). The neural differences suggest the possible use of different cognitive processes during word reading among different scripts, with a more elaborated visual-orthographic processing in reading non-alphabetic scripts (Tan et al., 2005). For example, it has been consistently found that compared with English word reading, Chinese word reading makes use of *additional* brain areas, such as the left middle frontal gyrus and several areas in the right hemispheric occipital and fusiform regions (e.g., Tan, Liu, Perfetti, Spinks, Fox, & Gao 2001; Tan et al., 2005; Perfetti et al., 2007). Several studies using Chinese-English bilingual participants found asymmetry between the neural networks of Chinese and English reading, which suggests that the Chinese word reading procedures may be universal and are applicable to alphabetic scripts, whereas the alphabetic reading procedures seem to be more specific and not applicable to non-alphabetic scripts (Wang, Koda, &Perfetti, 2003; Liu & Perfetti, 2003). Altogether, it can be concluded that studying word reading in non-alphabetic scripts such as logographic Chinese can bring important and unique insight on word reading research. It can further expand our understanding of word reading processes. In this potentially new area of reading research, a comparative perspective between alphabetic versus non-alphabetic reading is useful because it can highlight

what is general and what is specific in reading process (Perfetti et al. 2005). Taking just such a perspective, the current study examines potential differences in the use of WM by comparing its involvement in reading two contrasting scripts - alphabetic English and logographic Chinese. Specifically, the current study tested the plausibility of the theoretical assumption that corresponding to the significant linguistic differences between the two scripts, reading logographic Chinese may to a greater degree require the involvement of visuo-spatial WM in word processing, whereas reading alphabetic English may demand more involvement of verbal WM in word reading (Wang, Linderholm, & Fang, under review).

Research Questions

The current study aims at addressing three research questions:

- Are visuo-spatial WM and verbal WM differentially involved in word reading in Chinese versus in English?
- Do reading skills in one's native language affect the involvement of visuo-spatial WM and verbal WM in word reading in Chinese or in English?
- Does word frequency affect the involvement of visuo-spatial WM and verbal WM in word reading in Chinese or in English?

Significance of the Study

An empirical examination of the issue of whether word reading in Chinese and English differentially involves visuo-spatial WM and verbal WM has important theoretical and practical implications. First of all, empirical investigations of the issue may bring a *new perspective to explore and explain individual differences* in reading processes. In current reading literature, how WM contribute to individual differences in reading processes has been an important concern (Just & Carpenter, 1992). However, almost all of the existing studies in this aspect focus on how individual differences in *WM*

capacity influence reading processes. To date, there is still no study examining whether the involvement of the different components of WM (e.g., visuo-spatial and verbal WM) may also contribute to individual differences in reading comprehension. To fill in this gap, the current study is one of the first to explore the potential differences in reading comprehension by examining the involvement of different WM components in reading processes. The findings of the study will not only shed light on the specific cognitive differences in reading Chinese versus English at the lower level word reading, but also lay a foundation for future investigations of higher-level reading processes. In the current literature, research has demonstrated that visuo-spatial WM and verbal WM are responsible for different aspects of some higher-level reading processes (e.g., Friedman & Miyake, 2000; Robinson & Molina, 2002). For example, Friedman and Miyake (2000) found that whereas spatial dimensions of situation models were maintained in visuo-spatial WM, causal dimensions of situation models were maintained and elaborated on independently in verbal WM. Robinson and Molina (2002) found that different types of adjunct displays (e.g., outlines and graphic organizers that were inserted in texts to assist students in comprehending texts) were maintained independently in visuo-spatial WM and verbal WM respectively. Based on these findings, it is plausible to reason that if reading Chinese and English does differentially rely on visuo-spatial WM and verbal WM in word processing, this difference at the word reading level between Chinese and English readers might further cause them to have different performance in some higher-level reading processes (e.g., the construction of situational models); or the difference may trigger Chinese and English readers to use different strategies during reading

activities. In this sense, the findings from the current study may provide a foundation for the proposal and examination of these new research questions in this area.

Secondly, an empirical examination of the relative reliance of visuo-spatial and verbal WM in word reading in Chinese versus English also will shed light on the specific role of visuo-spatial WM in lower-level reading processes. For many years, reading research has been focusing on the examination of the role that verbal WM plays in reading processes. In contrast, there is still limited research examining the role of visuo-spatial WM in reading processes, particularly in lower-level reading processes. By investigating and comparing the involvement of visuo-spatial WM in reading across scripts, this study brings new insight on the issue of how visuo-spatial WM is involved in lower-level word reading process.

Finally, empirical examinations of the potentially differential involvement of WM in reading Chinese versus English will have important implications for reading instruction, especially for Chinese/English bilingual readers. With increasing economic globalization, more and more people are becoming Chinese/ English bilingual readers in both U.S. and China. According to the relevant statistics, there were at least 300,000 American students in the U.S. who were learning Chinese as their second language in 2005 (Modern Language Association, 2005). The number of Chinese/English bilingual readers has reached a few million in China over the past 10 years as English Language became a required course in most of the middle schools in the country. Since word reading is a vital and fundamental skill for fluent reading and it influences higher level reading processes, effective reading instruction for Chinese/English bilingual readers has to take it into account if reading Chinese and English turns out to differentially

involve WM at the word reading level. This potential cognitive difference may influence the way in which Chinese/English bilingual readers encode and decode words or effectively use a particular reading strategy when they are reading a given script. For instance, it is possible that due to the distinctive features of the two scripts, a given reading strategy that is very effective in reading one of the two scripts may be less effective in reading another script. For example, native-English speakers who are learning Chinese as a second language often find that their Chinese reading does not benefit from the strategy of “reading aloud” as much as their English reading does. In addition, it might also be possible that the potential differences in word reading in Chinese and English somewhat influence the *multiple-media* reading of Chinese and English readers (e.g., reading an educational website on a computer). Different from text reading on a paper, reading in a multiple-media setting typically involves more concurrent processing of word information and pictorial information (e.g., illustrations, background pictures, figures). If it turns out that word reading in Chinese and English, to a certain degree, requires the involvement of visuo-spatial WM and verbal WM, it is possible that English readers may benefit from many pictorial illustrations embedded in texts, whereas Chinese readers, particularly unskilled readers, might somewhat suffer from the simultaneous demonstration of multiple pictorial illustrations because it complete limited visuo-spatial WM resources with their word reading.

Another practical implication that the current study may have is for the intervention of English dyslexia, especially English dyslexia with phonological deficits. Typically, English readers with phonological dyslexia have difficulties reading pesudowords and irregular words due to their inability to segment, analyze, and

synthesize speech sounds (Eden, Jones, Cappell, Gareau, Wood, Zeffiro, Dietz, Agnew, & Flowers, 2004). The investigation of the involvement of visuo-spatial WM in Chinese word reading might eventually reveal some specific mechanisms of word visual processing by which Chinese readers rehearse the orthography of words without resorting to any phonological processing of words. By helping English dyslexics acquire these Chinese-style methods of visually processing words, educators might greatly improve English dyslexics' ability to read pseudowords and irregular words in a new way.

To summarize, investigating the potentially different involvement of visuo-spatial WM and verbal WM in word reading in Chinese versus English has important theoretical and practical implications. Such an investigation not only brings a new perspective to explore individual differences in lower-level reading processes, but also may bring important improvement to reading instruction practice for Chinese/English bilingual readers. In the long run, it might also add new intervention methods to English dyslexia.

CHAPTER 2
REVIEW OF LITERATURE

Introduction

The current chapter is a review of the literature related to my investigation of the differential involvement of visuo-spatial and verbal WM in word reading in Chinese versus in English. I begin the chapter with a review of Baddeley's Working Memory Model (Baddeley 2000, Baddeley & Hitch, 1974), which serves as the theoretical framework for the current study. Then, I summarize the major contrasting linguistic features of the Chinese and English writing systems. In the third section, I review the empirical evidence for the involvement of WM in word reading of skilled readers. Finally, I provide a comprehensive review and critique of the existing evidence for a potentially different involvement of visuo-spatial WM and verbal WM in word reading in Chinese versus in English.

Working Memory Model

Baddeley's WM model (Baddeley, 2000; Baddeley & Hitch, 1974) was chosen as the theoretical framework of the current study for two reasons. First, the model has been widely used in the reading research field in the last two decades; secondly, the model itself has been well supported by behaviorally based research and neural imaging research (Gathercole, 1994).

According to Baddeley's WM model (Baddeley, 2000; Baddeley & Hitch, 1974), WM is a short-term memory system that provides simultaneous storage and manipulation of information. Structurally, WM consists of four components: the central executive, the phonological loop, the visuo-spatial sketchpad, and the episodic buffer. The central executive is a domain-general coordinator and regulator of cognitive

resources. The phonological loop and visuo-spatial sketchpad are two slave systems affiliated to the central executive. These two slave systems are domain-specific. Their roles are to respectively store and manipulate verbal and visuo-spatial information for a very short time (Baddeley & Hitch, 1974). The episodic buffer is mainly in charge of integrating the information in the two slave systems and the information between the two slave systems and long-term memory (Baddeley, 2000). In the following section, I provide a detailed discussion of each of the four components.

The two slave systems, the phonological loop and visuo-spatial sketchpad, are simpler components within WM (Baddeley, 1992). Functionally, the phonological loop is responsible for temporarily storing and manipulating acoustic or speech-based information in various cognitive activities. The functions are achieved by a joint work of the two components of the phonological loop: the phonological store and the articulatory rehearsal subsystem (Baddeley & Hitch, 1974). Specifically, the phonological store is in charge of temporarily maintaining acoustic information until it naturally decays or is further processed by the articulatory rehearsal subsystem. The articulatory rehearsal subsystem, on the other hand, is responsible for actively holding phonological information within the loop by rehearsal processes, for example, repeating information over and over (Baddeley, 1992).

Similar to the phonological loop, the visuo-spatial sketchpad is the other domain-specific slave system of the central executive. Its function is to temporarily manipulate and store visual and spatial information in cognitive activities (Baddeley & Hitch, 1974). Structurally, Logie (1995) has suggested that the visuo-spatial sketchpad also has a two-component structure, consisting of a passive storage component -*the visual cache*

and an active processing component - *the inner scribe.* The function of the visual cache is to simply store visuo-spatial information in the sketchpad. The role of the inner scribe is comparable to that of the rehearsal subsystem in the phonological loop. It is responsible for maintaining and refreshing visuo-spatial information with the sketchpad.

As a domain-general supervising component of WM, the central executive is assumed to play an important role within WM in three ways. First, the central executive functions as an attention-regulator responsible for supervising, dividing, and switching attention within WM (Baddeley, 2000). Secondly, the central executive also regulates and coordinates all the activities of the two slave systems. Lastly, with its independent storage system, the episodic buffer, the central executive can form an interface that connects the two slave systems and long-term memory so that all the information in these systems can be integrated (Baddeley, 2000; 2002). The episodic buffer is a newly added component in the WM model (Baddeley & Hitch, 1974; Baddeley, 2000). As a pure storage component within WM, the episodic buffer is affiliated to the central executive and in charge of retrieving information from long-term memory and forming an interface that connects the two slave systems and long-term memory so that all the information in these systems can be blended into episodic memory (Baddeley, 2000; 2002).

Although the central executive is conceptually separable from its two slave systems, this pure processing component of WM always functions closely together with either one or both of its two domain-specific slave systems in daily life. For this reason, rather than using the terms phonological loop and visuo-spatial sketchpad, many reading researchers use the terms “verbal WM” and “visuo-spatial WM” to distinguish

the two slave systems that work in conjunction with the central executive (e.g., Just & Carpenter, 1992). In the current study, visuo-spatial WM and verbal WM are also referred as to the two subsystems that work in conjunction with the central executive. Specifically, visuo-spatial WM in the current study is defined as the system consisting of the visuo-spatial sketchpad and central executive, which jointly implement the function of temporarily manipulating and storing visuo-spatial information in cognitive activities (Logie & Marchetti, 1991). Verbal WM refers to the system consisting of the phonological loop and central executive, which together are responsible for temporary retention and manipulation of verbal information (Kondo & Osaka, 2004).

Chinese and English Writing Systems

To understand how the linguistic features of the Chinese and English writing systems may cause a potentially different use of the two subsystems of WM in reading the two scripts, I will provide a brief linguistic analysis of the two writing systems in this section before I move on the empirical review.

Logographic Chinese and alphabetic English are two contrasting writing systems (Liu, Dunlap, Fiez, & Perfetti, 2007). The first linguistic difference between the two writing systems is that Chinese is essentially meaning-based whereas English is sound-based. Unlike English words, which are comprised of 26 abstract alphabetic letters with various combinations, Chinese characters are made of thousands of meaningful radicals (i.e., stroke patterns having semantic meanings) with the spoken sounds arbitrarily assigned to each character. For example, the Chinese character 明 is comprised of the two meaningful semantic radicals 日 (/ri/ meaning *sun)* and 月 (/yue/ meaning *moon*). By putting these two semantic radicals (*sun and moon*) together, a new

character 明 (meaning *bright*) is formed. The pronunciation of 明 /ming/ is arbitrarily assigned and has nothing to do with either of the two component radicals (/ri/ and /yue/). This characteristic of Chinese words makes it possible for one to ascertain the correct meaning of an unknown Chinese character by simply making a guess based on the meanings of radicals. However, it is much less likely for the reader to correctly sound out a new word before having really learned its pronunciation. The situation is opposite when it comes to the sound-based English script. For English words, it is easier for one to correctly sound out an unknown word, while it is less likely that the reader can guess the meaning of an unknown English word. In this sense, English script is sound dependent, whereas Chinese script is more visually dependent.

The Chinese and English writing systems are also different in terms of sound-to-word associations (Tan & Perfetti, 1997). In English, it is typical that one written word is only associated with *one* spoken sound. Accordingly, phonological representations of English words can serve as *unambiguous* codes as a reader tries to build up a mental representation of a text. In Chinese, however, a spoken sound is often simultaneously associated with several written characters, which makes the phonological codes of words less useful in Chinese word reading (Zhou, Shu, Bi, & Shi, 1999). An issue that highlights the lack of phonologically unambiguous cues in Chinese is that the Chinese writing system is full of homophones. According to Contemporary Chinese Frequency Dictionary (Wang, 1986), there are about 420 unique phonemic forms in spoken Chinese that are shared by about 4,500 high-frequency Chinese characters. In other words, roughly 10 Chinese characters share only one sound. For instance, a sound /sheng/ in spoken Chinese is associated with at least 10 characters in the written

system, such as 升, 生, 声, 笙, 甥, etc. By adding the characters that have the same syllable but slightly different tones, the number of the homophonic characters in this case could be above 20 or more. Since different Chinese characters often share an identical spoken sound, phonological codes of Chinese characters can not always serve as *unambiguous* codes in Chinese reading as it typically does in English reading.

Another difference between Chinese and English is that Chinese characters are visually more complex than English words. Whereas English words have relatively simple linear structures (i.e., letters are always put into a linear sequence from left to right), Chinese characters have complex internal structures. To illustrate the structural complexity of Chinese characters, let us decompose a Chinese character 壒 (meaning dust). Structurally, the character 壒 can be first decomposed into two main parts, the left part, “radical 土” and the right part. Then, the entire right part can be further decomposed into three meaningful radicals: the top part 艹, the middle part 去, and the bottom part 皿; each of these radicals can be further decomposed into symbolic strokes (e.g., 一 , /). When strokes and stroke patterns are put together into a character, there are a series of complex spatial arrangement rules that must be applied. Because of this structural complexity, the recognition of Chinese characters may require a more elaborate analysis of spatial relations of radicals and strokes that the recognition of linear English words does not need (Tan et al., 2001).

In summary, logographic Chinese is different from alphabetic English in several important aspects. Unlike English words, Chinese characters are essentially meaning-

based, which are difficult to be sounded out without really knowing the characters. Since there are tremendous numbers of homophones in Chinese, it is also difficult for Chinese readers to rely on phonological codes as unambiguous codes to build up mental representations of texts during reading. These characteristics of Chinese suggest that it is theoretically possible that reading Chinese characters may rely less on the phonological processing of words and thus may require less involvement of verbal WM, precisely the phonological loop component of verbal WM, relative to reading English. On the other hand, Chinese characters have two-dimensional and visually more complex structures. This characteristic of Chinese, as well as its meaning-based constituents, suggests that reading logographic Chinese may require a more intensive and elaborate visual processing of words than English words (Tan et al., 2005), which may invite more involvement of the visuo-spatial sketchpad of visuo-spatial WM in word processing. Taken together, the cognitive demands of processing these two scripts, with the logographic Chinese demanding more elaborate visual processing and the alphabetic English demanding more phonological processing, may result in a differential reliance on visuo-spatial and verbal WM in reading these two contrasting scripts. The primary purpose of the current study is to empirically examine the plausibility of this theoretical assumption.

Working Memory in Skilled Word Reading

To examine and compare the relative reliance on visuo-spatial WM and verbal WM in word reading in Chinese versus English, a fundamental issue that this study has to deal with is whether or not word reading of skilled readers consumes WM resources. In the past years, the literature has been dominated by the position that word recognition in skilled reading is automatic and does not require WM recourses (e.g.,

Lien, Ruthruff, Cornett, Goodin, & Allen, 2008). The Stroop effect was often cited as the evidence for this automated word reading position (Ruthruff, Allen, Lien, & Grabbe, 2008). In Stroop experiments, participants showed difficulty to suppress the interference of verbal information in naming the ink color of a word, although they did not need the verbal information to complete the task. In Face, the phonological activation of the word impaired and slowed down their performance in the task. The finding that verbal information was activated and used in a task that it was not useful at all (i.g., the Stroop effect) was thus interpreted that visual word recognition in skilled reading occurs automatically (MacLeod, 1991). For researchers holding the automated word recognition position, it is the phonological loop, but not the verbal WM as a whole, that plays a critical role in lower-level reading processes such as word recognition and word decoding (Caplan & Waters, 1999).

In contrast to this traditional position, newer research has shown that even for skilled readers, word reading requires attentional resources and demands the involvement of the central executive (e.g., McCann, Remington, & Selst, 2000; Lien, et al., 2008). Using psychological refractory period (PRP), a new paradigm for investigating automaticity of word recognition, McCann et al. (2000) provided evidence that word reading takes attentional, or WM, resources for skilled reader. The PRP paradigm involves measuring response-time delays in a dual-task situation, in which participants are typically asked to quickly respond to two tasks with different stimulus onsets (e.g., the second task is started a few msec later than the first task). If the processing of the second task shows pronounced delay because of the first task, the delay would indicate that the second task requires the central-processing resources that

the first task is still taking and therefore can not be automatically processed due to the unavailability of central-processing resources. Using such a paradigm, McCann et al. (2000) found that the discrimination of represented pitch in the first task dramatically increased participants' lexical decision and naming latencies in the second word recognition task as the stimulus onset asynchrony between the tasks was reduced. Based on the findings, McCann et al. (2000) made the conclusion that rather than an automatic process, word reading, even that of skilled readers, takes central attentional resources, which is managed by the central executive of WM.

Using a similar task, Lien et al. (2008) provides convergent electrophysiological evidence for the non-automaticity of visual word processing in skilled reading. Furthermore, Tan et al. (2003) provided neural-imaging evidence that the recognition of Chinese characters recruits a neural system involving left middle frontal and posterior parietal gyri, cortical regions, which are responsible for spatial information representation, spatial working memory, and coordination of cognitive resources as a central executive system (e.g., Courtney, Petit, Maisog, Ungerleider, & Haxby, 1998).

To summarize, current literature has shown that word reading is not automatic for skilled reading and does take WM resources (e.g., McCann, Remington, & Selst, 2000; Lien, et al., 2008, but see Cleland, Gaskell, Quinlan, & Tamminen, 2006 for a different view). The non-automaticity of word reading makes it possible to further examine the relative reliance on visuo-spatial WM and verbal WM in word reading in Chinese versus in English.

Working Memory with Word Reading in Chinese versus English

A potentially different involvement of visuo-spatial WM and verbal WM in word reading in Chinese versus in English has been, to an extent, suggested by existing

empirical findings from neural-imaging research, dyslexia research, and behaviorally based comparison studies. In the following section, supporting empirical findings from these research areas will be reviewed in detail.

Evidence from Neural Imaging Research

A comparison of brain-imaging data of Chinese and English word reading has suggested that visuo-spatial WM may, to a greater extent, be involved in word reading in Chinese than in English. It has been found that the neural areas regularly recruited in spatial WM tasks and several right hemispheric areas were distinctively associated with Chinese word reading (e.g., Tan et al., 2001; Tan et al., 2005; Liu & Perfetti, 2003). In contrast, these areas were rarely reported in corresponding English word reading studies (Tan et al., 2001). The distinctive right hemispheric areas showing in the neural network of Chinese word reading included the right frontal pole (BA10/11), frontal operculum (BA 47/45), the superior and inferior parietal lobules (BAs 7, 40/39), and visual form areas. Previous research has demonstrated that the right BAs 7 and 40/39 were typically recruited to support the completion of spatial WM tasks (Courtney, Petit, Maisog, Ungerleider, & Haxby, 1998). And other right hemispheric areas found in the neural network of reading Chinese were more or less associated with episodic memory that requires the retrieval of spatial relations of objects (Lepage, Ghaffar, Nyberg, & Tulving, 2000). Researchers have suggested that these distinctive neural areas in the neural network of reading Chinese were recruited to analyze the spatial locations of radicals and strokes of Chinese characters. The areas were typically not found in the neural network of reading English because linear English words may not necessarily need a similar two-dimension spatial analysis of words during word recognition (Tan et al., 2001). Taken together, the distinctive associations of the right hemispheric areas,

particularly the areas routinely activated in spatial WM tasks, with the neural network of reading Chinese suggest that reading logographic Chinese may demand a greater involvement of visuo-spatial WM relative to reading alphabetic English.

As far as verbal WM is concerned, current research seems to suggest that verbal WM may, to a greater level, be involved in English word reading relative to Chinese word reading. A comparison of neural-imaging data of Chinese and English word reading shows that the common areas in the neural circuits of phonological processing of Chinese and English words typically show a *weaker* activation in word reading tasks in Chinese than in English (Tan et al., 2005). In addition, several neural-imaging studies (e.g., Bolger et al., 2005; Tan et al., 2005) have demonstrated that different neural areas are associated with the neural circuits of phonological processing of Chinese and English words, suggesting the use of different cognitive mechanisms. According to Tan and his colleagues (Tan et al., 2005), word reading in English primarily involves the use of assembled phonology. In contrast, reading logographic Chinese employs another mechanism called addressed phonology. In addressed phonology, the activation of phonological representations of words does not involve grapheme-to-phoneme conversions, but is accessed by directly retrieving phonological representations of entire words from long-term memory through a direct look-up or mapping process (Tan et al., 2005). Considering that the phonological loop processes information in a serial manner (Baddeley, 1986), it seems plausible to assume that verbal WM, or more precisely, the phonological loop of verbal WM, may be more involved in English word reading due to the need of doing grapheme-to-phoneme conversions (Tavassoli, 2002). In contrast,

Chinese word reading may, to a lesser extent, involve verbal WM in word processing because of the use of addressed phonology.

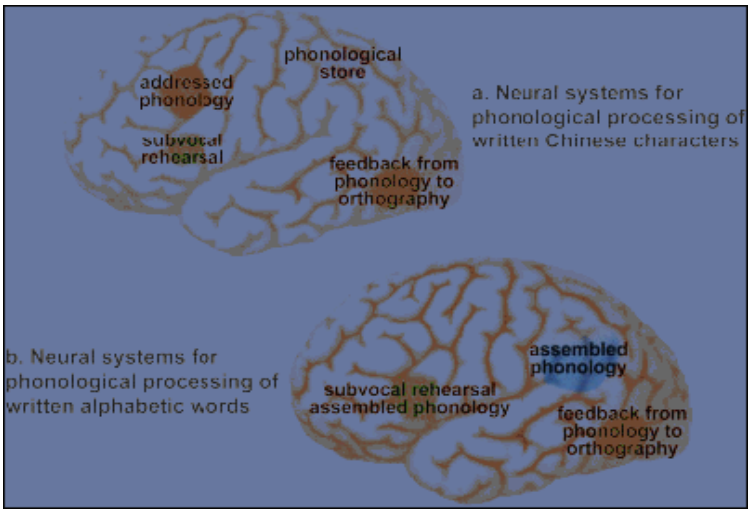

Figure 2-1. Neural systems for phonological processing of Chinese characters and alphabetic words (Reprinted with permission from Tan, Laird, Li, & Fox, 2005)

Interestingly enough, the aforementioned neural differences in reading Chinese versus English found in native speakers were also demonstrated in English participants with no previous knowledge of Chinese when they were completing Chinese and English word reading tasks (Liu et al., 2007). In a recent study, Liu et al (2007) trained a group of native English speakers to learn 60 Chinese characters in a 3-4-day period (about 2 hours a day). All participants had no previous knowledge of Chinese. After the training, fMRI scans were conducted when the participants underwent computerized testing of 60 characters. Apart from the learned characters, novel Chinese characters, English words, and English pseudowords were also used as stimuli during fMRI scans. The results showed that although participants had such a short-term training on Chinese (total 6-9 hours only), they engaged a neural network that is very similar to that of skilled Chinese readers in the word recognition tasks with Chinese stimuli. When

compared with the neural network that the participants used in matching English word recognition tasks, their Chinese neural network contains the distinctive areas typically found in neural-imaging studies using native Chinese speakers. Once again, researchers linked the distinctive areas in the neural network of reading Chinese words with the special linguistic characteristics of the Chinese writing system. The strong activation of those distinctive right hemispheric areas was suggested to play an important role in analyzing the spatial relations of radicals (right-left, top-bottom, or inside-outside) during word recognition. The distinctive activation of the areas in the left middle frontal gyrus (LMFG) was assumed to be used for temporarily retaining the orthography of a word in WM until the meaning and probably pronunciation of the word is retrieved from long-term memory. Taken together, Liu et al (2007) further supported the existence of a distinctive neural network associated with Chinese word reading in beginning Chinese learners. Since the study used native English participants who did not know Chinese at all previously, the findings in this study can safely lead to the conclusion that the writing system is the factor that caused the different activation patterns in the neural networks of Chinese and English reading (Liu et al., 2007). Based on the findings, researchers have proposed a System Accommodation Hypothesis, which states that reading in a new writing system demands the use of different neural resources that can specifically support the linguistic features of the new writing system. In other words, the reading neural network has to change to “accommodate” the new writing system (Liu et al., 2007; Perfetti et al., 2007).

To summarize, current neural-imaging research has provided considerable evidence that distinctive brain areas were recruited in reading Chinese versus English

despite the existence of the common neural areas (Liu et al., 2007; Tan et al., 2005; Perfetti et al., 2007). Although researchers have suggested that the differences in the neural networks of reading Chinese and reading English means that different cognitive mechanisms may be involved in reading the two scripts (Tan et al., 2005), it is still unclear exactly which kind of different cognitive mechanisms are involved. Accordingly, the current study is designed to explore the potential differences in cognitive mechanisms by directly comparing the use of visuo-spatial and verbal WM in reading Chinese versus reading English.

Behaviorally Based Evidence from Comparison Studies

Echoing the finding that Chinese word recognition involved distinctive neural areas that support its intense visuo-spatial analysis of words (Tan et al., 2001; Liu et al., 2007), Tavassoli (2002) provided evidence that native Chinese participants relied more on visuo-spatial WM resources in their word processing than native English participants. In this study, Tavassoli (2002) directly compared spatial memory of native Chinese readers for words and pseudowords with that of native English readers. Participants were asked to study a paper panel for a short time with a general instruction of studying the information presented. On the paper panel, either the names of 16 animals (written in Chinese/English words respectively) or the pictures of the animals (the control condition) were presented with a given pattern of spatial arrangement. After the short-term study, participants were given a new paper panel to identify the changes on the positions of pictures or words. The number of items that participants correctly identified the changes in their positions was used as the measure of spatial memory. The results revealed that Chinese participants showed statistically better spatial memory for the positions of the words compared to native English participants. However, they did not

show the similar spatial memory advantage for pictorial information in the control condition. When pseudowords and abstract symbols were used to respectively substitute for the real words and the pictures (Experiment 2), the same results were replicated. These results suggest that the spatial memory advantage of Chinese participants was only associated with Chinese logography. To interpret the above findings, Tavassoli proposed that Chinese participants may rely more on spatial WM resources to process the words on the panel, which resulted in a better encoding for the spatial positions of the words and thus a better incidental spatial memory of words later on. In contrast, English participants may rely on more the phonological loop of verbal WM, rather than visuo-spatial WM, to process English words. Therefore, they did not encode and remember the positions of the words as well as Chinese participants did.

Tavassoli's study (2002) is informative to the possibly different involvement of visuo-spatial WM and verbal WM in reading Chinese and English words. However, it must be noted that the study has one methodological limitation, that is, the study did not directly measure spatial WM to support the conclusion that there was a different reliance on spatial WM between Chinese and English participants in word processing during the task. Instead, the conclusion was made based on participants' long-term spatial memory for word positions. The rationale for the use of this long-term memory measure is that if one group of participants (e.g., Chinese participants) use more spatial WM to process word information during the task, they would encode word positions better than the other group (e.g., English participants); and then the better encoding would result in a advantage of remembering word positions in long-term memory. As convincing as the reasoning sounds, such a design may not exclude the potential

influence of some other factors that may also account for Chinese participants' better spatial memory for word positions. For example, it is possible that because Chinese characters are visually more distinctive with each other, Chinese participants may gain more clues to remember word related information during the task and thus showed better performance in remembering the word positions. To avoid these potentially confounding factors, the current study will directly measure and compare Chinese and English readers' performance in a visuo-spatial WM task and a concurrent word recognition task.

Evidence from Dyslexia Research

In addition to neural-imaging research and behaviorally based comparative studies, research on dyslexia also provides empirical support for the assumption that Chinese and English reading may differentially involve visuo-spatial and verbal WM in word processing (Wang, Linderholm, & Fang, under review). First, it has been suggested that the primary cognitive deficits underlying Chinese and English dyslexia are different (Ho, Chan, Lee, Tsang, & Luan, 2004). Whereas the phonological processing deficit is the main cause of English dyslexia (e.g., Hulme & Snowling, 1992; Jeffries & Everatt, 2004; Morris, Stuebring, Fletcher, Shaywiz, Lyon, Shankweiler, Katz, Francis, & Shaywitz, 1998), orthography-related difficulties seem to be the core cause of Chinese dyslexia (Ho et al., 2004). Secondly, the dysfunction of different brain areas is associated with reading difficulties of Chinese and English readers, which suggests different biological origins of dyslexia in the two languages (Soik, Perfetti, Jin, & Tan, 2008).

Reading researchers agree that the dyslexic population is heterogeneous and dyslexic readers may have various manifestations of reading difficulties (Ho et al.,

2004). Although dyslexia has been linked with phonological processing, rapid naming, orthographic processing, and occasionally visual processing deficits (e.g., Ho et al., 2004; Jeffries & Everatt, 2004), it seems that the primary cause of Chinese and English dyslexia is different and may be contingent on the specific linguistic characteristics of the writing systems (Soik et al., 2004). As for English dyslexia, the main difficulty of English dyslexic readers lies in phonological processing (e.g. Berninger, Abbott, Thomson, Wagner, Swanson, & Wijsman, 2006; Hulme & Snowling, 1992; Jeffries & Everatt, 2004). This finding indicates that successful reading in English requires an active involvement of verbal WM, particularly the phonological loop of verbal WM, during word processing. This notion is nicely supported by a large number of studies showing that English dyslexics' performance was significantly lower than their non-dyslexic peers in digit span tests and other measures of verbal WM (e.g., Berninger et al., 2006; Jeffries & Everatt, 2004; Swanson, Ashbaker, & Lee, 1996). In contrast to their inferior performance in the measures of verbal WM, English dyslexics did not show impaired performance in visuo-spatial WM tasks when compared to non-dyslexic peers (Jeffries & Everatt, 2004; Swanson et al., 1996).

In contrast to English dyslexia, Chinese dyslexia shows a different profile of cognitive deficits. Research has shown that it is orthographic-related difficulties, rather than phonological processing deficits, that are the major cognitive deficits underlying Chinese dyslexia (Ho et al., 2004). In addition, the Chinese reading literature also shows that it is possible that reading difficulties of Chinese dyslexic readers is dissociated with a deficit in phonological processing at least in some cases (Ho & Fong, 2005). These findings, as a whole, suggest that the active involvement of visuo-spatial

WM in Chinese word reading is important because it supports the intense visual-orthographic processing of words required for successful reading Chinese.

Echoing the above findings from behaviorally based research, neural-imaging research has provided evidence that distinctive neural areas' dysfunction is responsible Chinese and English dyslexia (Siok et al, 2004). Whereas impaired Chinese word reading was associated with a functional disruption of LMFG (Siok et al., 2004), English reading impairment was rooted in dysfunction of left temporoparietal brain regions (Hoeft, Meyler, Hernandez, Juel, Taylor-Hill, & Martindale, 2007). As for the functions of these neural areas, researchers have suggested that LMFG is responsible for coordinating and integrating information regarding Chinese words in verbal and spatial working memory (Perfetti et al., 2007). In other words, this neural area is in charge of mapping Chinese characters' orthographies to their corresponding syllables and/or semantics during word recognition. In contrast, left temporoparietal brain regions have been suggested to play a role in the phonological processing of words during English word reading (Hoeft et al., 2007). Based on the findings, researchers have proposed that rather than having a universal origin, reading impairments are different across cultures and may be closely related to the writing systems used (Soik et al., 2008).

Evidence from Priming Word Reading Studies and Developmental Studies

The potentially different involvement of visuo-spatial WM and verbal WM in word reading in Chinese versus in English can also be somewhat supported by behaviorally based studies using priming paradigms and developmental reading studies.

Reading studies using priming paradigms typically investigate word recognition by comparing the influence of different types of primes (e.g., homophones or homographs of target words) on the recognition of target words. In a priming

experiment, words serving as primes are typically first presented to participants for a short time (e.g., 50 ms) and then are quickly followed by target words. Subsequently, participants are asked to make a quick response to targets, such as naming the words, judging semantic meanings of the targets, categorizing the words in terms of their semantic relations, or judging whether or not targets are real words (i.e., lexical decision tasks). By systematically manipulating the relationship between primes and targets (e.g., sharing the same sound or similar orthography), priming studies allow researchers to identify which factor, orthography or phonology, plays a more dominant role in word recognition. Although there are still some mixed findings on the role of phonology and orthography in reading Chinese or English, the current literature, as a whole, has favored the notion that whereas English word recognition is a predominantly phonological process (Frost, 1998; Lukatela & Turvey, 1994; Rastle & Brysbaert, 2006; Van Orden, 1987), Chinese word recognition is a visually-dominant process (Zhou et al., 1999).

A comparison of existing Chinese and English reading studies with priming paradigms has demonstrated two prominent differences. First, the strong *phonologically mediated semantic priming effect* found in English priming studies (e.g., Lukatela & Turvey, 1994) was not absent in Chinese reading (e.g., Zhou et al., 1999; Zhou & Marslen-Wilson, 2000). Using phonologically mediated semantic priming task, or PMSP, English reading studies have supported the predominant role of the phonological processing in reading English words (e.g., Lukatela & Turvey, 1994). A study using PMSP tasks typically involves comparing whether and to what extent the recognition of target words is influenced by two different kinds of word primes: semantic associates of

the targets (e.g., *beach* for the target *sand*) and the homophones of those semantic associates (e.g., *beech* for the target *sand*). The rationale of this paradigm is that if semantic meanings of a word are mediated by its phonological representation, then a facilitative priming effect should be observed not only from semantic associates of the target, but also from the homophones of its semantic associates (Lukatela & Turvey, 1994; Zhou et al., 1999). Using the same PMSP task in Lukatela and Turvey's study (1994), Zhou et al. (1999) revealed that only semantic primes of a Chinese character (e.g., the prime 歌 /ge/ *song* to the target 舞 /wu/ *dance),* but not the homophones and pseudohomophones of the semantic associates (e.g., 鸽 /ge/ *pigeon* to the same target 舞), significantly facilitated the recognition of Chinese target characters. The absence of the *phonologically mediated semantic priming effect* in Chinese word reading indicates that phonology code does not mediate the initial lexical access of Chinese words as it does in English word reading.

Convergent to what was found in the studies using PMSP tasks, studies examining the time course of Chinese word recognition also show that phonological processing plays a restricted role in Chinese word reading (e.g., Zhou & Marslen-Wilson, 2000; Zhou et al., 1999). As a whole, these studies demonstrate that phonological activation tends to lag behind semantic activation during the recognition of Chinese characters (Zhou & Marslen-Wilson, 2000). When various experimental tasks and stimuli exposure lengths were used, the phonological activation only occurred at long exposures of stimuli and in tasks that required the use of phonological information (e.g., the naming and phonological judgment tasks). In contrast, strong semantic effects always occurred no matter which task or exposure length was used (Zhou et al., 1999).

It was therefore proposed that phonological activation may play a restricted role in Chinese character recognition and phonological activation is, at least under some circumstances, an optional process in the recognition of Chinese characters (Zhou et al., 1999).

To summarize, current findings from priming studies, as a whole, has suggested that whereas English word recognition is a predominantly phonological process (e.g., Frost, 1998; Lukatela & Turvey, 1994; Rastle & Brysbaert, 2006; Van Orden, 1987), Chinese word recognition seems to be a visually-dominant process (Zhou et al., 1999). In Baddeley's WM model (Baddeley, 2000; Baddeley & Hitch, 1974), it has been proposed that visuo-spatial information and phonological information has automatic access to the visuo-spatial sketchpad and phonological loop, the two domain-specific components of visuo-spatial WM and verbal WM (Baddeley, 1986; Logie, 1989). The findings on the predominant phonological processing in reading English words and more dominant visual processing in reading Chinese characters provides additional evidence for a potentially different involvement of visuo-spatial and verbal WM in reading these two scripts.

Convergent with what priming studies have shown, comparative studies on reading development provided evidence for a closer relationship between visual skills and Chinese word recognition compared to English word reading. For instance, Huang and Hanley's (1995) study showed that whereas significant correlations were found between Chinese children's word recognition scores and their performance in a test of visual skills ($r = .70$, $p < .001$), the correlations between word reading and the same test of visual skills were not significant in corresponding native English children participants

(r = .20). In addition, regression analysis revealed that whereas phonological awareness were the most powerful predictor of English word reading, visual skills were the best predictor of Chinese word reading. Using Chinese-English bilingual children as the participants, McBride-Chang and Suk-Han Ho (2005) found similar results. In their study, it was shown that the orthographic knowledge of Chinese-English bilingual children significantly accounted for unique variance only in their Chinese reading, but not in their English reading.

To summarize, current literature from different research areas has suggested a potentially different involvement of visuo-spatial WM and verbal WM between reading Chinese and English. To examine the plausibility of the theoretical assumption, two experiments were designed in the current study to empirically test the assumption.

CHAPTER 3
OBJECTIVE AND OVERVIEW OF THE STUDY

The objective of this study was to empirically test the theoretical assumption that word reading in Chinese and English may involve a varying degree of visuo-spatial WM and verbal WM due to the linguistic differences between the two writing systems (Wang, Linderholm, & Fang, under review). In the study, I conducted two experiments that recruited native Chinese participants (Experiment 1) and native English participants (Experiment 2) to test the three hypotheses. The first and primary hypothesis being tested was that because of the linguistic features of the scripts, reading logographic Chinese may, to a greater degree, involve visuo-spatial WM in word processing, whereas reading alphabetic English may demand more involvement of verbal WM. The rationale for the hypothesis has been provided in the previous chapter in detail. In addition to this primary hypothesis, the study also tested whether *reading skills* and *word frequency* have any effect on the relative use of visuo-spatial WM and verbal WM in reading Chinese or reading English as two secondary hypotheses.

Reading research has shown that *reading skills* may affect adult readers' word reading (e.g., Dixon, LeFevre, & Twilley, 1988; Ruthruff et al., 2008). In such studies, adult participants were often grouped into more-skilled readers versus less-skilled readers and the performance of the two groups in various word reading tasks was then compared. As a whole, these studies have suggested that reading skills contribute to individual differences in several aspects of word reading (Ruthruff et al., 2008). For example, it has been found that more-skilled readers recognized words with a faster speed and better accuracy compared with less-skilled readers (e.g., Dixon et al., 1988; Ruthruff et al., 2008). Ruthruff et al. (2008) reported the evidence that word reading of

less-skilled readers took more WM resources than that of skilled readers. In Ruthruff et al (2008), participants were grouped into skilled and less-skilled groups based on their performance in Nelson-Denny Reading Comprehension Test, a reading comprehension test for adults, and then were asked to complete a lexical decision task with either concurrent verbal noise or visual noise. It was found that the performance of less-skilled readers in the lexical decision task was significantly more influenced by the concurrent verbal or visual noise that that of skilled readers. According to Ruthruff et al (2008), the significantly lower performance of less-skilled readers was because less-skilled readers had less automatic word reading and thus had to use more WM resources in the lexical decision task than skilled readers. Considering that the current literature has shown that reading skills contribute to individual differences in several aspects of word reading, such as word reading speed, accuracy, and automaticity (e.g., Dixon et al., 1988; Ruthruff et al., 2008), it seems reasonable to hypothesize that reading skills may also effect the relative reliance of visuo-spatial WM and verbal WM among Chinese or English readers. For this reason, I tested whether there is an interaction between reading skills and the use of the two subsystems of WM in reading Chinese and English as a secondary hypothesis in this study.

In addition to reading skills, *word frequency* was also found to have a robust influence on Chinese and English readers' performance in word reading tasks (e.g., Lien et al., 2008; Liu & Perfetti, 2003). For example, behavioral studies have shown that word recognition for high frequency (HF) words is faster and/or better than that for low frequency (LF) words (Yan, Tian, Bai, & Rayner, 2006). Neural-imaging research also has reported that different neural areas were associated with reading HF and LF words,

suggesting the use of possibly different word processing (Liu & Perfetti, 2003). Liu and Perfetti (2003) reported that reading LF Chinese and English words showed a longer activation in visual areas than reading HF words in the two scripts. And reading LF English words showed additional activation in the right occipital area (right BA 18), whereas reading HF English words showed the activation in the left occipital only (left BA 17).

The above neural differences in reading LF and HF words seems to be quite understandable if one considers them in light of the linguistic differences between LF and HF words in both scripts. Compared with HF English words, LF English words typically consist of more letters and thus are visually more complex. For this reason, it is possible that reading LF English words might take more visuo-spatial WM resources during word processing than HF words. A potentially different involvement of visuo-spatial WM in reading LF versus HF Chinese words, however, may be caused for a totally different reason. LF Chinese words are not necessarily more complex in visual forms than HF words. However, the pronunciations of LF Chinese words are less accessible than those of HF Chinese words. This is because most Chinese words have arbitrarily assigned pronunciations. To know the exact pronunciations of many words, Chinese speakers have to learn the arbitrary associations between the pronunciations and words through rote memory. If a word has a low frequency of occurrence in Chinese script, it often means that the sound-word association is used less than HF words and the sound is therefore less accessible during word recognition. As a result, reading LF Chinese words might have to primarily resort to a visual analysis of words and thus requires a more involvement of visuo-spatial WM in word processing. For HF

Chinese words, however, the sound can be quickly activated in the first stage of word recognition because of the over-learned practices (Tan & Perfetti, 1998). The fast phonological activation in reading HF Chinese words might require the active involvement of both visuo-spatial and verbal WM in word processing.

Taken together, based on the current empirical findings and a linguistic analysis of HF and LF words in the two scripts, it seems reasonable to predict that there might be an interaction between word frequency and the involvement of visuo-spatial and verbal WM in reading Chinese and reading English. Accordingly, I tested this hypothesis in the current study as another secondary hypothesis.

In this study, I adopted a dual-task paradigm in order to design the experimental task. Specifically, the experimental task consists of a word reading task and a concurrent WM task, either a visuo-spatial WM task or a verbal WM task, which serves as an interfering task (Figure 3-1). The primary logic behind using the dual task is to examine to what extent word reading in Chinese and English is interfered with by the concurrent visuo-spatial and verbal WM tasks. Since Chinese word reading is a visually-dominant process in which the phonological processing only plays a secondary role (Zhou et al., 1999), it is predicted that word reading in Chinese would be interfered with by the concurrent visuo-spatial WM task more than the concurrent verbal WM task. An opposite pattern may be seen for word reading in English. That is, English word reading may be interfered with by the concurrent verbal WM to a greater level than the concurrent visuo-spatial WM task.

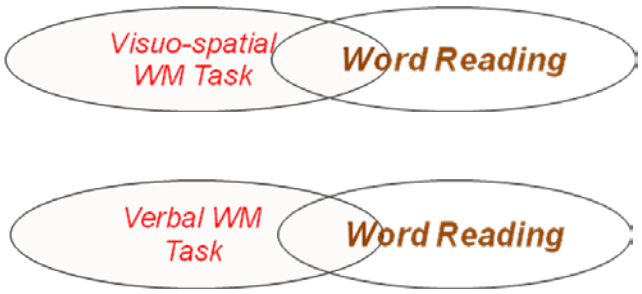

Figure 3-1.The experimental design.

The dual-task paradigm was adopted in the current study for two reasons. First, for skilled reading, lower-level word reading is a considerably fast and efficient process (Frost, 1998), which may not take much WM resources under normal reading circumstances. Accordingly, it is difficult to empirically detect the relative involvement of different subsystems of WM (e.g., visuo-spatial WM or verbal WM) in this basic-level reading process in normal reading conditions. By letting participants complete a concurrent WM task (i.e., a visuo-spatial WM task in Condition 1 and verbal WM task in Condition 2) while they are completing the word reading task, the experimental task would significantly increase the workload of participants' WMs during word reading. As participants' WMs approach the limitation because of the increased workload, it becomes possible to empirically detect and compare to what extent word reading of skilled adult readers makes use of the two subsystems of WM in the basic-level word reading process. Secondly, the dual-task paradigm also allows me to make a direct comparison between the relative involvement of visuo-spatial WM and verbal WM in word reading between the two experimental conditions.

The word reading task used in this study is a lexical decision task. As one of the most common word reading tasks, the lexical decision task has been widely used in numerous word reading studies. In a typical lexical decision task, a set of words and

pseudowords are serially presented to participants for a very short time (e.g., 500 mill-second for each word). The participants' task is to quickly judge whether the presented stimuli are real words or not by clicking on a given button on the keyboard of a computer. The lexical decision task that I used in the current study is a typical version of the task. The task involves the use of both Chinese words and English words. Chinese characters will be used to test word reading of Chinese participants (Experiment 1) while English words will be presented only to English participants (Experiment 2).

The word stimuli in the lexical decision task were manipulated in terms of visual complexity and familiarity. The visual complexity of word stimuli was manipulated by controlling the number of alphabetic letters in English words and the number of strokes/radicals in Chinese words. The letters of English word stimuli were controlled within the range of 5-12 letters each word. The strokes of Chinese words were controlled within the range of 8-15 each word (on average 2-4 radicals each word). The familiarly was primarily controlled by word frequency. There were both LF and HF words used in both experiments. On average, LF words have an occurrence of 30-90 /million. HF words have an occurrence of 400-700/million. The frequency of Chinese word stimuli in Experiment 1 is controlled through the Modern Chinese Frequency Dictionary (1986). The frequency of English word stimuli in Experiment 2 is controlled through British National Corpus (2007). During the experiments, each participant responded to a total of four hundreds words, among which there were 55% LF words, 15% HF words, and 30% pseudowords. These words were put into forty word sets, with ten words in each set. Among the forty sets, twenty sets are comprised of LF words and pseudowords with a ratio of 7:3 in each set (Low Frequency Set). The other twenty sets,

however, consist of both LF words and HF words, apart from pseudowords (Mixed Frequency Sets). The ratio of the three kinds of words is 4:3:3. The Low Frequency and Mix Frequency sets were presented to each participant in a randomized order and the order was different among all participants. For example, participant A may see the forty word sets in an order of mixed set, low frequency set, another mixed set whereas participant B may see the forty word sets in an order of low frequency set, mixed set, another mixed set. The presentation order of real words and pseudowords is also randomized in each word set and is different among the sets. The study used higher percentage of LF words and lower percentage of HF words as the stimuli mainly because current literature has shown that reading LF words is non-automatic for skilled adult readers and does take WM resources (Ruthruff et al., 2008), whereas it is still controversial whether reading HF words is also automatic in skilled reading.

The two WM tasks, serving as interfering tasks, make up of two experimental conditions. In condition 1, participants' word reading is accompanied with a concurrent visuo-spatial WM task. A computerized Corsi-Block task was developed to serve for this purpose in this study. In the current literature, the Corsi Block task has been widely used for measuring visuo-spatial WM (Berch, Krikorian, & Huha, 1998). The original Corsi apparatus consists of a series of nine blocks arranged irregularly on a board. When administering a Corsi task, an examiner randomly taps a sequence of blocks while participants are watching his or her moves; then, participants are asked to reproduce the sequence of blocks after a very short delay. The maximum number of blocks in the sequence that participants can correctly produce represents the visuo-spatial WM capacity of participants, that is, the absolute visuo-spatial WM span.

Considering that there is still no standard Corsi task available in the current literature, I designed a computerized version of Corsi Block task to serve as the interfering visuo-spatial WM task. Specifically, I followed the principles of designing and administrating Corsi tasks proposed by Berch et al., (1998) to develop a set of own configurations. The difficulty levels of these configurations were carefully matched in order to get equivalent sets. Specifically, the computerized Corsi Block task that I used in the study follows the following procedures. First, a board consisting of nine white small blocks is presented on a computer screen for 1/2 second. Then, five of the nine white blocks are quickly filled out with black color in a given sequence (See Figure 4). The task of participants is to maintain the sequence in which the blocks were filled out with black color in their WM while they are completing the subsequent word reading task, and then recall the sequence as soon as they finish the word reading task.

I chose to develop a computerized Corsi Block task, rather than use the traditional version with a board and 9 blocks, to serve as the interfering visuo-spatial WM task mainly for two reasons. First, it has been argued that WM tasks are particularly well-suited to computerization because such tasks allows examiners control the presentation time of each stimulus, which is crucial to WM tasks (Vock & Holling, 2008). In addition, a computerized Corsi Block task is operationally more convenient and efficient than paper-and-pencil tests and can be easily combined to the concurrent word recognition task in the experiment.

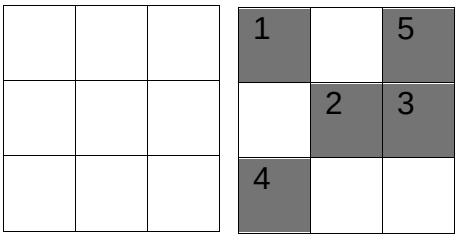

Figure 3-2. The computerized Corsi Block task used in the study. (Note: on the left is the while color matrix consisting of nine small blocks that participants see at the beginning of the Corsi Block task. On the right is what the matrix looks like after five blocks in the matrix were already filled out with black color in a given sequence. For illustrative purpose, I added the numbers in the figure to represent the order in which the blocks were filled out. These numbers, however, do not show up on the computer screen in the real study).

In the other condition of both experiments, participants' word reading is accompanied with a concurrent verbal WM task (Figure 3-1.). The verbal WM task used in the study is a revised version of digit span task. In this verbal WM task, a set of digits were serially presented on a computer screen computer. Upon seeing the digit set, participants need to quickly complete the following two procedures. 1) add number 2 to the very first and last digits of the set to get a new set of digits; 2) maintain the new digit set in WM while they are completing the subsequent word reading task, and then recall the new digit set with the original order as soon as they finish the word reading task. To give a concrete example of the mental processes involved in the revised digit span task, if this digit set, 2, 8, 3, 9, 1, 6, 5, appears on the computer screen, participants need to first add number 2 to the first digit 2 (2+2=4) and the last digit 5 (2+5 =7) in order to get the new set of digits 4, 8, 3, 9, 1, 6, 7. After the calculation is complete, participants need to maintain the new set of digits until they finish the subsequent word reading task and then recall the new digit sets on a worksheet. Different from the other versions of digit span tasks, which passively maintain the digits in short-term memory and are

generally considered as a task taping the storage component of WM only (Oberauer, Schulze, Wilhelm, & Wittmann, 2000), this new version of the digit span task taps *both* the storage component of WM with its delayed digit recall *and* the processing component of WM with the active manipulation of numeric information involved in additions.

The use of a numeric WM task as the verbal WM measure is based on the following rationale. First, a numeric WM task can provide a perfectly equivalent measure to all participants no matter which kind of language (Chinese or English) participants use. Secondly, it has been shown that WM tasks using numeric information were not functionally differentiated from WM tasks using verbal stimulus, such as in reading span or verbal span tasks. Both types of WM task were supported by verbal WM system (Oberauer et al., 2000).

Thus far, I have provided a detailed description of the dual-task design followed by a discussion of the rationale for the design and the use of each task. An important operational concern embedded in this dual-task design is the equivalence of the two interfering WM tasks in the two experimental conditions. To make sure the two WM tasks were indeed equivalent, a pilot study was conducted to test and balance the difficulty level of the two interfering WM tasks. In the first trial of the pilot study, 20 English participants and 12 Chinese participants were enrolled to complete the dual-task experimental task. Participants were asked to maintain 5 digits in the verbal WM condition and recall the visual sequence of 5 blocks in the visuo-spatial WM condition during this trial, that is, the same number of items were assigned to the two WM tasks in the original experimental task. The results showed that participants' performance in the

verbal WM task had a ceiling effect while their performance in the visuo-spatial WM task was poor. In addition, the self-reported data also revealed that most participants claimed that remembering 5 digits in the verbal WM condition was an easier task than remembering the visual sequence of 5 blocks in the visuo-spatial WM condition. With several other participants, I then tested whether the differences in participants' performance in the two WM tasks was significantly reduced when 6 items were used in each set in the verbal WM condition. This change to the verbal WM task again did not lead to equivalent conditions. Finally, I increased the number of digits to 7 items in each set in the verbal WM condition but kept 5 items in each set in the visuo-spatial WM condition. I then recruited another 25 participants in order to test the revised experimental task. 17 of the participants were enrolled from the human-participants research pool located in the School of Human Development and Organizational Studies in Education at a large southern university of U.S. The participants were all native English speakers whose ages ranged between 18-23 years. The 8 other participants were college students who were enrolled in a large northern university of China. They were all native Chinese speakers whose ages ranged between18-23 years. The results in this trial showed that participants' scores in the two WM tasks were not significantly different, t (24) = - .285, p = .776. The means in the two WM tasks were close to each other in difficulty level (M = 0.736 for the verbal WM task; M = 0.74 for the visuo-spatial WM task). The similarly between WM scores that participants showed that the difficulty level of the two WM tasks were equated. As a result of equating the two interfering WM tasks in the two experimental conditions, different numbers of items were finally used in the two interfering WM tasks in the current study. In the visuo-spatial WM condition,

there were 5 items in each set. In the verbal WM condition, there were 7 items in each set.

To summarize, in the current study, I adopted a dual-task paradigm and conducted two experiments to investigate the potentially different involvement of visuo-spatial WM and verbal WM in reading Chinese versus English. In Experiment 1, word reading of native Chinese readers was examined in two experimental conditions, one with a concurrent visuo-spatial WM task and the other with a concurrent verbal WM task. Since it has been suggested that reading Chinese words is a visually-dominant process in which phonological processing may play a secondary role (Zhou et al., 1999), I hypothesized that Chinese readers' word reading may be interfered by the concurrent visuo-spatial WM task more than the concurrent verbal WM task. As the result, native Chinese participants' word reading would show a significantly lower accuracy in the visuo-spatial WM condition than in the verbal WM condition. In Experiment 2, word reading of native English readers was examined in the same two conditions. Since the literature has suggested that reading English is a predominantly phonological process (Frost, 1998), I hypothesized that English readers' word reading may be interfered by the concurrent verbal WM task more than the concurrent visuo-spatial WM task. As the result of English word reading and the concurrent verbal WM task competing for the limited WM resources, these native English participants' word reading would show a significantly lower accuracy in the verbal WM condition compared to the visuo-spatial WM condition.

CHAPTER 4
EXPERIMENT 1

In Experiment 1, I tested how visuo-spatial WM and verbal WM are involved in Chinese word reading. In the experiment, native Chinese speakers were asked to read Chinese words under two experimental conditions. (1) Participants' word reading was accompanied with a concurrent visuo-spatial WM task (Condition 1); (2) participants' word reading was accompanied with a concurrent verbal WM task (Condition 2). Considering that it has been suggested that the recognition of Chinese words is a visually-dominant process in which the phonological processing is secondary (Zhou et al., 1999), I hypothesized that Chinese participants' word reading would take more cognitive resources from the visuo-spatial WM subsystem than the verbal WM subsystem. As a result, Chinese word reading may, to a greater level, be interfered by the concurrent visuo-spatial WM task than a concurrent verbal WM task. If that was the case, Chinese participants' word reading accuracy may be lower when it is accompanied with a concurrent interfering visuo-spatial WM task than a concurrent verbal WM task. This hypothesis was tested in Experiment 1 as the primary hypothesis.

Considering that individual differences in WM capacity may affect participants' performance in an experiment that involves WM tasks, I checked participants' verbal and visuo-spatial WM capacity through two prescreening tests in this study. Specifically, participants' verbal WM capacity was tested by a Reading Span task (Unsworth, Heitz, Schrock, J& Engle, 2005) and their visuo-spatial WM capacity was tested by a Corsi task, which is different from the one serving as the interfering visuo-spatial task in the experimental condition. Through the two prescreening tests, participants who had lower WM capacity were excluded from the study. Operationally, participants who scored

below minus one standard deviation in either the verbal or visuo-spatial WM test were considered as participants with lower WM capacity and were excluded from the study. Participants who scored above minus one standard deviation in both WM tests were recruited for Experiment 1. Participants with very low WM capacity were excluded from the experiment mainly because of the dual-task experimental design. To significantly increase participants' WM load during their word reading, I used two demanding WM tasks as the secondary interfering tasks in the two experimental conditions. In the pilot study, I have found that few participants had very lower scores in either of the two interfering WM tasks or both. This indicates that it is possible that the cognitive demands required for completing the two interfering WM tasks may be beyond the WM capacity of some participants if they have significantly lower WM span. To avoid the possible biased data from such participants, I excluded participants with very lower WM capacity through the prescreening tests.

In addition to the primary hypothesis, Experiment 1 also tested two secondary hypotheses examining whether *reading skills* and *word frequency* have an effect on the involvement of visuo-spatial and verbal WM in word reading in Chinese. In the current literature, it has been demonstrated that reading skills make a difference in participants' performance in word recognition tasks. For example, it has been found that compared with less-skilled readers, more-skilled readers were faster in word reading speed and had better accuracy in recognition (e.g., Dixon, et al., 1988). More-skilled readers also took less central attentional or WM resources in word recognition than less-skilled readers (Ruthruff, et al., 2008). Given these previously reported individual differences in word reading caused by reading skills, I hypothesize that more- and less-skilled readers

might be also different in terms of their relative reliance on visuo-spatial WM and verbal WM in word reading. This secondary hypothesis was also examined in Experiment 1. Specifically, I measured participants' reading skills with a reading comprehension measure that examined readers understanding of informational texts (Linderholm & Zhao, 2008). Based on their scores in the reading comprehension test, participants were divided into two groups: *more-skilled readers* and *less-skilled readers*. Participants scoring at the 50th percentile rank or above in the test were put into the group of more-skilled readers; participants scoring below 50th percentile in the test were put into the group of less-skilled readers. Furthermore, based on the current empirical findings on word frequency effect, I also tested whether there is an interaction between word frequency and the involvement of visuo-spatial WM and verbal WM in reading Chinese in Experiment 1.

Method

Participants

60 undergraduate students in the College of Education at a large northern university in China participated the study voluntarily. After the measurement of the two prescreening tests, 6 participants were dismissed without completing the experiment because their scores in the prescreening tests were below the criteria. The rest of 54 participants were enrolled in Experiment 1. These participants were all native Chinese speakers. During the experiment, there were 4 participants who did not follow the experimental procedures strictly and there was 1 participant who did not complete the entire experiment. These five participants were eliminated from Experiment 1. Thus, the final sample size of Experiment 1 was 49. The average age of participants was 21.0

years and the range was18-24 years. There were 55% female participants and 45% male.

Materials

The materials include a reading comprehension measure that differentiates participants' reading skills and the dual-task experimental task as described in Chapter 3. In addition, two prescreening tests that measure participants' WM capacity were also administered before the experiment. These tasks and measures are described next.

The Prescreening WM Tasks. For the prescreening purpose, a computerized Reading Span task (Unsworth et al., 2005) was administered to measure participants' verbal WM capacity. In this task, participants read several sets of unrelated Chinese sentences, one sentence at a time. These Chinese sentences were translated from the sentences in the original English version of the Reading Span task (Unsworth et al., 2005). Following each sentence in a given set, an alphabetic letter was quickly presented on the screen. Participants needed to do two things in order to complete the task. (1) Participants need to judge whether the sentences make sense; and (2) participants are required to temporarily maintain the presented alphabetic letters in their WM and then recall these letters in the original presentation order after all sentences in a given set were finished. The sentence sets have different sizes with 2-7 sentences in each set. For each participant, the order they were presented to the sentence sets were randomized. In addition, it needs to be mentioned that the alphabetic letters used in this task are from the phonetic script of Chinese, *Pinyin*, with which the pronunciations of Chinese words are represented. Since Pinyin is taught in almost all elementary schools in the mainland of China, all Chinese participants in the experiment were very familiar with it since their childhood. Even though the sounds of alphabetic letters in Pinyin script

are different from those in English script, the written forms of the letters are the same. This makes this verbal WM measure applicable to both Chinese participants and English participants in the current study. This is one of the reasons why I adopted this measure to manipulate participants' verbal WM capacity in the study. Another and more important reason that I adopted this verbal WM measure for the prescreening purpose is that the reading span task is currently the most widely used measure in reading research and its validity and reliability have been well established in the literature.

In addition to the Reading Span task, a computerized Corsi task was also administered in the prescreening to measure participants' visuo-spatial WM capacity. This prescreening Corsi task has a fundamental difference with the one used as the interfering task in the dual-task experimental condition. The Corsi task used in the experimental dual-task condition does not have differentiated levels of difficulty among sets. Instead, it was purposefully designed to have similar levels of difficulty in all sets to serve its function - working as an interfering task in the dual-task design. In contrast, the prescreening Corsi task is a typical WM span task, which consists of multiple stimuli sets with increasing difficulty. The essential function of such a visuo-spatial WM task is to differentiate subjects' visuo-spatial WM capacity.

In traditional Corsi task, two factors determine the difficulty level of block sequences. One is the number of blocks in each sequence; the other is the configuration of block sequences. In designing the computerized Corsi task for purposes of prescreening participants, I considered both factors to set up the block sequences on a computer. Specifically, I gradually increased the difficulty level of sets with two procedures by (1) using different numbers of blocks in various trials, from 3 to 7

blocks; and (2) systematically manipulating the configuration of block sequences among the trials with the same number of blocks. In the prescreening, the Corsi task started with easier block sequences with three blocks in each sequence; then the number of the blocks in block sequences is increasingly add to seven blocks in each sequence. For the sequences with same number of blocks, which typically are 5 sequences in each level, the first two sequences have simpler configurations and the latter three sequences have more complex configurations. In this test, participants were shown block sequences on a computer with increasing difficulty level. After each block sequence was presented on a computer screen, participants took several seconds to visually rehearse the sequence in their mind and then replicate the sequence on a work sheet by giving out the order of the blocks in the sequence showing up on the screen.

The Dual-task Experimental Task. This task requires participants to complete two different tasks simultaneously. One is a word reading task; the other is an interfering WM task (See Figure 4-1). At the beginning of the experiment, either a visuo-spatial WM task (Condition 1) or a verbal WM task (Condition 2) was presented to participants for seven seconds, in which participants need to process and maintain visuo-spatial or verbal information in their WM. Upon starting the WM task, the word reading task – a lexical decision task- was presented. In the word reading task, participants need to quickly read and judge whether presented words are real words or not. While participants were completing the word reading task, they had to keep the information from the WM task in their WM simultaneously. As soon as participants finished reading words in a given set, they were asked to recall visuo-spatial or verbal information that had been maintained (from the WM task) during word reading. For each

participant, he or she responded to a total of 40 word sets with 10 words in each set of the experiment. Among the 40 word sets, 20 sets started with the visuo-spatial WM task. The other 20 sets began with the verbal WM task. For each word set, it took 19 seconds to complete.

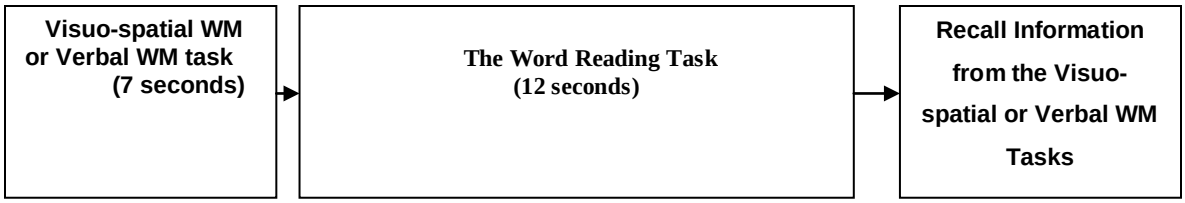

Figure 4-1. The Flowchart of the Experimental Task

The experimental task was set up in a computer with E-prime software. Participants' responses to words in the lexical decision task were automatically recorded by the E-prime software. For a real word, participants press a "Yes" button on the keyboard. For a nonsense word, participants press a "No" button on the keyboard. Apart from the yes/no responses to words, participants' reaction time to each word was also recorded by the computer. Participants' recall of visuo-spatial and verbal information in the two interfering WM tasks was written on specially designed answer sheets. They wrote down the kept information as soon as they finished reading and judging all words in a given set.

The Reading Comprehension Test. A reading comprehension test from Linderholm and Zhao (2008) was administered to measure participants' reading skills during the experiment. In the test, five expository texts and the corresponding reading comprehension tests were presented to participants in a booklet form. The difficulty level of the five texts is between 13.2 and 15.8 Flesch-Kincaid grade level, which is

appropriate for freshman to senior college students. For each text, six five-alternative multiple-choice questions were given at the end. Half of these questions are factual types of questions and the other half are inferential questions. Before the test, participants were specifically instructed that they need to do their best to get as many questions as correct in this test.

Procedures

Participants were first administered the two prescreening tests to test verbal and visuo-spatial WM capacity. After the prescreening tests, participants who had passed the prescreening tests completed the experiment in a quiet room. Participants were tested in a small group format, with three or four people at a time. The experiment started with the dual-task experimental task. Participants first had each task explained to them and then were given several trials to practice until they become familiar with the three tasks involved in the dual-task experiment. When participants indicated that they were ready for the experiment after several practice trials, the experiment started. The computerized experimental task was designed as a self-paced model. In the middle of the experiment, participants could pause the experimental program and take a short break whenever they felt they need one. This design is important because it can help participants stay concentrated during the entire experiment. Participants were made aware of this design feature and were encouraged to take several breaks in order to maintain full concentration during the entire experiment. In addition, participants were also forced to have two one-minute breaks in the middle of the experiment so that no participants could rush through the experiment. After participants finished the dual-task experimental task, they were checked whether they followed the experimental procedures and instruction strictly. Following the dual-task experiment, participants

were given the reading comprehension test. They were instructed to give their best during the test by answering as many questions correctly as they can. Before participants were dismissed, they were asked whether they had any questions and were debriefed.

Results and Discussion

Data was analyzed using two procedures by which outliers were removed. In the first data cleaning procedure, I eliminated a participant's data if his or her reaction times to over 5% of words were "fast outliers" (< 300 msec) or "slow outliers" (> 1200 msec) *and* their response to these words was less than 50% accurate. In this procedure, I followed the methods of cleaning up contaminants in reaction time data proposed by Ratcliff and Tuerlinckx (2002). According to Ratcliff and Tuerlinckx (2002), in order to identify fast outliers in a set of reaction time data acquired in a lexical decision task, a researcher can set up a tentative range (e.g., 0-150 msec) and then examine the percentage of the data that fall within the range and the accuracy of these responses. If there are over 5% responses falling within the range and the responses were at chance, the participant becomes a candidate for elimination from the experiment. Researchers then can increase the upper cutoff value to see whether accuracy begins to rise above chance. This process should be repeated several times until the increasingly larger cutoff values allow the researcher to determine an ideal cutoff value for fast outliers. Following this method, I determined 300 msec as the upper cutoff value to eliminate fast outliers. The cutoff value for eliminating slow outliers was determined at 1200 msec because that is the upper cutoff value of the time range in which participants had to complete their responses to words in the E-prime program of the experiment. Through this data cleaning procedure, nine participants were candidates for elimination from the

experiment. These participants' entire data sets were thus not included in the data analysis in Experiment 1.

The second cleaning procedure was to eliminate data in which either of the interfering WM tasks did not play its interfering role in the dual-task design. With this procedure, I eliminated data from some word sets in which a participant's recall of information in either of the two interfering WM tasks was below the criteria without eliminating any participants from the sample. To be specific, participants' performance in the interfering WM tasks was scored with the accuracy rate of recalling digits or visual-sequences of blocks. A participant was scored 1 point if he or she recalled all 7 digits in the digit-span task. The score was 0.85, 0.72, 0.57, 0.43, 0.29, 0.14, and 0 for a recall of 6, 5, 4, 3, 2, 1, and 0 digits in the digit-span task. If a participant recalled 2 digits incorrectly in a given set (i.e., the accuracy of recall in the digit-span task was below 70%), his or her data in the set was discarded. In the Corsi task, a participant was scored 1 point for a fully correct recall of visually tracking 5 blocks. The score was 0.8, 0.6, 0.4, 0.2, and 0 for a correct recall of 4, 3, 2, 1, and 0 blocks, respectively. If a participant recalled 2 blocks wrong in a given set (i.e., the accuracy of recall in the Corsi task was below 60%), his or her judgment of words in that set was then excluded from data analysis. Through the second data cleaning procedure, there were about 11% word sets excluded from the sample.

The adoption of this procedure is primarily in reference to the method used by Conway, Kane, Bunting, Hambrick, Wilhelm, and Engle (2005). According to Conway et al. (2005), to score a WM span task that has a dual-task design, one has to consider subjects' performance in both tasks due to the close relationship between the tasks.

Taking the Reading Span task introduced in the previous section as example, the Reading Span task consists of two concurrent tasks: (1) To judge whether presented sentences make sense, which aims at testing the information processing function of WM; (2) to maintain and recall alphabetic letters in a given order, which targets at testing the storage function of WM. To score such a task with the dual-task design, one has to consider subjects' performance in both processing and storage tasks. If accuracy on the processing component of a WM span task is below a certain level (e.g., 85%), although the subject may have good performance in remembering letters, the entire data set for a subject can be discarded. Despite some differences in details, the dual-task design of the experimental task in this study is, in principle, the same with the dual-task design in a WM span task. Functionally, the word reading task in the experimental task is corresponding to the processing task in a WM span task; the digit recall or the block sequence recall in the experimental task is corresponding to the storage task in a WM span task. Considering the similarities, I adopted the general procedures and method from Conway et al (2005) in Experiment 1 to further clean up data sets in which a participant's performance in the interfering WM tasks was below the criteria. The *theoretical* rationale for this second cleaning procedure is to avoid the possible *trade-off* between the word reading task and the concurrent WM tasks that were supposed to serve as interference. If a participant's recall accuracy in the interfering WM tasks was too low in a given set, it is possible that the participant may prioritize the word reading task over the interfering WM tasks by putting most of his or her effort on reading and judging words during the experiment. As a result, the WM tasks may not play its "interfering" function in such word sets as they are supposed to.

It should be noted that the criteria for deleting data associated with given word sets were set up as *two wrong items* in both WM tasks. However, since there are 7 items in the digit span task and 5 items in the Corsi task, the specific percentage serving as the cutoffs was not exactly same in the two WM tasks (the digit-span task is 70% and the Corsi task is 60%). Putting different number of items into the two WM tasks was primarily a result of matching the difficulty level of the two interfering tasks in the pilot study. As mentioned in Chapter 3, the digit span task originally had the same number of items. However, it turned out that remembering 5 digits with a given order in the verbal WM condition was a significantly easier task to complete than maintaining the visual tracking of 5 blocks in the visuo-spatial WM condition. As such, participants' scores in recalling 5 digits in the verbal WM condition showed a ceiling effect. To match the difficulty level of the two WM tasks, I then increased the number of digits from originally 5 items to 6 and then 7 items in the verbal WM condition until the statistics showed that participants 'scores in the two WM conditions did not have significant difference with 7 items in the verbal WM condition and 5 items in the visuo-spatial WM condition.

With the above two cleaning procedures, participants' data were finalized. I then conducted data analysis by first calculating descriptive statistics of 40 participants in the finalized sample. As shown in Figure 4-2, 4-3, when reading HF words, Chinese participants had a lower accuracy in the visuo-spatial WM condition than in the verbal WM condition. The same was true for reading LF words. The mean for reading LF words in the visuo-spatial WM condition was lower than in the verbal WM condition. The

means and standard errors of Chinese participants' word reading accuracy are summarized in Table 4.1.

Table 4-1: Means and standard errors of reading accuracy in Experiment 1

		More-skilled readers		Less-skilled readers	
WM condition	word frequency	Means	SE	Means	SE
Visuo-spatial WM	HF	0.9785	0.0215	0.9589	0.0411
	LF	0.9345	0.0655	0.8957	0.1043
Verbal WM	HF	0.9436	0.0564	0.9314	0.0686
	LF	0.8909	0.1091	0.8542	0.1458

I then conducted a 2 × 2 × 2 mixed analysis of variance (ANOVA) to test the following three hypotheses. (a) Chinese participants' word reading accuracy in the two WM conditions would be significantly different; (b) the difference in word reading accuracy between the two WM conditions would be more salient for less-skilled readers than more-skilled readers; and (c) the involvement of visuo-spatial and verbal WM in reading Chinese would be different in reading HF words versus LF words. The independent variables used in the ANOVA included WM Condition (verbal WM condition vs. visuo-spatial WM condition), Reading Skills (more-skilled readers vs. less-skilled readers), and Word Frequency (HF words and LF words). Both WM Condition and Word Frequency served as within-subjects variables whereas Reading Skills served as a between-subjects variable. The dependent variable was word reading accuracy (% correct). For all analyses, the criterion I used to determine significance was set to an alpha level of .05.

The results of the ANOVA demonstrated a main effect of WM Condition on word reading accuracy, which supported the first hypothesis of the experiment. A significant difference in word reading accuracy was found between the two WM conditions, F (1, 37) = 34.713, p <.001. Compared with the verbal WM task (M = 0.9395, SE = .0605),

the concurrent visuo-spatial WM task brought significantly more interference to participants' word reading, which resulted in a lower accuracy in this condition (*M* = 0.9056, *SE* = .0944). No other effects of WM Condition were found, *F*s < 1.

As for Reading Skills, the results of ANOVA rejected the second hypothesis. There was no a main effect of reading skills or interactions between WM condition and Reading Skill, *F*s < 1. Specifically, participants' reading skills did not have an effect on their performance under the two WM conditions, F (1, 37) =2.205, p =.146. This means that skilled-readers and less-skilled readers, to the same extent, showed a disadvantage in word reading when it was accompanied with a concurrent visuo-spatial WM task compared with the concurrent verbal WM task.

There was a main effect of Word Frequency. Participants' accuracy for reading HF and LF Chinese words had a significant difference, F (1, 37) = 63.225, p <.001. Compared with reading LF words (*M* = 0.8948, *SE* = .1052), participants' accuracy for reading HF words was significantly better (*M* = 0.9504, *SE* = .0496). This result is not surprising and expected considering the big difference in the range of frequency set up for HF words (400-700/million) and LF words (30-90/million) in the experiment. However, the results of Experiment 1 showed that there was no an interaction between word frequency and WM condition, F < 1, which resulted in the rejection of the third hypothesis of Experiment 1.

To summarize, the findings of Experiment 1 demonstrated that Chinese participants showed significantly lower accuracy in word reading when it was accompanied with a concurrent visuo-spatial WM task than a verbal WM task. The significant difference between the two WM conditions was the case for reading both HF

and LF words. Reading skills and word frequency did not have an effect on the relative involvement of visuo-spatial WM and verbal WM in Chinese word reading. Based on these results, it seems that a concurrent visuo-spatial WM task to a greater level interfered word reading in Chinese than a concurrent verbal WM task. The reduced accuracy in the visuo-spatial WM condition in Experiment 1 is presumably because reading logographic Chinese takes more visuo-spatial WM resources, which makes it have to compete for limited cognitive recourses with the concurrent visuo-spatial WM task in the same subsystem of WM. In contrast, the higher accuracy in the verbal WM condition is probably because the two concurrent tasks, the wording reading task and the digit-span task, may be primarily processed in the two different subsystems of WM and thus have less competition for cognitive resources.

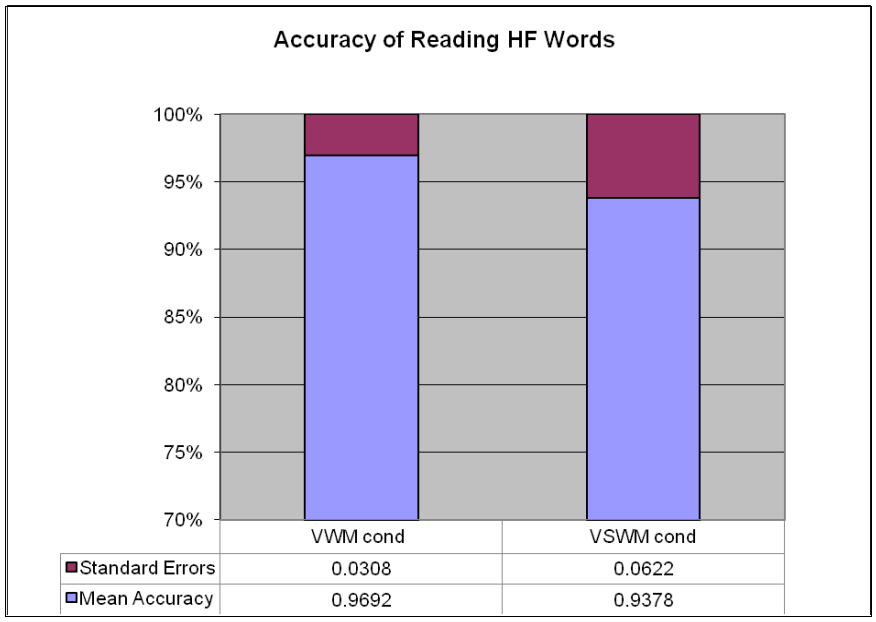

Figure 4-2. Mean accuracy rates and standard errors for reading HF words in the two WM conditions (Experiment 1)

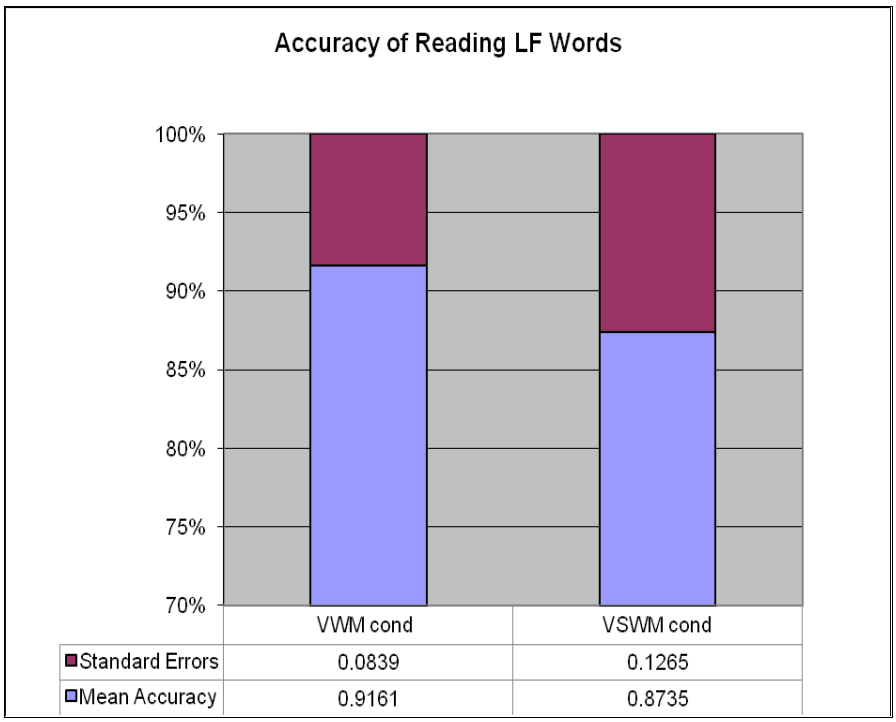

Figure 4-3. Mean accuracy rates and standard errors for reading LF words in the two WM conditions (Experiment 1)

CHAPTER 5
EXPERIMENT 2

In Experiment 2, I tested how visuo-spatial WM and verbal WM are involved in English word reading with the same experimental design. A group of native English speakers were asked to read English words under two experimental conditions. Participants' word reading was accompanied with a concurrent visuo-spatial WM task (Condition 1) and participants' word reading was accompanied with a concurrent verbal WM task (Condition 2). Considering that current literature has suggested that word recognition in English is a phonologically predominant process (Frost, 1998), which inherently requires the intense involvement of verbal WM in word processing, I hypothesized that English participants' word reading may compete for limited WM resources more with a concurrent verbal WM task than a concurrent visuo-spatial WM task. Accordingly, native English speakers may show a lower word reading accuracy in the verbal WM condition than in the visuo-spatial WM condition.

With two prescreening tests, I checked English participants' visuo-spatial and verbal WM capacity before the experiment. Specifically, participants' verbal WM capacity was measured by the English version of the Reading Span Task used in the prescreening of Experiment 1. Participants' visuo-spatial WM capacity was measured with the Corsi task used in the prescreening of Experiment 1. Participants who scored below one minus one standard deviation in either of the two measures were considered as low WM capacity participants who were not included in the participant pool of Experiment 2. Participants who scored above minus one standard deviation in both WM tests were recruited for Experiment 2.

In order to measure participants' reading skills, the English version of the same Reading Comprehension test used in Experiment 1 was used to test reading skills of all participants. Based on their scores in this test, participants were divided into more- and less-skilled readers with the same grouping method and criteria as used in Experiment 1. A secondary hypothesis that I tested in Experiment 2 is whether reading skills have an effect on the involvement of visuo-spatial WM or verbal WM in English word reading. In addition, based on the current empirical findings on word frequency effect, I also tested whether there is an interaction between word frequency and the involvement of visuo-spatial WM and verbal WM in reading English in Experiment 2.

Method

Participants

57 undergraduates from the human-participants research pool in the School of Human Development and Organizational Studies in Education at a large southern university of the United States participated the study to fulfill part of their course requirements. After the measurement of the two prescreening tests, 6 participants were dismissed without completing the experiment because their scores in the prescreening tests were below the criteria. The remaining 51 participants were enrolled in Experiment 2. These participants were all native English speakers. During the experiment, there were 3 participants who did not follow the experimental procedures strictly and there were 2 participants who did not complete the entire experiment. These participants were eliminated from Experiment 2. Thus, the final sample size of Experiment 1 was 46. The average age of participants was 20.2 years and the range was 18-26 years. The sample consisted of 66% female and 34% male participants.

Materials

The materials included the English version of the Reading Comprehension measure that group participants in terms of reading skills, the English version of the dual-task experimental task, and two prescreening WM measures to control participants' WM capacity. These measures and tasks are described as follows.

The Prescreening WM Tasks. For the prescreening purpose, I used the same two WM tasks to measure English participants' WM capacity. Specifically, I used the computerized Corsi task to measure participants' visuo-spatial WM capacity. The task measuring participants' verbal WM capacity was the English version of the Reading Span Task used in Experiment 1.

The Experimental Task*.* The dual-task experimental task used in Experiment 2 was the same as Experiment 1. The only difference between the two experiments is that English words were used as the stimuli in Experiment 2. In the experiment, each participant responded a total of 400 English words that were arranged in 40 sets. Among the 40 sets, 20 sets started with the visuo-spatial WM task. The other 20 sets started with the verbal WM task. The digit sets and block sequences used in the two interfering WM tasks were the exactly same with Experiment 1.

The Reading Comprehension Test. The English version of the Reading Comprehension Test used in Experiment 1 was used to differentiate English participants' reading skills in Experiment 2.

Procedures

Participants were first administered the two prescreening tests to test verbal and visuo-spatial WM capacity. After the prescreening tests, participants who had passed the prescreening tests completed the experiment in a quiet room. Participants were

tested in a small group format, with three or four people at a time. The experiment started with the dual-task experimental task. Participants first had each task explained to them and then were given several trials to practice until they become familiar with the three tasks involved in the dual-task experiment. When participants indicated that they were ready for the experiment after several practice trials, the experiment started. The computerized experimental task was designed as a self-paced model. In the middle of the experiment, participants could pause the experimental program and take a short break whenever they felt they need one. This design is important because it can help participants stay concentrated during the entire experiment. Participants were made aware of this design feature and were encouraged to take several breaks in order to maintain full concentration during the entire experiment. In addition, participants were also forced to have two one-minute breaks in the middle of the experiment so that no participants could rush through the experiment. After participants finished the dual-task experimental task, they were checked whether they followed the experimental procedures and instruction strictly. Following the dual-task experiment, participants were given the reading comprehension test. They were instructed to give their best during the test by answering as many questions correctly as they can. Before participants were dismissed, they were asked whether they had any questions and were debriefed.

Results and Discussion

In Experiment 2, I used the same procedures to clean up outliers as the first step of data analysis. First of all, I eliminated participants' data when their reaction time to 5% of the words were considered fast outliers (< 300 msec) or slow outliers (>1200 msec) and the accuracy of their responses to these words was less than 50%. The

methods of cleaning up contaminants from the reaction time data set were from Ratcliff and Tuerlinckx (2002). With the first data cleaning procedure, eight participants were qualified candidates for elimination from the experiment. The data sets from these participants were not included in the data analysis of Experiment 2. In the second data cleaning procedure, I eliminated the data from a single word set in which a participant's recall of information in either of the interfering WM tasks was below the criteria. Through the second data cleaning procedure, there were about 18 % words sets excluded from the sample. It needs to be mentioned that during the second cleaning procedure, three English participants were found to recall only 20% -25% of the 20 verbal WM sets, even though they had good performance in the visuo-spatial WM sets. Considering the significantly less word sets that these participants had in the verbal WM condition after the cleaning procedure, the data of these three participants were excluded from data analysis.

After cleaning up data, I calculated the descriptive statistics by getting the means and standard errors for reading HF and LF words in the two WM conditions. As demonstrated in Figure 5-1, 5-2, for reading HF words, English participants showed a lower accuracy in the verbal WM condition than in the visuo-spatial WM condition. For reading LF words, English participants had a slightly lower accuracy in the visuo-spatial WM condition than in the verbal WM condition. The means and standard errors of Chinese participants' word reading accuracy were summarized in Table 5.1.

Table 5-1: Means and standard errors of reading accuracy in Experiment 2

		More-skilled readers		Less-skilled readers	
WM condition	word frequency	Means	SE	Means	SE
Visuo-spatial WM	HF	0.9729	0.0271	0.9274	0.0726
	LF	0.9139	0.0681	0.8828	0.1172
Verbal WM	HF	0.9926	0.0074	0.9752	0.0248
	LF	0.9004	0.0996	0.8874	0.1126

I then conducted a 2 × 2 × 2 mixed analysis of variance (ANOVA) to test the following three hypotheses. (a) English participants' word reading accuracy in the two WM conditions would be significantly different; (b) the difference in word reading accuracy between the two WM conditions would be more salient for less-skilled readers than more-skilled readers because of their relatively less efficient reading skills; and (c) the involvement of visuo-spatial and verbal WM in English word reading would be different for HF words versus LF words. The independent variables of the ANOVA were WM Condition (verbal WM condition vs. visuo-spatial WM condition), Reading Skills (more-skilled readers vs. less-skilled readers), and Word Frequency (HF words and LF words). Both WM Condition and Word Frequency served as within-subjects variables whereas Reading Skills served as a between-subjects variable. The dependent variable was word reading accuracy, which was calculated by percentage. The criterion for all analyses was again set at an alpha level of .05.

The results of the ANOVA showed that there was a main effect of WM Condition on word reading accuracy, F (1, 32) = 9.101, p <.05. Compared with the visuo-spatial WM task (M = 0.9384, SE = .0616), the concurrent verbal WM task brought significantly more interference to participants' word reading, which resulted in a lower accuracy in this condition (M = 0.9231, SE = .0769). This result supports the first hypothesis that

English participants' word reading accuracy would be significantly different between the two WM conditions.

As for Reading Skills, the results of the ANOVA rejected the second hypothesis again. There was not a main effect or interaction with Reading Skill, *F*s < 1. In other words, reading skills did not differentiate participants' performance under the two WM conditions. Skilled-readers were not any different from less-skilled readers in terms of their relative reliance on the visuo-spatial WM and verbal WM in word reading.

As Experiment 1, Experiment 2 also found a main effect of Word Frequency on word reading accuracy, F (1, 32) = 118.884, p <.001. Compared with reading LF words (M = 0.8954, SE = .1046), participants' accuracy for reading HF words was significantly better (M = 0.9661, SE = .0339). This result is not surprising and was expected considering the big difference in the range of frequency set up for HF words (400-700/million) and LF words (30-90/million) in the experiment. Different from Experiment 1, however, the results of Experiment 2 showed that there was an interaction between WM Condition and Word Frequency, F (1, 32) =12.321, p <.05.

Since the ANOVA showed an interaction between WM Conditions and Word Frequency in Experiment 2, I conducted a series of dependent sample t-tests to further locate the source of the interaction. I summarized the means and standard errors involved in the t-tests in Table 5-2.

Table 5-2: Means and standard errors of reading accuracy in the two WM conditions

	HF words		LF words	
	Means	SE	Means	SE
Visuo-spatial WM	0.9834	0.0166	0.8934	0.1066
Verbal WM	0.9488	0.0512	0.8974	0.1026

The result of the t-tests showed that there was a significant difference in participants' accuracy of reading HF words between the two WM conditions, t (33) = 3.744, $p < .05$. The significantly lower accuracy in the verbal WM condition indicates English participants' word reading was interfered with by the concurrent verbal WM task more than by the visuo-spatial WM task when they read HF words. This is probably because English word reading involves intense phonological processing (Frost, 1998), which competed for verbal WM resources with the concurrent verbal WM task. In comparison, participants may resort to the two different subsystems of WM, the visuo-spatial WM and the verbal WM, to conduct the concurrent word reading and the Corsi task respectively, which cause them have a better performance in the word reading task.

Different from the case of reading HF English words, the second t-test showed lack of significance in accuracy for reading LF English words between the two WM conditions, t (33) = - 0.673, p = .506. It seems that English participants did not rely on either of the two WM subsystems more than the other when they read LF English words. The lack of significance found in the second t-test may be explained by some possibilities. For instance, it may be possible that English participants in the experiment may consciously use a visual-analysis of words to respond the compound LF words in the lexical decision task. As one often finds, many LF English words are compound words consisting of few morphemes. For such English words, it is theoretically possible that readers can decode words through a purely visual analysis in a lexical decision task, in which participants only need to judge whether the presented strings of letters are real or not. Although I manipulated the visual complexity of words by strictly controlling the

number of the constituent letters in words, it is very difficult to completely exclude compound words from the LF word lists. For such words, it is possible that some participants consciously use cognitive strategy (e.g., a visual analysis of words' authenticity) during the experiment.

In Experiment 2, I also conducted t-tests that respectively compared the means of reading HF and LF words in the verbal WM conditions and in the visuo-spatial WM condition. Both t-tests reported significant differences, t (32) = 6.311, p < .001 (verbal WM condition), t (32) = 10.076, p < 001 (visuo-spatial WM condition). The significant difference between reading HF and LF words in the same WM condition was expected considering reading HF words is an easier task to complete than reading LF words when word reading was accompanied with an interfering task. The better familiarity of participants toward HF words makes them process the words more quickly and may use less WM resources. As such, the two concurrent tasks had relatively less interference with each other during the experiment.

To summarize, the findings of Experiment 2 demonstrated that English participants showed a significant difference in word reading accuracy between the two WM conditions. There was an interaction between WM Condition and Word Frequency. In the case of reading HF words, it was found that English participants had significantly lower accuracy in word reading in the verbal WM condition than in the visuo-spatial WM condition. In the case of reading LF words, no significance was found between the two WM conditions. Similar to Experiment 1, the results of Experiment 2 also showed that reading skills did not have an effect on the relative involvement of visuo-spatial WM and verbal WM in English word reading. The results of Experiment 2 demonstrated that a

concurrent verbal WM task brought significantly more interference to English word reading than a concurrent visuo-spatial WM task, at least this was the case for reading HF words, which suggests more reliance on verbal WM in word processing.

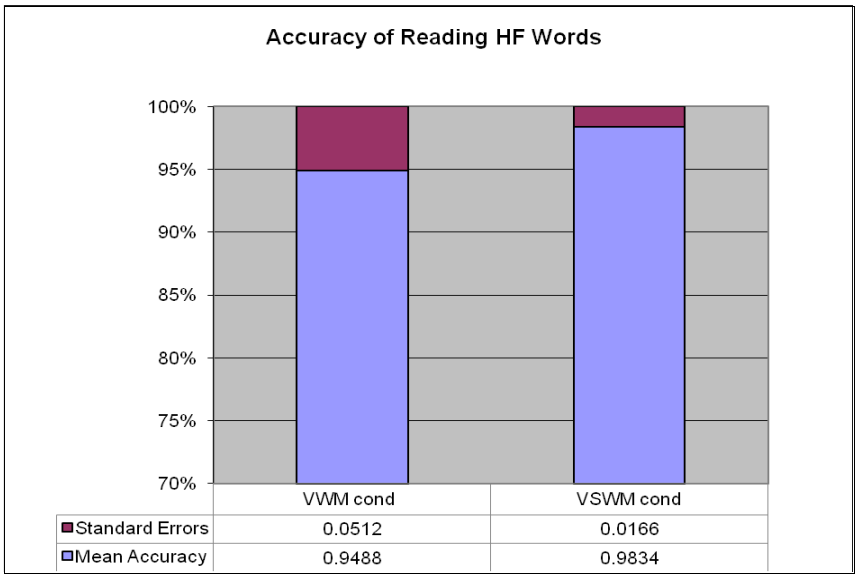

Figure 5-1. Mean accuracy rates and standard errors for reading HF words in the two WM conditions (Experiment 2)

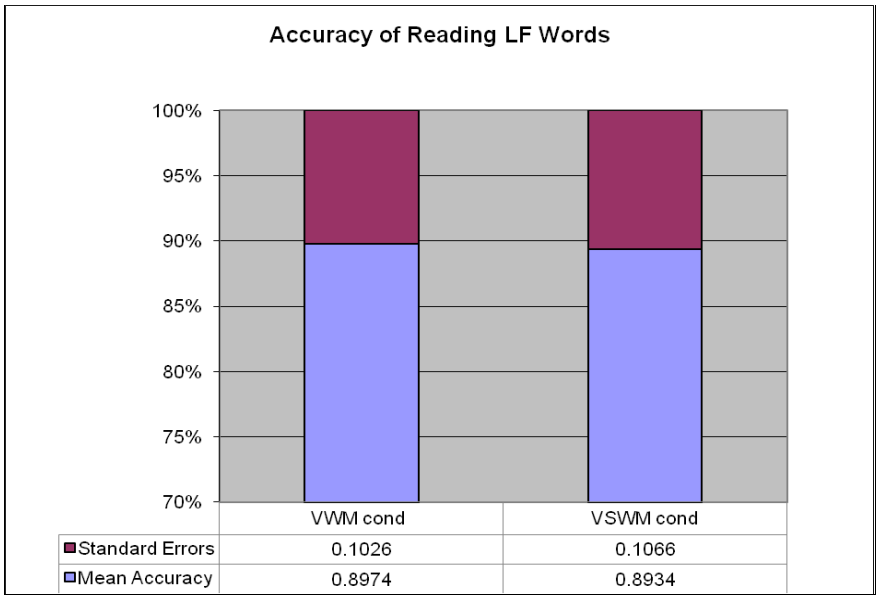

Figure 5-2. Mean accuracy rates and standard errors for reading LF words in the two WM conditions (Experiment 2)

CHAPTER 6
GENERAL DISCUSSION AND CONCLUSIONS

In the reading research field, how WM contributes to individual differences in reading processes has been an important issue for investigation. However, most of the existing studies with regard to this issue were concerned with how WM capacity (e.g., low versus high WM capacity readers) accounts for individual differences in reading processes. As one of the first few studies, the current study explored whether the involvement of the different subsystems of WM (e.g., visuo-spatial and verbal WM) is also a source of individual differences in lower-level reading processes when different scripts are involved. In the study, I examined and compared the use of visuo-spatial and verbal WM in reading two significantly different scripts: logographic Chinese and alphabetic English. Specifically, two experiments were conducted to test the plausibility of the proposal that corresponding to the linguistic features of the two scripts, reading logographic Chinese may, to a greater level, involves visuo-spatial WM, whereas reading English may involve verbal WM more in word processing (Wang, Linderholm, & Fang, under review).

With native Chinese speakers as participants, Experiment 1 examined the involvement of visuo-spatial WM and verbal WM in reading logographic Chinese words. Three major findings were reported in Experiment 1. (1) Chinese participants showed lower accuracy in word reading when it was accompanied with a concurrent visuo-spatial WM task compared with a concurrent verbal WM task; (2) the lower word reading accuracy in the visuo-spatial WM condition applied to reading both HF and LF words; and (3) reading skills did not have an effect on the relative reliance of visuo-spatial WM and verbal WM in word reading in Chinese; both skilled readers and less-

skilled Chinese readers showed a significantly lower word reading accuracy in the visuo-spatial WM condition relative to the verbal WM condition. The lower accuracy in the visuo-spatial WM condition found in Experiment 1 indicates that the concurrent visuo-spatial WM task brought significantly more interference to Chinese word reading than the concurrent verbal WM tasks, suggesting that word reading in Chinese takes more visuo-spatial WM resources than the verbal WM resources. The finding is in line with the previous findings from priming studies that reading Chinese involves dominant visuo-orthographic processing of characters and words, whereas the phonological processing of words may be secondary (e.g., Zhou et al., 1999). The finding is also corresponding to the previous analysis on the linguistic features of the Chinese writing system. The two-dimensional layout of Chinese characters requires a visuo-spatial analysis of constituent radicals or strokes of characters during word recognition, which inherently requires the use of visuo-spatial WM. In contrast, the one-to-many association between a spoken sound and several written characters, along with the arbitrary arrangements between written characters and their pronunciations makes the phonological information of words relatively less useful during word recognition, which results in a less involvement of verbal WM.

With native English speakers as participants, Experiment 2 examined the involvement of visuo-spatial WM and verbal WM in English word reading. The major findings of Experiment 2 are as follows. First of all, English participants showed significantly lower accuracy in word reading when it was accompanied with a concurrent verbal WM task than a concurrent visuo-spatial WM task. The significantly lower word reading accuracy in the verbal WM condition indicates that the concurrent verbal WM

task brought significantly more interference to English word reading than the concurrent visuo-spatial WM task, which suggests that word reading in English takes relatively more verbal WM resources than the visuo-spatial WM resources. This finding is in line with the previous findings from priming studies that word reading in English is a phonologically predominant process (Frost, 1998). Considering that existing studies using priming paradigms have been showing mixed results in the phonological priming effects on the recognition of English words across studies, the results of Experiment 2 can be considered as indirect support for the stronger role of the phonological processing in the recognition of English words relative to the visuo-orthographic processing. Secondly, the results of Experiment 2 demonstrated that reading HF and LF English words showed a different pattern in the involvement of verbal and visuo-spatial WM in word processing. In the case of reading HF English words, participants showed significantly different accuracy in word reading between the two WM conditions. In the case of reading LF English words, however, no significance was found between the two WM conditions. These results were different from what was found in Experiment 1, where significance between the two WM conditions was found for reading both HF words and LF words. Finally, as for reading skills, it was found that reading skills did not effect the relative reliance of visuo-spatial WM and verbal WM in English word reading as the case in Chinese word reading.

With regard to the lack of significance found in reading LF English words between the two WM conditions, there are some possibilities that may account for the results. For example, it may be possible that reading LF English words may indeed make use of relatively more visuo-spatial WM resources compared with reading HF

English words. With the increased demands for visuo-spatial WM resources, reading LF English words may not show more reliance on verbal WM subsystem as is the case in reading HF words. The potentially increased demands for visuo-spatial WM resources for reading LF English words could come from two different sources. On one hand, LF English words are typically comprised of more letters than HF words, which makes them visually more complex. On the other hand, LF English words are often words that are comprised of morphemes. For example, the word *unbreakable* has three morphemes: "un-", "break", and "-able". It might be possible that when judging such words in the lexical decision task in Experiment 2, some English participants made their judgments on the authenticity of the words primarily through a visual analysis of the constituent morphemes. If that was the case, it is possible that reading LF English took more visuo-spatial WM resources for at least such participants during the experiment.

Admittedly, even though I manipulated the visual complexity of English word stimuli by strictly controlling the number of constituent letters, I did not completely rule out LF words with multiple morphemes from the stimuli pool because such words make up high percentage of LF English words. To be specific, there were about 20% LF English words in the study that consists of 3 or above morphemes. No matter what the resources for a potential increase in the use of visuo-spatial WM resources in reading LF English words are, current neural-imaging findings (Liu & Perfetti, 2003) seem to provide some support for the plausibility of this proposal. For example, Liu & Perfetti (2003) found that neural activation in reading HF and LF English words showed a different pattern in terms of the activated brain areas and the time course of activations. Whereas reading HF English words produced only left occipital activation, reading LF

English activated additional right occipital areas. And compared with reading HF English words, reading LF English words showed a later and longer activation in visual areas of the brain. Although the participants of this study were Chinese/English bilingual readers, not native English speakers, the findings are inspiring when one considers the findings in light of the linguistic differences between HF and LF English words. Typically, LF English words consist of more alphabetic letters and have longer word length than HF English words, which makes them visually more complex. Accordingly, it seems to make sense that reading LF English words may take relatively more visual processing, which may cause the insignificant result between the two WM conditions.

When comparing the findings of Experiment 1 versus Experiment 2, one would find that what was prominent in this study was that the involvement of visuo-spatial WM and verbal WM in reading these two scripts showed an opposite pattern when the word stimuli were HF words. Whereas Chinese participants showed a significantly lower accuracy in reading Chinese in the visuo-spatial WM condition, English participants showed a significantly lower accuracy in the verbal WM condition. This different pattern in the involvement of visuo-spatial WM and verbal WM in reading the two scripts suggests that reading Chinese and English to a differential degree makes use of the two subsystems of WM at least in the case for reading HF words. This finding nicely echoes the findings from previous brain-imaging research. In the previous research, it has been demonstrated that reading Chinese was associated with the activation of several distinctive brain areas, including LMFG and the brain areas routinely activated in visuo-spatial WM tasks (Pefertti et al., 2007; Tan et al., 2001) and reading English showed stronger activation in certain common brain areas presumably responsible for the

phonological processing of both English and Chinese words (Tan et al., 2005). Although researchers have proposed that the distinctive areas in the neural networks of reading Chinese and English suggest potentially different cognitive processing in reading Chinese versus English (e.g., addressed phonology vs. assembled phonology, Tan et al., 2005), brain-imaging research has not have proven conclusions on exactly what are the specific differences in the cognitive mechanisms underlying reading these two scripts. Filling in the gap, the findings of the current study provide direct evidence that one of the cognitive differences in reading the two scripts lies with the differential involvement of visuo-spatial WM and verbal WM in word processing. In this sense, the findings of the current studies are convergent to and extend the System Accommodation Hypothesis (Liu et al., 2007; Perfetti et al., 2007) by adding the specified cognitive differences in reading two different scripts. According to System Accommodation Hypothesis (Liu et al., 2007; Perfetti et al., 2007), reading in a new and different writing system requires the recruitment of neural areas that can specifically support the linguistic features of the writing system. The results of this study indicate that the superficial features of the Chinese and English writing systems not only require the “neural accommodation” in reading them, but also invite differences in cognitive mechanisms in processing the scripts. To “accommodate” the linguistic features of logographic Chinese, word reading in Chinese requires a more intense involvement of visuo-spatial WM for an elaborate visuo-orthographic processing of Chinese characters. In comparison, word reading in English requires a greater involvement of verbal WM in word processing because of its predominant phonological processing of words.

In the current study, both experiments showed that reading skills did not have an effect on the involvement of visuo-spatial and verbal WM in word reading in Chinese and in English. Considering that other studies have shown that reading skills affect some aspects of word reading of adult readers, such as word reading speed and accuracy (e.g., Dixon et al., 1988; Ruthruff et al., 2008), this finding seems “atypical”. Two interpretations may explain the lack of significance in reading skills in the current study. First, as an underlying cognitive mechanism of reading processes, the relative use of visuo-spatial WM and verbal WM may remain same and do not differentiate adult readers once adult readers’ word reading skills reach to a certain level of proficiency. Since participants of both experiments were college students who have had well-developed reading skills, it is theoretically possible that these readers’ word reading skills have reached a high level of proficiency so that reading skills do not affect their relative use of verbal and visuo-spatial WM in this lower-level reading process any more. In other words, it is possible that the differential involvement of verbal and visuo-spatial WM in reading across-scripts is primarily contingent to the linguistic features of scripts and does not cause individual differences in skilled readers. It will be important, however, for future research to be conducted to test whether reading skills have an effect on the involvement of visuo-spatial and verbal WM in reading Chinese and English words in younger readers, who have not developed efficient basic-level word reading skills and do have significant individual differences in basic-level word reading process. In addition, there might be another factor that partially influenced the results on the effect of reading skills in the current study. In the prescreening, about 10% participants were excluded from the experiments because of their low scores in the two

prescreening WM tests. This prescreening procedure was used to make sure that all participants in the experiments have enough WM capacity to complete the demanding dual-task experimental task. However, considering that reading skills have positive correlation with WM capacity (Daneman & Carpenter, 1980), it may be possible that some poor readers were thus excluded from the study because of this procedure of controlling participants' WM capacity. Although there were some participants in the actual sample of the experiments who scored low in the reading comprehension measure (less than 50% accuracy), it may be possible that relatively more skilled readers and less poor readers were included in the sample.

The findings of the study have important implications for both reading research and reading instructional practices. As far as reading research is concerned, the findings of the current study provide a foundation for a further investigation of other possible cognitive differences between reading Chinese and English at the levels of sentence and/or text comprehension. In the current literature, it has been demonstrated that visuo-spatial WM and verbal WM are responsible for maintaining different dimensions of situational models in mental representations of texts (Friedman & Miyake, 2000) and processing different types of adjunct displays during text comprehension (Robinson & Molina, 2001). Considering lower-level word reading shares cognitive resources with higher-level reading processes (Lundquist, 2004), it is theoretically possible that the difference in reading Chinese and English at the word reading level may cause further differences in these higher-level reading processes. For reading research, these new issues would be interesting topics to explore in the future. Similarly, it is also interesting to further explore whether Chinese and English children readers

show any developmental differences in the reliance on visuo-spatial WM and verbal WM in word reading at different phases in the future.

With regard to reading instructional practices, the findings of the current study provide important insights on the intervention to English dyslexia and instruction for Chinese/English bilingual readers. Typically, English dyslexics have difficulty processing phonological information in words (Jeffries & Everatt, 2004). Currently, the popular intervention methods for English dyslexia are to give dyslexics intense training on phonological processing skills to improve their word reading ability. The findings of the current study, however, suggest that it may also be possible to train English dyslexics to read English words in a Chinese style. That is, English dyslexics could primarily use visuo-spatial WM recourses to visually decode words during word reading. As far as reading instruction for Chinese/English bilingual readers, the findings of the current study indicate that reading in one's second language may involve some different cognitive mechanisms which are contingent to the linguistic characteristics of the new script (Tan et al., 2005). These differences in the underlying cognitive mechanisms have to be taken into consideration when teachers give instruction for bilingual readers so that bilingual readers can adjust their reading processes well to the new script. It is not uncommon that teachers in bilingual programs of U. S. tend to encourage native English speakers to use "read aloud" and other methods typical in English reading to read in the new writing system, logographic Chinese. For example, many teachers encourage Chinese learners of native English speakers to use Pinyin, the phonetic script of Chinese, in their reading in Chinese. Although the use of Pinyin can help these Chinese learners to make sense of the sentences and help them greatly improve spoken

Chinese, learners from such bilingual programs tend to do poorly in Chinese reading even years of learning. It is possible that successful reading in a new and different language not only requires students make corresponding adjustments in underlying cognitive processes, but also needs teachers to “teach” them how to effectively adjust their reading in the new script.

APPENDIX
SAMPLES OF EXPERIMENTAL TASKS

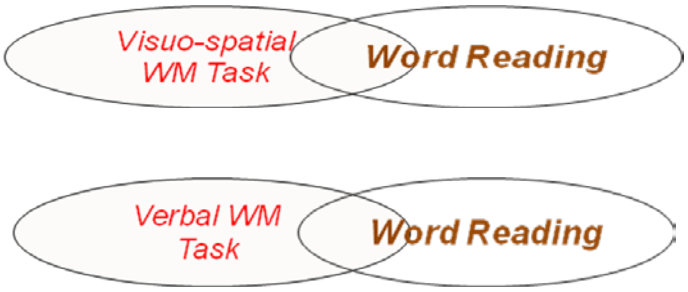

Figure A-1. Dual-task design of the experiments

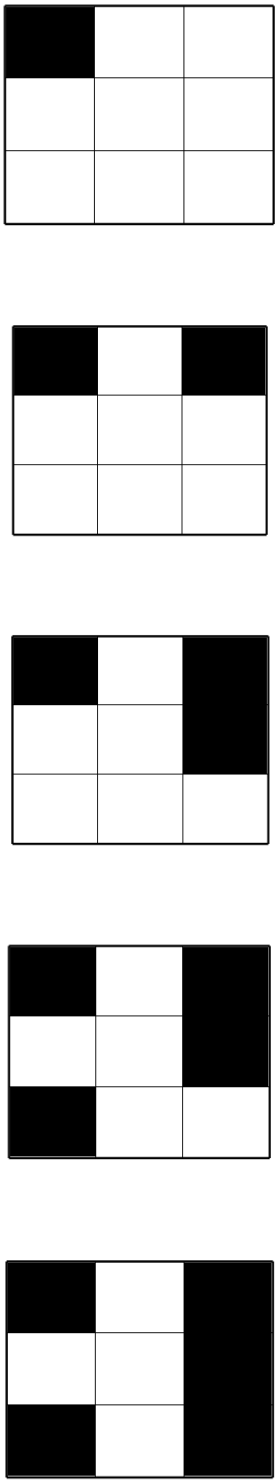

Figure A-2. Illustration of the Computerized Corsi Task (visuo-spatial WM task)

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Figure A-3. Samples of the digit span task (verbal WM task)

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