Inhibitory Stroke Neighbour Priming in Character Recognition and Reading in Chinese

Jingxin Wang¹, wjxpsy@126.com

Jing Tian¹, tjtnu@gmail.com

Wei Jin Han¹, hanweijin7665123@163.com

Simon P. Liversedge², s.p.liversedge@soton.ac.uk

Kevin B. Paterson³, kbp3@le.ac.uk

1. Academy of Psychology and Behavior, Tianjin Normal University, China
2. Centre for Visual Cognition, School of Psychology, University of Southampton, UK
3. School of Psychology, University of Leicester, Leicester, UK

Correspondence concerning this article should be addressed to:

Kevin Paterson
School of Psychology
Henry Wellcome Building
University Road
University of Leicester
LE1 9HN
Email: kbp3@le.ac.uk

Abstract

In alphabetic languages, prior exposure to a target word's orthographic neighbour influences word recognition in masked priming experiments (e.g., Segui & Grainger, 1990; Davis & Lupker, 2006) and the process of word identification that occurs during normal reading (Paterson, Liversedge, & Davis, 2009). We investigated whether similar neighbor priming effects are observed in Chinese in 4 masked priming experiments (employing a forward mask and 33ms, 50ms, and 67ms prime durations) and in an experiment that measured eye movements while reading. In these experiments, the stroke neighbor of a Chinese character was defined as any character that differed by the addition, deletion, or substitution of one or two strokes. Prime characters were either stroke neighbors or stroke non-neighbors of the target character, and each prime character had either a higher or lower frequency of occurrence in the language than its corresponding target character. Frequency effects were observed in all experiments, demonstrating that the manipulation of character frequency was successful. In addition, a robust inhibitory priming effect was observed in response times for target characters in the masked priming experiments and in eye fixation durations for target characters in the reading experiment. This stroke neighbor priming was not modulated by the relative frequency of the prime and target characters. The present findings therefore provide a novel demonstration that inhibitory neighbor priming shown previously for alphabetic languages is also observed for non-alphabetic languages, and that neighbor priming (based on stroke overlap) occurs at the level of the character in Chinese.

Keywords: Inhibitory stroke neighbours; Masked priming; Eye movements; Chinese reading

Abstract = 247 words

Main Text = 10722 words

A wealth of evidence indicates that the presentation of a word activates not only the orthographic representation of that word but also representations of orthographically similar words, such as the word's orthographic neighbours. Following Coltheart, Davelaar, Jonasson, and Besner (1977), orthographic neighbours are often defined as those words that can be formed from a target word by substituting one letter for another while preserving letter positions and word length (but for an expanded definition that includes neighbours created by the addition or deletion of letters, see, e.g., Davis & Taft, 2005).

The influence of a word's orthographic neighbours on word recognition has been studied extensively in alphabetic languages (see Andrews, 1997, for a review). In particular, studies using priming techniques have revealed that prior exposure to a word's orthographic neighbour as a prime slows recognition of that word when it is displayed as a target (e.g., blue – BLUR). Research also shows that this priming effect is modulated by the relative frequency of the prime and target words in the language. In unmasked priming, where the prime word is displayed for comparatively long durations (typically 350ms) without a mask, stronger inhibitory priming is usually observed when primes have a lower frequency of occurrence than target words (e.g., Colombo, 1986; Lupker & Colombo, 1994; Segui & Grainger, 1990). This is often explained in terms of conscious identification of the prime leading to inhibition of higher frequency lexical competitors (which will include the target word) and thereby impeding recognition of the target word.

In masked priming, in which the prime usually follows a mask and is displayed for only a relatively short duration (typically about 60-67ms; e.g., Bijeljac-Babic, Biarreau, & Grainger, 1997; Brysbaert, Lange, & Wijnendaele, 2000; Davis & Lupker, 2006; De Moor & Brysbaert, 2000; Drews & Zwitserlood, 1995; Grainger, Colé, & Segui, 1991; Grainger & Ferrand, 1994; Segui & Grainger, 1990), stronger inhibitory effects are usually observed when prime words are of higher frequency than

target words. In this case, it is argued that brief presentation of the prime activates that word's lexical representation and, because this provides a strong lexical competitor for the lower frequency target, this slows target word recognition. Inhibitory effects are not usually observed in masked priming when a non-word that differs by only one letter from the target word is presented as a prime (e.g., bontrast – CONTRAST), and in these conditions facilitation, rather than inhibition, is typically observed (e.g., Ferrand & Grainger, 1993; Forster & Davis, 1984; Forster, 1987; Forster, Davis, Schoknecht, & Carter, 1987; Forster, Mohan, & Hector, 2003; Forster, & Veres, 1998; Perea & Rosa, 2000). Proponents of competition-based accounts of word recognition argue this facilitatory form priming is consistent with the involvement of mechanisms of lexical competition and inhibition, as only related word primes should strongly activate lexical competitors of the target word and so produce strong effects of lexical inhibition (e.g., Davis & Lupker, 2006). Related non-word primes should not have this inhibitory influence because non-words are not lexically represented.

Neighbour Priming in Eye Movements While Reading

This earlier research shows that prior exposure to a word's neighbour can influence performance in word recognition experiments. More recent research by Paterson, Liversedge, and Davis (2009) expanded on this by examining whether similar inter-word priming effects are observed in eye fixations for words encountered normally during reading when a "prime" word is presented just a few words earlier in a sentence than the target word. Paterson et al. found this was the case, and that eye fixation durations were longer for target words that followed a neighbour word prime than a non-neighbour word prime. As this effect was obtained in eye movement measures that are sensitive to early word processing (e.g., first-fixation duration, gaze duration on the target word), Paterson et al. argued that processing a target word's neighbour earlier in a sentence can influence early stages of word identification for that target word. However, by contrast with findings from studies of isolated

word recognition, there was no modulating effect of word frequency and similar priming effects were observed when the prime was of either higher or lower frequency than the target.

Paterson et al. (2009) offered two explanations for this inhibitory neighbour priming effect in reading. They argued that the effect may be explained in terms of competition between lexical entries, as proposed by competitive network models of word recognition, such as the interactive activation (IA) and SOLAR models (e.g., Davis, 2003; Grainger & Jacobs, 1996; McClelland & Rumelhart, 1981). This explanation would hold so long as activation of the prime word's lexical entry has not decayed or been inhibited substantially in the period between identifying the prime and encountering the target. Accordingly, residual activation of the prime word's lexical entry may provide a strong lexical competitor during processing of the target word and thereby slow this word's identification. However, given the relatively long-lasting priming in this experiment, which carried over several intervening words, the effect may have a different locus from effects observed in masked priming research. Indeed, these effects may be better explained by an episodic memory approach in which memory traces associated with processing of the neighbour word are evoked during the subsequent processing of the target and interfere with target word identification (Tenpenny, 1995).

According to this account, identification of a word causes an episodic trace to be formed. This episodic trace encodes not just the word itself, but also contextual information, including a non-response code associated with any orthographically similar words that were partially activated and had to be suppressed. When one of these words occurs later in the sentence, it reinstates that episodic trace, including the non-response information, and this may interfere with word identification. While episodic accounts have previously been invoked to explain negative priming effects in visual and auditory word recognition (e.g., Mayr & Buchner, 2006; Neill, Valdes, & Terry, 1995), little is known about the role of episodic memory processes during reading.

Neighbour Priming in Non-Alphabetic Languages

Although neighbour priming effects are well-established for alphabetic languages, especially in studies of isolated word recognition, less is known about effects of orthographic relatedness in non-alphabetic languages. A recent masked priming study by Nakayama, Sears, and Lupker (2011) showed word recognition was slowed when target words written in Japanese Katakana were primed by words that were neighbours, although these effects were not modulated by the relative frequency of prime and target words. This study suggests that lexical competition is an important component in languages that do not employ the Roman alphabet. However, as Katakana is a syllabic script, often used to describe words that originate in foreign languages, and not a logographic script like Japanese Kanji or Chinese, it remains to be determined whether similar competition-based processes are observed for logographic languages.

The present research therefore investigated whether neighbour priming effects similar to those found for alphabetic languages are obtained for Chinese characters. The key issues we addressed concern what form of orthographic priming might be observed in Chinese, whether any such effects are inhibitory or facilitatory in nature, and whether they are modulated by frequency. Although Chinese characters are quite different from words in alphabetic languages in many respects, the mechanisms that underlie word recognition in different languages may follow some common rules (Frost, 2012). For instance, it is widely agreed that activation of the graphical representation of a character occurs prior to activation of its associated phonological codes and access to semantic information in Chinese (Tan, Hoosain, & Peng, 1995; Liu, Perfetti, & Hart, 2003) as well as in alphabetic languages (e.g., Van Orden, 1987; Seidenberg & McClelland, 1989; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Warren, & McConnell, 2009). Chinese characters also have orthographic structure; thus, they may have orthographic neighbours, and if they have, it seems likely

that we may obtain neighbour priming effects in Chinese. An important question is whether similar mechanisms of competition and inhibition underlie character recognition in Chinese as proposed for word recognition in alphabetic languages (e.g., Davis, 2003; Grainger & Jacobs, 1996; McClelland & Rumelhart, 1981). The present research is therefore aimed at determining whether inhibitory neighbour priming effects similar to those in alphabetic languages are observed in Chinese, and to determine the level of the linguistic unit over which neighbour relations should be defined.

Text in Chinese is formed from distinctive symbols (characters) that occur alone or combine with other characters to form words. These characters comprise (usually 1 or 2) radicals, which are sub-character units formed from a configuration of character strokes. Rather little research has examined orthographic priming in Chinese, but a major issue concerns the level at which orthographic similarity should be defined. Prior research has used various definitions of neighbour relations, often based on a shared radical or a common character in words formed from two characters (e.g., Chen & Peng, 2001; Chen, Wang, & Peng, 2003; Huang, Lee, Tsai, Lee, Hung, & Tzeng, 2006; Perfetti & Tan, 1998; Tan et al., 1995; Wang & Yan, 2006; Wu & Chen, 2003; Zhou, Marslen-Wilson, Taft, & Shu, 1999). However, a different approach was taken in the present research, where neighbour relations were defined at the level of stroke overlap rather than the radical or the character, and we defined a character's stroke neighbours as those characters that could be formed by substituting, adding, or deleting one or more character strokes. This definition was based on three considerations. First, the stroke is the minimal constituent of a Chinese character's structure. The minimal constituent of words in alphabetic languages is the letter. Thus, character strokes in some sense may be considered to be analogous to letters in words, and radicals may correspond to larger morphemes. Second, the stroke composition of Chinese characters is important, and has been shown to have structure that plays an important role in Chinese character recognition (Yan, Bai, Zang, Bian, Cui, Qi,

Rayner & Liversedge, 2011). Third, because phonological or semantic information can be conveyed at the level of the radical, Chinese characters that differ by one or two strokes are not necessarily phonologically or semantically similar. Consequently, employing a definition of orthographic similarity based on stroke overlap enabled an assessment of neighbour priming effects that are orthographic in nature and not confounded by other associative aspects.

We consider this to be an advantage over previous research on neighbour priming in Chinese. Our approach may also be argued to be advantageous over many studies of neighbour priming in alphabetic languages. Neighbour words in many alphabetic languages (e.g., English, Dutch, French) frequently both look and sound similar to each other because of grapheme to phoneme correspondences (or grapheme-phoneme mappings). Such correspondences help readers to parse strings of graphemes and convert them into phonemes during word recognition. Thus, it is often difficult to avoid effects of phonological similarity when assessing neighbour priming effects in alphabetic languages and studies of neighbour priming do not always systematically take account of both orthographic and phonological similarity. In Chinese, however, there is a much looser relationship between a character's orthographic form and its corresponding phonological representation. Consequently, the present study of neighbour priming in Chinese provided a valuable opportunity to assess effects of orthographic similarity on character recognition while excluding effects of phonological overlap.

To our knowledge, only one previous study, by Shen and Forster (1999), has examined orthographic priming effects defined at the level of the stroke. The focus of this study was on phonological priming, but the experiments included control conditions in which simple or compound target characters were primed by an orthographically similar prime character that differed from the target by no more than two strokes. The effect of these primes was investigated using both naming

and the lexical decision task, in experiments where prime characters were displayed for 50ms following a pattern mask. In both experiments, the orthographically similar prime character facilitated target character recognition relative to a dissimilar control character. The orthographic neighbour priming effect therefore differs from that frequently reported for words in alphabetic languages, and for words in Japanese Katakana (Nakayama et al., 2011), as stroke or letter overlap produced inhibition rather than facilitation.

The aim of the present research was to more fully explore mechanisms that underlie character recognition in Chinese. In particular, we aimed to determine whether stroke neighbour priming is observed in Chinese character recognition and if the effects are inhibitory, and therefore similar to those for alphabetic languages in masked priming, or facilitatory, as Shen and Forster (1999) observed. Inhibitory priming effects would provide evidence that a process of inhibition is used to select between alternative candidates during character recognition, analogous to proposed mechanisms of competition and lexical inhibition in alphabetic word recognition (e.g., Davis, 2003; Davis & Lupker, 2006). However, if facilitation is observed, this would provide evidence against such an account of character identification in Chinese. Two further issues also arise. If masked priming effects in the present research are similar to those for alphabetic languages, then the question arises as to whether these effects are modulated by character frequency, as observed for alphabetic prime and target neighbour words and as predicted by competitive network models (e.g., Davis, 2003). Finally, following Paterson et al. (2009), we wished to determine whether orthographic similarity gives rise to inter-character priming effects in eye fixation times for characters during reading, and hence demonstrate priming effects in normal reading.

Experiment 1

In Experiment 1, we used a masked priming paradigm in which a forward mask was followed

by a Chinese character that was the prime, and this in turn was followed by a target character that participants responded to by indicating whether it was a Chinese character or a pseudo-character. Prime characters were neighbours that differed from a target character by no more than two character strokes, or non-neighbours, and each prime character had either a higher or lower frequency of occurrence than the corresponding target character. Masked priming research in alphabetic languages often uses a sequence of hash symbols as a forward mask (e.g., #####). However, hash symbols may be less effective at masking Chinese characters (Tan et al., 1995; Perfetti & Tan, 1998; Liu et al., 2003) and so following previous research we used Chinese pseudo-characters as a mask.

Predictions were straightforward and based on findings from masked priming in alphabetic languages and previous research by Shen and Forster (1999). A particular concern was whether prior exposure to a character that differs by no more than two strokes provides an orthographic competitor for the target character and therefore impedes target character recognition. If this is the case, response times should be slower for targets that follow a neighbour prime than a non-neighbour prime. Moreover, if the influence of a neighbour prime depends on the relative frequency of prime and target characters, prior exposure to a higher frequency prime should inhibit recognition of a lower frequency target. Consequently, response times should be slower for lower frequency targets that follow a higher frequency neighbour prime than a higher frequency non-neighbour prime, but response times may not differ for higher frequency targets that follow either a lower frequency neighbour or a lower frequency non-neighbour prime. Alternatively, if the findings are in line with those of Shen and Forster, prior exposure to an orthographically similar prime will facilitate target character recognition irrespective of the relative frequency of the prime and target characters.

Method

Participants. 48 undergraduate students from Tianjin Normal University (Tianjin, China) took

part. All were Mandarin-speaking, right-handed, and had normal or corrected-to-normal vision.

Stimuli. One hundred and twelve pairs of characters were selected from “A Dictionary of Chinese Character Information” (Li & Liu, 1988). These were arranged into 56 pairs of neighbour characters that differed by only one or two strokes (e.g., 勺 spoon / 习 study) and where one character in each pair had a significantly lower frequency of occurrence than the other (high frequency characters: mean = 717 counts per million, range = 107-3183 counts per million; low frequency characters: mean = 24 counts per million, range = 1-68 counts per million; $t(55) = 8.06, p < .001$). High and low frequency characters were matched on number of strokes (high frequency characters, mean = 6.6 strokes, range = 2-13 strokes; low frequency characters, mean = 6.6 strokes, range = 3-13 strokes, $t < 1$). In addition, 112 non-neighbour prime characters were matched with neighbour characters from each pair for both frequency ($ts < 1$) and number of strokes ($ts < 1$).

Although prime and target character pairs were phonologically dissimilar, these sometimes had the same tone. In spoken Chinese, each syllable comprises an onset and a rime and is articulated in one of four tones, which vary in pitch and contour. Prior research has shown that tone has little influence on judgments of phonological similarity between characters (Taft & Chen, 1992; see also Ding, Peng, & Taft, 2004), and so the present research focused on phonological similarity at the level of the syllable. In order to ensure that prime and target characters differed phonologically, 20 native Chinese speakers (who did not take part in any of the experiments) rated the phonological similarity of the prime (neighbours and controls) and target characters on a 7-point scale (where 1 was very dissimilar and 7 was very similar). Neighbour pairs ($M = 1.1$) and control-target pairs ($M = 1.1$) were rated as equally highly phonologically dissimilar ($t < 1$). Ten further native Chinese speakers (who also did not take part in the experiments) rated the visual similarity of the primes and matched control characters using a 7-point scale (where 1 was very dissimilar and 7 was very similar). This confirmed

that prime and control words (and therefore also control and target words) were perceived as visually dissimilar ($M = 1.2$). Consequently, any priming effects would be due to the perceived visual similarity of prime and target words. A further 56 pseudo-character targets were constructed as foils that should produce a pseudo-character response in the decision task and these were paired with 56 prime characters that were selected randomly. Pseudo-character targets were constructed by combining two or more radicals that do not combine to form real Chinese characters. A full list of the neighbour character pairs is given in the Appendix.

In neighbour priming conditions, each higher frequency neighbour served as a prime for a lower frequency target (e.g., 习 study / 勺 spoon) and vice versa (e.g., 勺 spoon / 习 study). In control conditions, either a higher frequency non-neighbour character served as a prime for a lower frequency target (e.g., 立 stand / 勺 spoon) or a lower frequency non-neighbour character served as a prime for a higher frequency target (e.g., 叉 fork / 习 study). These prime-target displays were counterbalanced across participants using a Latin Square design, so that each participant viewed one prime-target pair from each stimulus set and an equal number of prime-target pairs in each prime condition. In pseudo-character target conditions, a randomly selected character served as the prime for a pseudo-character target. Therefore, each participant made character decisions for 56 character targets and 56 pseudo-character targets.

Apparatus and Procedure. Participants were tested individually in a quiet room. Stimuli were presented on a 14-inch laptop using E-prime (Psychology Software Tools, Pittsburgh, PA). The laptop had a screen refresh rate of 60Hz. Each trial started with a fixation point in the centre of the screen, followed by a pseudo-character forward mask displayed for 493ms. The mask was replaced by the prime character, which was presented in size 36 Songti Font for 67ms. The prime was replaced immediately by a target character displayed in the same size and font, and this character remained on

the screen until a response was made or the display timed out (after 2000ms). Stimuli were displayed as white characters against a black background. Reaction times (from target character onset until response) were recorded automatically. Participants classified the target as a character or a pseudo-character by pressing one of two keys on the keyboard. Trials on which no response was made before the time-out were omitted from the data analysis. Each participant received 30 practice trials with feedback, and started the experimental trials once the accumulative accuracy was greater than 90% (the 30 practice trials were repeated until each participant achieved this criterion).

Results and Discussion

Error rates and the latency of correct responses for target characters were analysed. Incorrect responses and responses with latencies beyond each condition mean plus/minus 3 standard deviations were excluded from the analysis (accounting for 4.2% of trials). A two-way Analysis of Variance (ANOVA) was conducted with factors target character frequency (lower, higher) and prime type (neighbour, non-neighbour), computing error variance over participants (F_1) and items (F_2). Mean error rates and response latencies are shown in Table 1.

Insert Table 1 about here

For error rates, only a main effect of target character frequency was obtained, and only in the participants analysis, $F_1(1,47) = 8.67$, $MSE = 13.52$, $p < .001$, $\eta_p^2 = .16$, and, $F_2(1,110) = 3.20$, $MSE = 42.77$, $p = .08$, $\eta_p^2 = .03$. No other effects were found, $F_s < .90$. This showed that participants made more errors for lower frequency characters. For correct response times, a main effect of target character frequency was observed, $F_1(1,47) = 64.41$, $MSE = 1,557.76$, $p < .0001$, $\eta_p^2 = .58$, and, $F_2(1,110) = 28.03$, $MSE = 4,725.18$, $p < .0001$, $\eta_p^2 = .20$. This showed that response times were shorter for higher frequency characters, and therefore that the manipulation of character frequency was effective. There was also a main effect of prime type, $F_1(1,47) = 4.49$, $MSE = 2,077.05$, $p < .05$,

$\eta_p^2 = .09$, and, $F_2(1,110) = 4.70$, $MSE = 2,214.94$, $p < .05$, $\eta_p^2 = .04$, that did not interact with frequency, $F < .50$. This showed that targets that followed a neighbour prime were recognized more slowly than targets that followed a non-neighbour prime and that this inhibitory priming effect was not modulated by the relative frequency of prime and target characters.¹ Masked priming research in alphabetic languages has shown that the inhibitory influence of a neighbour prime occurs only when the prime is higher in frequency than the target. However, the present findings suggest that frequency does not modulate stroke neighbour priming in Chinese. This contrasts with findings from (Latin) alphabetic languages, and with the findings of Shen and Forster (1999), but is consistent with Nakayama et al.'s (2011) findings for words in Japanese Katakana.

Experiments 2a-c

Experiment 2 further tested the neighbour priming effect in Chinese character recognition using masked priming and shorter prime durations. Experiment 1 showed clear neighbour priming when prime characters were displayed for 67ms. However, the magnitude of the priming effect was unaffected by the relative frequency of prime and target characters. One reason why we may not have obtained a modulating effect of frequency is because a 67ms prime duration may be sufficiently long to allow participants to consciously identify the prime. In neighbour priming studies using alphabetic stimuli where the relative frequency of prime and target stimuli do modulate priming effects, prime durations that do not allow for conscious identification of the prime stimulus have usually been used (e.g., Brysbaert et al., 2000; Davis & Lupker, 2006; Segui & Grainger, 1990). Such prime durations are usually of the order of 60ms or 67ms (hence our choice of prime duration for Experiment 1). However, Chinese characters are quite compact, and the language quite dense (Zang, Livsedge, Bai, & Yan, 2011). Thus, although a 67ms prime duration may be sufficiently short to prevent conscious identification of an alphabetic word prime, this may not hold for single Chinese characters (that are

often not a full word in their own right). A second concern was to further investigate the inhibitory priming effect we obtained. Shen and Forster (1999) used a prime duration of only 50ms and found that neighbour primes facilitated character recognition. It was therefore also possible that the inhibitory effect we observed was due to the longer prime duration enabling conscious identification of prime characters. For this reason, we decided to re-run Experiment 1 with shorter (33ms & 50ms) prime durations to avoid the possibility that participants would consciously identify the prime. In this way, we could be sure that any inhibitory effects we observed, and any lack of a modulatory effect of frequency, were not due to conscious identification of the prime.

We predicted that if neighbour priming is inhibitory, but not modulated by character frequency, we would obtain the same pattern of effects as in Experiment 1. However, if the effects in Experiment 1 were due to conscious identification of the prime when a 67ms prime duration was used, a facilitatory effect may be produced, in line with Shen and Forster (1999), at the shorter prime durations used in Experiments 2a (33ms) & 2b (50ms). Alternatively, the priming effect may still be inhibitory, and a modulating effect of lexical frequency may be observed at these shorter prime durations, in line with previous research on alphabetic languages.

Experiment 2a

Method

Participants were 48 undergraduate students from Tianjin Normal University (Tianjin, China). All were Mandarin-speaking, right-handed, and had normal or corrected-to-normal vision. No participant had also taken part in Experiment 1. The stimuli, design, and procedure were identical to Experiment 1, except that the prime duration was reduced from 67ms to 33ms.

Results and Discussion

Data analysis methods were the same as in Experiment 1. Incorrect responses and responses

with latencies beyond the condition mean plus/minus 3 standard deviations were excluded from the analysis (accounting for 4.9% of trials). The resulting data were analysed using an ANOVA with factors target character frequency (lower, higher) and prime type (neighbour, non-neighbour), computing error variance over participants (F_1) and items (F_2). Mean error rates and response latencies are shown in Table 1.

For error rates, only a main effect of target frequency was reliable, $F_1(1,47) = 19.80$, $MSE = 23.67$, $p < .0001$, $\eta_p^2 = .30$, and $F_2(1,110) = 10.38$, $MSE = 33.35$, $p < .005$, $\eta_p^2 = .09$. No other effects were found, $F_s < 1.5$. This showed participants made more errors for lower frequency target characters. For correct response times, a main effect of target character frequency was observed, $F_1(1,47) = 91.40$, $MSE = 1502.07$, $p < .0001$, $\eta_p^2 = .66$, and $F_2(1,110) = 49.18$, $MSE = 3773.93$, $p < .0001$, $\eta_p^2 = .31$. This showed again that the manipulation of character frequency was successful. A main effect of prime type was marginal in the participants analysis, $F_1(1, 47) = 3.31$, $MSE = 1427.64$, $p = .075$, $\eta_p^2 = .07$, and $F_2(1, 110) = 1.31$, $MSE = 3315.91$, $p = .256$, $\eta_p^2 = .01$, and the interaction between prime type and character frequency was not significant, $F_s < .10$. Experiment 2a therefore produced a similar pattern of inhibitory priming as Experiment 1, and showed that this inhibitory neighbour priming is not influenced by the relative frequency of prime and target characters even at short prime durations.

Experiment 2b

Method

Participants were 48 undergraduate students from Tianjin Normal University (Tianjin, China). All were Mandarin-speaking, right-handed, and had normal or corrected-to-normal vision. No participant had also taken part in Experiment 1 or 2a. The design and procedure were identical to the previous experiments, except that the prime duration was 50ms. The same stimuli were presented but on a 17-inch CRT monitor which had a higher screen refresh rate of 100Hz.

Results and Discussion

Data analysis methods were the same as in Experiments 1 and 2a. As in these experiments, incorrect responses and responses with latencies beyond the condition mean plus/minus 3 standard deviations were excluded from the analysis (accounting for 4.3% of trials). The resulting data were analyzed using an ANOVA with factors target character frequency (lower, higher) and prime type (neighbour, non-neighbour), computing error variance over participants (F_1) and items (F_2). Mean error rates and response latencies are shown in Table 1.

For error rates, only a main effect of target character frequency was reliable, $F_1(1,47) = 14.19$, $MSE = 19.18$, $p < .0001$, $\eta_p^2 = .23$, and $F_2(1,110) = 10.34$, $MSE = 30.70$, $p < .005$, $\eta_p^2 = .09$. No other effects were found, $F_s < 1.3$. For correct response times, a main effect of target character frequency was observed, $F_1(1,47) = 116.43$, $MSE = 1,342.67$, $p < .0001$, $\eta_p^2 = .71$, and $F_2(1,110) = 47.14$, $MSE = 4115.24$, $p < .0001$, $\eta_p^2 = .30$. Therefore, as in Experiments 1 and 2a, participants made more errors and had longer responses for lower frequency target characters. A main effect of prime type was marginal in the participants analysis, $F_1(1, 47) = 3.98$, $MSE = 1180.80$, $p = .05$, $\eta_p^2 = .08$, and $F_2(1,110) = 1.50$, $MSE = 4069.98$, $p = .223$, $\eta_p^2 = .01$, and the interaction between prime type and character frequency was not significant, $F_s < .30$. Experiment 2b, therefore, produced a similar pattern of inhibitory priming as Experiment 1 & 2a, and showed again that this effect in Chinese is not influenced by the relative frequency of prime and target characters.

Experiment 2c

Experiments 2a and 2b show that the pattern of findings obtained with 33ms and 50ms prime durations is very similar to that obtained for a 67ms prime duration in Experiment 1. These findings show an inhibitory influence of the stroke neighbour on target word recognition, which contrasts with the facilitatory effect reported by Shen and Forster (1999). Moreover, even at these shorter prime

durations there was no interaction of prime type and the relative frequency of prime and target characters, and so no indication that the modulating influence of frequency typically observed in neighbour priming in alphabetic languages is found for stroke neighbour priming in Chinese. The shorter prime durations used in Experiments 2a and 2b rule out the possibility that this is due to differences in prime duration. However, a further potentially important methodological issue was that, unlike in the present experiments, Shen and Forster displayed prime and target characters in a different font (the prime was displayed in Kaiti font and the target was displayed in Songti font, both of which are familiar fonts for Chinese readers) and in a slightly different font size, to minimize effects of overlap in the visual form of the two characters. Therefore, in order to address this methodological difference, we performed a further experiment using a similar display procedure as Shen and Forster and a 50ms prime duration. Apart from these changes to the prime and target display, the design and procedure were identical to Experiment 2b.

Method

Participants were 48 undergraduate students from Tianjin Normal University (Tianjin, China). All were Mandarin-speaking, right-handed, and had normal or corrected-to-normal vision. No participant had also taken part in the previous experiments. The design and procedure were identical to Experiment 2b, except that the prime was displayed in Kaiti font and the target was displayed in Songti font, and the prime was of a slightly smaller font size than the target. Stimuli were presented on a 17-inch CRT monitor. Mean error rates and response latencies are shown in Table 1.

Results and Discussion

Data analysis methods were the same as in the previous experiments. Incorrect responses and responses with latencies beyond the condition mean plus/minus 3 standard deviations were excluded from the analysis (accounting for 4.3% of trials). The resulting data were then analysed using an

ANOVA with factors target character frequency (lower, higher) and prime type (neighbour, non-neighbour), computing error variance over participants (F_1) and items (F_2). Mean response latencies and error rates are shown in Table 1.

For error rates, only a main effect of target frequency was reliable, $F_1(1,47) = 18.65$, $MSE = 19.18$, $p < .0001$, $\eta_p^2 = .23$, and $F_2(1,110) = 6.01$, $MSE = 30.70$, $p < .05$, $\eta_p^2 = .09$. This showed participants made more errors for lower frequency targets. There was no main effect of prime type ($F_s < 1$) and the interaction was not significant, $F_1(1,47) = 3.00$, $MSE = 19.18$, $p = .09$, $\eta_p^2 = .23$, and $F_2(1,110) = 1.24$, $MSE = 30.70$, $p > .05$, $\eta_p^2 = .09$. For correct response times, a main effect of target character frequency was observed, $F_1(1,47) = 175.00$, $MSE = 1342.67$, $p < .0001$, $\eta_p^2 = .71$, and $F_2(1,110) = 51.33$, $MSE = 4115.24$, $p < .0001$, $\eta_p^2 = .30$. There was also a main effect of prime type in the participants analysis, $F_1(1, 47) = 4.50$, $MSE = 1180.80$, $p < .05$, $\eta_p^2 = .08$, and $F_2(1, 110) = 2.45$, $MSE = 4069.98$, $p = .12$, $\eta_p^2 = .01$. The interaction between prime type and target character frequency was not significant, $F_s < .10$. Experiment 2c, therefore, produced a very similar pattern of priming effects to Experiment 1, 2a, and 2b, and showed that inhibitory stroke neighbour priming is observed even when prime and target characters are displayed in different fonts and different font sizes and only a 50ms prime duration is used. As in the previous experiments, this inhibitory priming was not influenced by the relative frequency of prime and target characters.

Meta-analysis

Although the pattern of effects in Experiment 1 and Experiments 2a-c were similar, effects of neighbour priming were not always fully statistically reliable. Therefore, in order to assess these effects in a more powerful analysis, correct response times were analysed using a three-way ANOVA with factors target character frequency (lower, higher), prime type (neighbour, non-neighbour) and experiment (1, 2a, 2b, 2c). This enabled a comparison of effects across different prime durations,

ranging from 33ms to 67ms, and when prime and target characters were displayed in the same or different fonts and font sizes. This analysis produced a main effect of target character frequency ($F_1(1,141) = 266.25$, $MSE = 1467.50$, $p < .0001$, $\eta_p^2 = .65$, and $F_2(1,110) = 120.94$, $MSE = 4204.78$, $p < .0001$, $\eta_p^2 = .27$) and a main effect of prime type ($F_1(1,141) = 11.68$, $MSE = 1561.83$, $p < .005$, $\eta_p^2 = .08$, and $F_2(1,330) = 6.31$, $MSE = 3200.28$, $p < .05$, $\eta_p^2 = .02$). No other effects were significant, $F_s < 1.2$. Thus, this meta-analysis reveals a robust stroke neighbour priming effect in Chinese that did not differ significantly across experiments, and therefore was not influenced by either different prime durations (33ms, 50ms, & 67ms) or display characteristics (i.e., whether prime and target characters are displayed in the same or different fonts and font sizes). Moreover, this inhibitory neighbour priming effect was not influenced by the relative frequency of prime and target characters at either long (67ms) or short (33ms & 50ms) prime durations.

Experiment 3

An inhibitory neighbour priming effect was observed in mask priming with prime durations of 67ms, 50ms, and 33ms. These findings therefore reveal that inhibitory neighbour priming occurs during Chinese character recognition when neighbour relations are defined at the level of the individual character stroke. Experiment 3 was conducted to reveal whether neighbour priming effects based on stroke overlap are also observed between Chinese characters encountered normally in a sentence during reading. Previous research in English suggests inter-word priming occurs naturally during reading comprehension and that prior exposure to a word's lexical neighbour a few words earlier in a sentence can slow word identification (Paterson et al., 2009; see also Paterson, Alcock, & Liversedge, 2011). This effect was observed in eye movement measures sensitive to early word processing.

Consequently, if a similar priming effect is observed between characters read normally in

Chinese, character identification should be slowed when a prime character appears a few characters earlier in a sentence than a target character that is its neighbour, and this effect may be observed in measures of early character processing. Such an effect would also be consistent with the effects in Experiments 1 and 2a-c. Evidence from other eye movement research shows that word and character frequency influences eye movements while reading Chinese (Yan, Tian, Bai, & Rayner, 2006). Consequently, effects of character frequency on fixation duration may well be observed in the present experiment. However, as both the results of Paterson et al. (2009) and Experiments 1 and 2a-c show that neighbour priming effects are uninfluenced by the relative lexical frequency of prime and target words, it is unlikely that character frequency will have a modulating influence on neighbour priming in the present experiment.

Method

Participants. Participants were 40 undergraduate and graduate students from Tianjin Normal University (Tianjin, China). All were Mandarin-speaking, right-handed, and had normal or corrected-to-normal vision. No participants had also taken part in Experiments 1 or 2a-c.

Stimuli. The prime and target character pairs used in Experiments 1 and 2a-c (excluding the pseudo-character stimuli) were inserted into sets of sentence frames so that in one sentence pair a lower frequency target character followed either its higher frequency stroke neighbour or a higher frequency non-neighbour character and, in the other sentence pair, the higher frequency target character followed either its lower frequency stroke neighbour or a lower frequency non-neighbour character.

Insert Figure 1 about here

An initial 56 sets of sentences (see Figure 1 for examples) were constructed and evaluated for meaningfulness and naturalness by 20 native Chinese speakers (who did not take part in the earlier

masked priming experiments or the eye-tracking experiment). From these, 40 sets of sentences were selected that were closely matched for meaningfulness and naturalness (mean meaningfulness score = 1.52, where a score of 1 equated to very meaningful; mean naturalness score = 4.44, where a score of 5 equated to very natural, $F_s < 1$). The sentences were between 13 and 22 characters (mean = 17 characters) in length and prime and target characters were always located in the middle portion of sentences. Most Chinese characters can combine with other characters to form words in Chinese. Primes that were stroke neighbours of target characters and primes that were non-neighbour controls often had to be combined with different characters to form words, and this created small differences in content across the stroke neighbour prime and non-prime conditions. Nevertheless, differences between the alternative versions of each sentence pair were minimized. Care was taken to match the lexical frequency of words in which prime/control and target characters appeared. The mean frequency for these words is shown in Table 2. The number of characters in the text region between the prime and target characters was identical for sentences containing the same target character and either a neighbour or non-neighbour prime ($M = 1.9$, $SD = 0.7$), and did not differ significantly between sentence pairs in which a lower or higher frequency stroke neighbour was the target ($F < 2.9$). Sentences were arranged into lists that were counterbalanced for presentation across participants so that each participant viewed only one sentence from each set of sentences and an equal number of sentences in each condition.

Insert Table 2 about here

Apparatus & Procedure. Participants were tested individually in the eye-tracking laboratory in Tianjin Normal University using an EyeLink II eye-tracker (SR Research, Canada) to record the movements of the right eye. Sentences were presented as black text on a white background at size 21 Songti Font on a 19-inch monitor. Before the start of the experiment, participants had the procedure

explained to them. Participants were then seated in front of the monitor at a viewing distance of 60 cm. A chin-rest was used to minimize head movements. A calibration procedure was then performed, followed by 8 practice trials. After this, participants read 40 experimental sentences intermixed with 8 filler sentences. Each trial started with a fixation point located on the left side of the screen.

Participants were instructed to fixate this point, and when they fixated it accurately, the experimenter initiated the presentation of a sentence. The first character of this sentence replaced the fixation point. Participants read sentences silently and for comprehension, and pressed a response key when they had finished reading each sentence. On 25% of trials, this was followed by a comprehension question that participants responded to by pressing a response key to give a “yes” or “no” response.

Results and Discussion

Sentences were divided into four scoring regions (see Figure 1). Region 1 was the prime character. Region 2 was the intervening region comprising characters between the prime and target characters. Region 3 was the target character. Region 4 was the next, spill-over, character.

Prior to analysis, eye movement data were cleaned of track losses, blinks, and short (less than 80ms) and long (more than 1000ms) fixations. This accounted for less than 1% of trials. Because first-pass measures for each region excluded trials in which the region was skipped, one item was removed from the analyses as all participants skipped the prime character when reading this sentence, and so fixation time data for this character were unavailable. An analysis of outliers was used to identify fixations that were more than 3 standard deviations from the condition mean and these were replaced by the respective boundary value (affecting only 1.2% of the data). Several standard eye movement measures were then computed (see, e.g., Rayner, 1998, 2009). For Regions 1-4, we report first fixation duration, which was the duration of the first fixation in a region. In addition, for Region 3 (the target character), we report single fixation duration, which was the duration of the fixation when

there was only one fixation in this region. For Regions 1-3, we report gaze duration, which is the sum of the duration of all fixations made from the first fixation within a region until a fixation outside this region (also known as first-pass reading time for regions containing more than one character), regression path reading time, which is the sum of the duration of all fixations from the first fixation in a region until a fixation to the right of this region, and total reading time, which is the sum of the duration of all fixations in a region. We also report the character-skipping rate for Region 3 (the target character), the frequency of regressions out of a region for Regions 3 and 4 (the target character and the post-target region), and the frequency of regressions into a region for Regions 1 and 3 (the prime character and the target character). The resulting data were analyzed using repeated measures ANOVA with factors character frequency (higher, lower) and orthographic similarity (neighbours, non-neighbours), computing error variance over participants (F_1) and items (F_2). Mean eye movement data are shown in Table 3.

Insert Table 3 about here

Region 1 (Prime Character). A main effect of character frequency was obtained in regression path reading times, $F_1(1,39) = 11.76$, $MSE = 12601.46$, $p < .005$, $\eta_p^2 = .22$, and, $F_2(1,38) = 4.79$, $MSE = 26337.43$, $p < .05$, $\eta_p^2 = .11$, due to longer reading times for lower frequency prime characters. A similar effect of character frequency was found in the participants analyses for first fixation durations, ($F_1(1,39) = 6.95$, $MSE = 2204.36$, $p < .05$, $\eta_p^2 = .151$, $F_2(1,38) = 0.85$, $MSE = 4769.16$, $p = .364$, $\eta_p^2 = .02$), gaze durations ($F_1(1,39) = 6.64$, $MSE = 3526.84$, $p < .05$, $\eta_p^2 = .15$, $F_2(1,38) = 1.81$, $MSE = 6132.65$, $p = .186$, $\eta_p^2 = .046$), and total reading times ($F_1(1,39) = 8.72$, $MSE = 9406.80$, $p < .01$, $\eta_p^2 = .18$, $F_2(1,38) = 2.65$, $MSE = 29686.84$, $p = .112$, $\eta_p^2 = .07$). There were no effects for regressions back to the prime character ($F_s < 1.5$), and no other significant effects ($F_s < 3.4$). The results for the prime region therefore showed that the manipulation of character frequency was successful, that character

frequency affected reading times, and that this effect was observed most clearly in regression path reading times.

Region 2 (Intervening Text). There was only one reliable effect in the intervening region: a main effect of orthographic similarity in first fixation durations, $F_1(1,39) = 4.25$, $MSE = 1423.59$, $p < .05$, $\eta_p^2 = .10$, and, $F_2(1,38) = 5.23$, $MSE = 1520.37$, $p < .05$, $\eta_p^2 = .12$. This was short-lived and not observed in later fixation time measures, and so most likely reflected minor differences in the content of the sentences across conditions within this region rather than an anticipatory effect due to the visual similarity between the prime and the target character in the following region.

Region 3 (Target Character). An inhibitory priming effect was observed in first fixation durations for target characters, $F_1(1,39) = 7.13$, $MSE = 2443.53$, $p < .05$, $\eta_p^2 = .15$, and $F_2(1,38) = 5.58$, $MSE = 2714.54$, $p < .05$, $\eta_p^2 = .13$. First fixation durations were longer for target characters that followed a neighbour character than a non-neighbour character. A similar inhibitory priming effect was observed in single fixation durations, gaze durations, and total reading times, although this was not always fully reliable in both participant and items analyses (single fixation durations: $F_1(1,39) = 3.90$, $MSE = 5802.90$, $p = .06$, $\eta_p^2 = .09$, and $F_2(1,38) = 5.03$, $MSE = 4483.82$, $p < .05$, $\eta_p^2 = .12$; gaze durations: $F_1(1,39) = 6.29$, $MSE = 2973.88$, $p < .05$, $\eta_p^2 = .14$, and $F_2(1,38) = 2.6$, $MSE = 4159.42$, $p = .094$, $\eta_p^2 = .07$; total reading times: $F_1(1,39) = 3.97$, $MSE = 8744.34$, $p = .05$, $\eta_p^2 = .09$, and $F_2(1,38) = 3.90$, $MSE = 8192.29$, $p = .06$, $\eta_p^2 = .09$). This effect was not found in regressions back to this region or in regression path reading times ($F_s < 1.3$). A main effect of prime type was reliable only in the items analysis for regressions out of this region, $F_1(1,39) = 3.41$, $MSE = 572.60$, $p = .07$, $\eta_p^2 = .08$, and $F_2(1,38) = 5.86$, $MSE = 446.96$, $p < .05$, $\eta_p^2 = .13$, due to readers making slightly more regressions when the prime was a control character rather than a neighbour. No other effects were significant ($F_s < 3$). The findings for target characters, and the fixation time effects in particular, are generally

consistent with the inhibitory priming effect reported by Paterson et al. (2009), as well as the priming effects in Experiments 1 and 2a-c, and show that prior exposure to a character's neighbour a few characters earlier in a sentence slows identification of that character.

A main effect of target character frequency was also observed in regressions and total reading times in the participant analyses (regressions: $F_1(1,39) = 7.61$, $MSE = 220.79$, $p < .05$, $\eta_p^2 = .16$, $F_2(1,38) = 3.86$, $MSE = 446.21$, $p = .057$, $\eta_p^2 = .09$; total reading times: $F_1(1,39) = 7.96$, $MSE = 9054.89$, $p < .01$, $\eta_p^2 = .17$, $F_2(1,38) = 2.74$, $MSE = 23246.38$, $p = .106$, $\eta_p^2 = .07$). This effect was not found in first fixation durations, single fixation durations, gaze durations, or regression path reading times ($F_s < 1.9$). Moreover, although the inhibitory priming effect in first fixation durations was numerically larger for higher frequency targets that followed lower frequency primes than vice versa (25ms vs. 16ms), this interaction effect was not significant ($F_s < .50$). No other interaction effects were significant ($F_s < 1.6$). Thus, the inhibitory neighbour priming effect we observed was not modulated by the relative frequency of prime and target characters.

Region 4 (Spillover). No effects were significant ($F_s < 2.8$). This confirmed that effects of stroke neighbour priming were short lived, and no effects spilled over from the target character to affect processing of text in the following region.

Experiment 3 provided evidence that inter-character priming occurs naturally during the reading of Chinese text and that prior exposure to a character that is orthographically similar (in terms of stroke overlap) a few characters earlier in a sentence can interfere with the normal process of character identification. This priming effect was not modulated by the relative frequency of prime and target characters (although character frequency effects were observed during prime character processing). The effect is similar to the lexical neighbour priming effect reported by Paterson et al. (2009), who found that inhibitory inter-word neighbour priming occurs naturally during reading in English and is

not modulated by word frequency. Indeed, the only difference between the effect for words in this previous research and for Chinese characters in the present experiment is that Paterson et al. observed effects of frequency in first fixation durations for both prime and target words whereas in the present experiment effects of frequency were observed reliably only in regression path reading times (and in participants analyses for first fixation durations, gaze durations, and total reading times) for prime characters and in regressions and total reading times for target characters.

General Discussion

This study investigated whether orthographic similarity, defined in terms of stroke overlap at the level of the individual Chinese character, influences performance in character recognition experiments and in eye fixation durations during reading. Experiment 1 used a masked priming paradigm in which a target character followed a 67ms character prime. This showed that neighbour relations based on stroke overlap affect the recognition of Chinese characters, and that brief exposure to a character's neighbour as a prime can slow the subsequent recognition of this character when it is presented as a target. This effect is similar to the inhibitory neighbour priming effect typically observed for alphabetic languages (e.g., Bijeljac-Babic et al., 1997; Brysbaert et al., 2000; Davis & Lupker, 2006; De Moor & Brysbaert, 2000; Drews & Zwitserlood, 1995; Grainger et al., 1991; Grainger & Ferrand, 1994; Nakayama, Sears, & Lupker, 2008; Segui & Grainger, 1990), where neighbour relations are defined in terms of overlap between the letters of prime and target words (Coltheart et al., 1977; Davis & Taft, 2005). However, unlike the effects for words in these languages (in many studies), no modulating influence of the relative frequency of prime and target characters was observed. Moreover, even though clear effects of frequency were observed in response times for target characters, the priming effect was similar when targets had either a higher or lower frequency of occurrence than prime characters. Experiment 2 further explored this effect using shorter prime

durations (33ms & 50ms) and a modified procedure in which prime and target characters were displayed in a different font and font size (Experiment 2c), and produced essentially the same pattern of inhibitory priming, with no evidence of a modulating influence of character frequency. These experiments therefore show that neighbour priming defined in terms of stroke overlap are observed in Chinese character recognition and that these effects are not modulated by relative character frequency.

As we noted above, this inhibitory influence of a stroke neighbour is consistent with numerous studies showing that an orthographically similar prime can inhibit word recognition in alphabetic languages. However, the present findings differ from those reported by Shen and Forster (1999), which although concerned with effects of phonological priming on character recognition in Chinese, also assessed effects of stroke neighbour primes on lexical decisions (and naming times) for target characters. As in the present experiments, stroke neighbour primes differed by no more than two strokes from the target characters. However, in contrast with the present research, Shen and Forster found that stroke neighbour primes facilitated character recognition. We have shown this difference in findings is not readily accounted for by a number of differences in experimental procedure, as inhibitory effects were obtained even when we used the same prime duration (50ms) and similar display procedures as Shen and Forster. Indeed, our findings show a consistent pattern of inhibitory priming across long (67m) and short (33ms & 50ms) prime durations, and this is consistent with recent research showing that prior exposure to a word's neighbour can slow lexical decisions even at short prime durations (De Moor, Van der Herten, & Verguts, 2007).

While effects of prime duration and display procedure cannot explain differences in the findings in present experiments and those reported by Shen and Forster (1999), other differences in design and procedure may be relevant, including differences in stimulus composition and the design of pseudo-characters. For instance, there were potentially important differences in the proportion of simple and

compound characters used as stimuli in the two studies. Both studies ensured that neighbour characters differed by no more than two character strokes. However, almost half the prime-target pairs (i.e., 30 of 62 prime-target pairs) in the Shen and Forster study were composed of simple characters, for which the orthographic relationship between prime and target characters may be particularly salient, and this may have been accentuated in the Shen and Forster study by presenting simple and compound character targets to participants separately, in different experimental sessions. By comparison, the present experiments used a smaller proportion of simple characters (only 10 high frequency characters, and 13 low frequency characters that served as either primes or target characters, from a total of 128 characters) and these were presented to participants intermixed with compound prime and target characters in the same session.

Differences in the construction of the pseudo-characters used to produce non-character responses in the decision task may also be relevant. In the present experiments, pseudo-characters were created by combining radicals that do not combine to form real Chinese characters, in order to ensure an appropriate level of difficulty in the character decision task. Shen and Forster (1999) used the same procedure to create pseudo-character foils for their compound characters, but created pseudo-character foils for their simple characters by changing up to two strokes in a real simple Chinese character to produce a non-character. Finally, a further difference, which may be relevant, was that participants in the Shen and Forster study were graduate students (or their spouses) studying at a US university, and so likely to be bilingual and to have greater recent experience of reading in English, whereas all the participants in our experiments were mainland Chinese students from a largely monolingual community. It is unclear precisely how this difference in participant characteristics, or potentially important differences in stimulus composition and pseudo-character construction, will have produced contrasting findings, and it is evident that further work is required to

more fully understand the circumstances in which stroke neighbours produce inhibitory or facilitatory influences. What is clear, however, is that procedures employed in the present research produced remarkably robust inhibitory priming across a range of prime durations, and across different display conditions, and that these findings are consistent with a broad range of findings from research in alphabetic languages and more recent research in Japanese Katakana (Nayakama et al., 2011). The present results therefore provide strong evidence that orthographic similarity, defined in terms of stroke overlap at the level of the individual Chinese character, influences performance in character recognition experiments, and that the underlying process of character recognition involves mechanisms of competition and inhibition.

Experiment 3 extended this investigation into the realm of natural reading, and used measures of eye movements during reading to determine whether inter-character priming effects similar to those in the character recognition experiments are observed in eye fixation durations for Chinese characters during normal reading. A previous study by Paterson et al. (2009) showed there is an analog in reading of the inhibitory neighbour priming effect observed in isolated word recognition for alphabetic languages, and that when a word's lexical neighbour is encountered a few words earlier in a sentence, this can interfere with the process of word identification that occurs naturally during reading. Experiment 3 used this manipulation to further explore the nature of inter-character neighbour priming in Chinese reading and showed that a similar inhibitory stroke neighbour priming effect was observed between characters encountered naturally in Chinese text, and that this priming effect was unaffected by the relative frequency of prime and target characters. Similar to the findings of Paterson et al. for words, this effect was seen to emerge early in target character processing and affected the duration of the very first fixation on a target character, which was longer when this character followed an orthographically similar than dissimilar prime.

The present experiments show robust and consistent inhibitory neighbour priming based on stroke overlap between Chinese characters both in isolated character recognition and in eye fixations during reading. The effects are similar to those observed for alphabetic languages, except that the relative frequency of prime and target words that has been shown to modulate the influence of a neighbour prime on word recognition in alphabetic languages did not affect character recognition in the present research. Nevertheless, similarities between inhibitory priming in the present research and in previous research in alphabetic languages suggest that a definition of neighbour relations based on stroke overlap is an effective means of exploring orthographic priming in Chinese word recognition that is not confounded by phonological similarity. Previous research that has examined neighbour priming effects in Chinese word recognition has often defined neighbours in terms of a shared radical or common character in words formed from two characters (e.g., Chen & Peng, 2001; Chen et al., 2003; Huang et al., 2006; Perfetti & Tan, 1998; Tan et al., 1995; Wang & Yan, 2006; Wu & Chen, 2003). Note, however, that lexical representations at the level of the character, or at the level of the radical, can be considered higher order than representations at the level of the stroke and, to this extent, the current study involves the manipulation of a simpler orthographic variable. This enabled us to have strict control over extraneous variables across our experimental conditions, and perhaps this is why effects are so consistent. What is clear is that the present research makes an important contribution to understanding how Chinese characters are recognized by revealing an influence of orthographic similarity at the level of individual strokes on character recognition.

The present findings suggest that similar systems and mechanisms may be responsible for neighbour priming effects in Chinese and in alphabetic languages. Competitive network accounts of word recognition (e.g., Davis, 2003; Grainger & Jacobs, 1996; McClelland & Rumelhart, 1981) account for neighbour priming effects in terms of competition between lexical entries. According to

this account, prior exposure to a word's orthographic neighbour provides activation for a lexical competitor and, because this competitor inhibits activation of the correct lexical entry, at least temporarily, this slows target word recognition. A similar mechanism can account for inhibitory neighbour priming in Chinese character recognition (and for a competitive network model of Chinese word recognition, see Taft, Zhu, & Peng, 1999) if it is assumed that exposure to a Chinese character activates not only the representation of that character, but also other characters that are similar in construction and that differ by one or two strokes. Accordingly, the prior display of a prime character that has a similar arrangement of strokes will activate the representation of this character and, because the prime is orthographically similar to the target, this will provide a strong competitor for the target character's representation and so slow recognition of the target character.

A competitive network approach provides a similar account of the neighbour priming effects that occurs during reading, and requires that prior exposure to the prime produces activation of a character's representation that provides an orthographic competitor for the target character so long as its activation has not decayed or been overwritten prior to the reader encountering the target. Although such an account has not been formally incorporated within current models of eye movements during reading (e.g., E-Z Reader), accounts of lexical neighbourhood effects based on these models frequently include the assumption that the slowdown in word identification associated with the availability of a word's higher frequency neighbour is a result of competition between lexical entries (e.g., Perea & Pollatsek, 1998; Pollatsek, Perea, & Binder, 1999; Williams, Perea, Pollatsek, & Rayner, 2006; Slattery, 2010). However, similar effects would also emerge in a model in which neighbour priming is accounted for in terms of episodic memory (e.g., Tenpenny, 1995), according to which a memory trace encoded during the processing of the prime (word or Chinese character) is evoked during the processing of the target and interferes with its identification.

Despite the similarities between neighbour priming effects in the present experiments and those reported previously for alphabetic languages, important differences need to be considered. Chief among these are the absence of a modulating influence of character frequency on orthographic priming in the masked priming experiments, the relatively weak effect of character frequency in eye fixation durations during reading, and the short-lived nature of the priming effect in fixation durations. By comparison with the present findings, which showed priming effects in early processing measures only, Paterson et al. (2009) obtained robust inhibitory priming effects in a broad range of fixation duration measures for target words, and these even spilled over to influence processing of the subsequent word. Several differences between the present experiments and prior research on neighbour priming in alphabetic languages may have contributed to these differences. First, particular care was taken in the present experiment to construct prime and target characters that, while orthographically similar, were phonologically dissimilar. This had the advantage in the present experiment of disentangling priming effects that are purely orthographic from those involving a combination of orthographic and phonological influences. It is difficult to disentangle these influences in alphabetic languages (because of fairly tight grapheme to phoneme mappings) and effects of orthographic and phonological overlap are often conflated in studies of neighbour priming effects in these languages. Consequently, while the present research reveals effects of orthographic influences on character recognition in Chinese, the conservative approach used to construct stimuli for these experiments may have produced less powerful priming effects, and this may have resulted in weaker effects of priming on fixations durations in reading.

Second, whereas studies of neighbour priming in alphabetic languages have relied primarily on letter substitution and the classic definition of neighbour relations (e.g., Coltheart et al, 1977) to assess effects of orthographic similarity, the present research examined priming effects for characters that

differed by the substitution, addition, or deletion of up to two character strokes. Both this broader definition of neighbour relations and the fact that character pairs differed in the number and location of stroke differences may have caused effects to be more variable in the present research than in previous studies using alphabetic languages. Third, Chinese characters are rarely read in isolation and usually combine with other characters to form words. Whether the prime and target characters we used in Experiment 3 were the first or second constituent of a word was difficult to control while also ensuring that sentences were meaningful and prime and target characters were the requisite distance apart. In addition, Chinese characters are rapidly combined to form words during reading, and these words will also differ in frequency. Evidence from other research has shown that while character and word frequency both influence eye movements while reading, the size of the character frequency effect is modulated by both the word frequency effect and whether this character is the first or second constituent of a two-character word (Yan et al., 2006). Consequently, the relatively weak influence of character frequency in the present experiment may be due to the short-lived nature of these effects and by whether the character typically forms the first or second constituent in a word. Again, this may have influenced effects of character frequency observed in the present experiments.

Third, effects of orthographic overlap between characters defined at the level of the stroke may differ from effects of orthographic similarity at the level of the letter in alphabetic languages. Indeed, while strokes and letters may be considered analogous levels of representation, differences in the status of strokes versus characters in word processing may lead to differences in sequential processing associated with lexical decomposition during reading in alphabetic and non-alphabetic languages (e.g., Tan et al., 1995; Chen & Peng, 2001; Chen et al., 2003; Liu et al., 2003; Yan et al., 2011; Yu, Feng, Cao, & Li, 1990). Such differences may also contribute to differential effects of orthographic similarity in alphabetic compared with character-based languages like Chinese. Finally, because

prime and target characters were only a short physical distance apart in Experiment 3, it is possible that the presence of a visually similar character in parafoveal vision will have interfered with target character identification. If this is the case, the effects may reveal a neighbour interference effect that is not dependent on memory for previously encountered targets. However, as the perceptual span for Chinese encompasses only 1 character to the left of fixation (and 3 characters to the right; Inhoff & Liu, 1998; see also Schotter, Angele, & Rayner, 2012), it was unlikely that readers could identify prime characters during the processing of target characters in our experiment.

In sum, the present research provides novel insights into effects of orthographic similarity on the recognition of Chinese characters using masked priming and measures of eye movements while reading. The findings show clearly that prior exposure to a character that differs by just one or two strokes from a target character, and therefore is its orthographic stroke neighbour, can slow recognition of that character, and so provide evidence of competition during character recognition in non-alphabetic languages. These findings, therefore, demonstrate that inhibitory neighbour priming effects shown previously for alphabetic languages are also observed for non-alphabetic languages and that neighbour priming (based on stroke overlap) occurs at the level of the character in Chinese.

Acknowledgements

This work was supported by the Chinese National Social Science Fund under Grant 13BYY071 to Professor Jingxin Wang. We are very grateful to Ken Forster and an anonymous reviewer for helpful comments on an earlier version of the manuscript.

References

- Andrews, S. (1997). The effect of orthographic similarity on lexical retrieval: Resolving neighbourhood conflicts. *Psychonomic Bulletin & Review*, 4, 439-461.
- Bijeljac-Babic, R., Biardeau, A., & Grainger, J. (1997). Masked orthographic priming in bilingual word recognition. *Memory & Cognition*, 25, 447-457.
- Brysbaert, M., Lange, M., & van Wijnendaele, I. (2000). The effects of age-of-acquisition and frequency-of-occurrence in visual word recognition: Further evidence from the Dutch language. *European Journal of Cognitive Psychology*, 12, 65-85.
- Chen, B. G., & Peng, D. L. (2001). The time course of graphic, phonological, and semantic information processing in Chinese character recognition (I). *Acta Psychologica Sinica*, 33, 1-6.
- Chen, B. G., Wang, L.X., & Peng, D. L. (2003). The time course of graphic, phonological, and semantic information processing in Chinese character recognition (II). *Acta Psychologica Sinica*, 35, 576-581.
- Colombo, L. (1986). Activation and inhibition with orthographically similar words. *Journal of Experimental Psychology: Human Perception & Performance*, 12, 226-234.
- Coltheart, M., Davelaar, E., Jonasson, J. F., & Besner, D. (1977). Access to the internal lexicon. In S. Dornič (Ed.), *Attention and performance VI* (pp. 535-555). Hillsdale, NJ: Erlbaum.
- Davis, C. J. (2003). Factors underlying masked priming effects in competitive network models of visual word recognition. In S. Kinoshita & S. J. Lupker (Eds.), *Masked priming: The state of the art* (pp. 121-172). Philadelphia: Psychology Press.
- Davis, C. J., & Lupker, S. J. (2006). Masked inhibitory priming in English: Evidence for lexical inhibition. *Journal of Experimental Psychology: Human Perception & Performance*, 32, 668-687.
- Davis, C. J., & Taft, M. (2005). More words in the neighbourhood: Interference in lexical decision due to deletion neighbours. *Psychonomic Bulletin & Review*, 12, 904-910.

- De Moor, W., & Brysbaert, M. (2000). Neighbourhood-frequency effects when primes and targets are of different lengths. *Psychological Research*, 63, 159-162.
- De Moor, W., Van der Herten, E., & Verguts, T. (2007). Is masked neighbour priming inhibitory? Evidence using the incremental priming technique. *Experimental Psychology*, 54, 113-119.
- Ding, G., Peng, D., & Taft, M. (2004). The nature of the mental representation of radicals in Chinese: A priming study. *Journal of Experimental Psychology: Human Perception & Performance*, 30, 530-539.
- Drews, E., & Zwitserlood, P. (1995). Morphological and orthographic similarity in visual word recognition. *Journal of Experimental Psychology: Human Perception & Performance*, 21, 1098-1116.
- Ferrand, L. & Grainger, J. (1993). The time-course of phonological and orthographic code activation in the early phases of visual word recognition. *Bulletin of the Psychonomic Society*, 31, 119-122.
- Forster, K. I. (1987). Form-priming with masked primes: The best-match hypothesis. In M. Coltheart (Ed.), *Attention & Performance XII*. (pp. 127-146). Hillsdale, N.J.: Erlbaum.
- Forster, K. I., & Davis, C. (1984). Repetition priming and frequency attenuation in lexical access. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 10, 680-698.
- Forster, K. I., Davis, C., Schoknecht, C., & Carter, R. (1987). Masked priming with graphemically related forms: Repetition or partial activation? *Quarterly Journal of Experimental Psychology*, 39A, 211-251.
- Forster, K. I., Mohan, K., & Hector, J. (2003). The mechanics of masked priming. In S. Kinoshita & S. J. Lupker (Eds.), *Masked priming: The state of the art* (pp. 3-37). Hove, England: Psychology Press.
- Forster, K. I., & Veres, C. (1998). The prime lexicality effect: Form priming as a function of prime awareness, lexical status, and discrimination difficulty. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 24, 498-514.
- Frost, R. (2012). Towards a universal model of reading. *Behavioral and Brain Sciences*, in press.
- Grainger, J., Colé, P., & Segui, J. (1991). Masked morphological priming in visual word recognition.

Journal of Memory & Language, 30, 370-384.

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

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

Huang, H-W., Lee, C-Y., Tsai, J-L., Lee, C-L., Hung, D. L., & Tzeng, O. J-L. (2006). Orthographic neighbourhood effects in reading Chinese two-character words. *NeuroReport*, 17, 1061-1065.

Inhoff, A. W., & Liu, W. (1998). The perceptual span and oculomotor activity during the reading of Chinese sentences. *Journal of Experimental Psychology: Human Perception and Performance*, 24, 20-34.

Li, G. Y. & Liu, R. S. (1988), *A dictionary of Chinese character information* (pp. 1228-1662). Beijing: Science Press.

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

Lupker, S. J., & Colombo, L. (1994). Inhibitory effects in form priming: Evaluating a phonological competition explanation. *Journal of Experimental Psychology: Human Perception & Performance*, 20, 437-451.

Mayr, S., & Buchner, A. (2006). Evidence for episodic retrieval of inadequate prime responses in auditory negative priming. *Journal of Experimental Psychology: Human Perception and Performance*, 32, 932-943.

McClelland, J. L., & Rumelhart, D. E. (1981). An interactive activation model of context effects in letter perception: Part 1. An account of basic findings. *Psychological Review*, 88, 375-405.

Nakayama, M., Sears, C. R., & Lupker, S. J. (2008). Masked priming with orthographic neighbours: A test

of the lexical competition assumption. *Journal of Experimental Psychology: Human Perception and Performance*, 34, 1236-1260.

Nakayama, M., Sears, C. R., & Lupker, S. J. (2011). Lexical competition in a non-Roman, syllabic script: An inhibitory neighbour priming effect in Japanese Katakana. *Language and Cognitive Processes*, 26, 1136-1160.

Neill, W.T., Valdes, L.A., & Terry, K.M. (1995). Selective attention and the inhibitory control of cognition. In F.N. Dempster & C.J. Brainerd (Eds.), *Interference and inhibition in cognition* (pp. 207–261). San Diego, CA: Academic Press, Inc.

Paterson, K. B., Alcock, A., & Liversedge, S. P. (2011). Morphological priming during reading: Evidence from eye movements. *Language and Cognitive Processes*, 26, 600-623.

Paterson, K. B., Liversedge, S. P., & Davis, C. J. (2009). Inhibitory neighbour priming effects in eye movements during reading. *Psychonomic Bulletin & Review*, 16, 43-50.

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

Perea, M., & Rosa, E. (2000). Repetition and form priming interact with neighbourhood density at a short stimulus-onset asynchrony. *Psychonomic Bulletin & Review*, 7, 668-677.

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

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

Rayner, K. (1998). Eye movement in reading and information processing: 20 years of research. *Psychological Bulletin*, 124, 372-422.

- Rayner, K. (2009). The Thirty-fifth Sir Frederick Bartlett Lecture: Eye movements and attention in reading, scene perception, and visual search. *Quarterly Journal of Experimental Psychology*, 62, 1457-1506.
- Reichle, E. D., Pollatsek, A., Fisher, D. L., & Rayner, K. (1998). Toward a model of eye movement control in reading. *Psychological Review*, 105, 125-157.
- Reichle, E. D., Warren, T., & McConnell, K. (2009). Using E-Z Reader to model the effects of higher-level language processing on eye movements during reading. *Psychonomic Bulletin & Review*, 16, 1-21.
- Schotter, E. R., Angele, B., & Rayner, K. (2012). Parafoveal processing in reading. *Attention, Perception, & Psychophysics*, 74, 5-35.
- Segui, J., & Grainger, J. (1990). Priming word recognition with orthographic neighbours: Effects of relative prime-target frequency. *Journal of Experimental Psychology: Human Perception & Performance*, 16, 65-76.
- Seidenberg, M. S., & McClelland, J. L. (1989). A distributed, developmental model of word recognition and naming. *Psychological Review*, 96, 523-568.
- Shen, D., & Forster, K. (1999). Masked phonological priming in reading Chinese words depends on the task. *Language and Cognitive Processes*, 14, 429-460.
- Slattery, T. (2010). Word misperception the neighbour frequency effect and the role of sentence context: An eye movement investigation. *Journal of Experimental Psychology: Human Perception and Performance*, 35, 1969-1975.
- Taft, M., & Chen, H. C. (1992). Judging homophony in Chinese: The influence of tones. In H. C. Chen, & O. Tzeng (Eds.), *Language processing in Chinese* (151-172). Amsterdam: North-Holland/Elsevier.
- Taft, M., Zhu, X., & Peng, D. (1999). Positional specificity of radicals in Chinese character recognition. *Journal of Memory and Language*, 40, 498-519.
- Tan, L. H., Hoosain, R., & Peng, D. L. (1995). Role of early presemantic phonological code in Chinese

character identification. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 21, 43-54.

Tenpenny, P. L. (1995). Abstractionist versus episodic theories of repetition priming and word identification. *Psychonomic Bulletin & Review*, 2, 339-363.

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

Wang, W. J., & Yan, G. L. (2006). Eye movement study on the graphic fast priming in Chinese reading. *Studies of Psychology and Behavior*, 4, 213-217.

Williams, C. C., Perea, M., Pollatsek, A., & Rayner, K. (2006). Previewing the neighbourhood: The role of orthographic neighbours as parafoveal previews in reading. *Journal of Experimental Psychology: Human Perception & Performance*, 32, 1072-1082.

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

Yan, G L., Bai, X. J., Zang, C. L., Bian, Q., Cui, L., Qi, W., Rayner, K., & Livversedge, S. P. (2011). Using stroke removal to investigate Chinese character identification during reading: Evidence from eye movements. *Reading and Writing*, 25, 951-979.

Yan, G. L., Tian, H. J., Bai, X. J., & Rayner, K. (2006). The effect of word and character frequency on the eye movements of Chinese readers. *British Journal of Psychology*, 97, 259-268.

Yu, B. L., Feng, L., Cao, H. Q., & Li, W. L. (1990). Visual perception of Chinese characters: Effects of perceptual task and Chinese character attributes. *Acta Psychologica Sinica*, 22, 141-148.

Zang, C. L., Livversedge, S. P., Bai, X. J., & Yan, G. L. (2011). Eye movements during Chinese reading. In S. P. Livversedge, I. Gilchrist, & S. Everling (Eds.), *The Oxford Handbook of Eye Movements* (pp. 961-978). Oxford: Oxford University Press.

Zhou, X., Marslen-Wilson, W., Taft, M., & Shu, H. (1999). Morphology, orthography, and phonology in reading Chinese compound words. *Language and Cognitive Processes*, 14, 525-565.

Footnote

1. The vast majority of prime and target character were compound characters. Further analyses showed that target characters that were simple or compound character both produced inhibitory priming, although this was larger for the compound characters (simple character target: $PE = -3$ ms; compound character target: $PE = -18$ ms).

Appendix: Neighbour Pairs Used as Prime and Target Characters in Experiments 1 and 2a-c*

HF	LF
细	绅
选	迭
响	晌
惑	惑
兵	丘
斤	斥
抗	坑
苦	苦
助	肋
尺	尸
太	犬
江	汇
卷	券
否	杏
九	丸
西	酉
任	仕
史	吏
参	叁
边	迈
白	臼
官	官
未	禾
待	侍
印	卯
猪	猪
抽	押
囚	囚
宅	宅
堤	堤
习	勺
庆	仄
伸	佃
闲	闲
究	穷
告	吉
义	叉
电	申
天	矢

*LF = low character frequency; HF = high character frequency. In the neighbour priming conditions, each higher frequency neighbour served as a prime for a lower frequency target (HF prime - LF target)

condition) or vice versa (LF prime - HF target condition).

Figure Title

Figure 1. Examples of sentence stimuli used in Experiment 3. Vertical lines delineate regions of analysis.