Character-Complexity Effects in Chinese Reading and Visual Search: A Comparison and Theoretical Implications

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Working draft; please do not cite without permission.

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Three eye-movement experiments were conducted to examine how the complexity of characters in Chinese words (i.e., number of strokes per character) influences their processing and eye-movement behavior. In Experiment 1, English speakers with no significant knowledge of Chinese searched for specific low-, medium-, and high-complexity target characters in a multi-page narrative containing characters of varying complexity (3-16 strokes). Fixation durations and skipping rates were influenced by the visual complexity of both the target characters and the characters being searched, with the latter findings replicating previous reports (e.g., Liversedge et al., 2014) but in participants with no knowledge of Chinese. In Experiment 2, native Chinese speakers performed the same character-search task and a similar pattern of results was observed. Finally, in Experiment 3, a second sample of native Chinese speakers read the same text used in Experiments 1 and 2, with text characters again exhibiting complexity effects. These results collectively suggest that character-complexity effects on eye movements may not be due to lexical processing per se but may instead reflect whatever visual processing is required to know whether or not a character corresponds to an episodically-represented target (Baddeley, 2002). The theoretical implications of this for our understanding of normal reading are discussed.

One of Keith Rayner's many contributions to the psychology of reading was his promotion of eye-movement methods to the study of Chinese reading. He and his colleagues conducted many of the first experiments using eye movements to make informed inferences about the mental processes that are engaged during Chinese reading (e.g., Rayner, Li, Juhasz, & Yan, 2005; Yan, Tian, Bai, & Rayner, 2006; Bai, Yan, Liversedge, Zang, & Rayner, 2008), and how those processes are similar to and—in some instances—different from those that are engaged during the reading of alphabetic languages like English and German (for a review, see Zang, Liversedge, Bai, & Yan, 2011). Although considerable progress has been made in this research, many basic questions about Chinese reading remain unanswered. One that will be addressed in this article concerns the relative importance of visual processing for the mental representation of Chinese characters. More precisely, the question that we attempt to address is: Do previous reports showing that the complexity of Chinese characters influences fixation durations on those characters have their basis in early visual processing, or do they instead reflect some later stage of lexical processing? However, before we describe how this question was addressed, it is necessary to provide a brief background about the Chinese writing system.

Chinese is written using logographic characters that historically often directly represented their referent (e.g., a character resembling a horse to represent the word "horse"; Chang & Chang, 1978). Each character is comprised of 1-36 short line segments that—again, historically—correspond to individual brush strokes (because Chinese was written with a brush and ink). These strokes are in turn often arranged into one or more smaller clusters called *radicals* that often provide information about the meaning or pronunciation of the character. Individual words in Chinese are then comprised of one or more of these characters, with approximately 70% consisting of two characters, 20% consisting of a single character, and the remainder consisting of three or four characters.

Given the above, one important difference between written Chinese and alphabetic writing systems is the relative lack of compositionality in the former. That is, whereas individual words in alphabetic languages are comprised of combinations of a relatively small number of letters (26 in English), the 3,000-5,000 words that a Chinese reader must know to read a newspaper are each unique, being comprised of unique arrangements of strokes, radicals, and characters. This difference between alphabetic writing systems and Chinese may have important ramifications for how words in the respective languages are identified on the printed page. In the case of English, for example, there is evidence that the visual features that comprise individual letters (e.g., line segments) are somehow rapidly converted to more abstract orthographic representations so that, for example, the visual features corresponding to “g” and “G” activate the same representation in memory despite of being visually distinct. This was perhaps most convincingly demonstrated by McConkie and Zola (1979; see also Rayner, McConkie, & Zola, 1980) in a gaze-contingent eye-movement experiment wherein text was written in alternating letter case (e.g., “LiKe ThIs”), with individual letters switching their case during specified saccades (e.g., “lIkE tHiS"). Remarkably, the eye movements in this condition were no different from those in which the alternating letter case did not switch with each fixation, providing evidence that the visual features corresponding to the individual letters were rapidly converted into more abstract orthographic codes. This suggests that, apart from providing the raw input to activate orthographic codes, the visual input may actually play a relatively minor role in the reading of alphabetic languages.

Additional evidence suggesting that the visual encoding of words can be dissociated from more abstract orthographic processing in alphabetic languages comes from eye-movement experiments in which *visual length* (i.e., spatial extent) is manipulated independently from *orthographic length* (i.e., number of letters). These experiments (e.g., McDonald, 2006; Hautala, Hyönä, & Aro, 2011) have shown that visual length influences fixation locations and skipping probabilities (e.g., words that are visually shorter tend to be skipped more often) but not fixation durations, whereas orthographic length shows the opposite pattern (e.g., words that are orthographically shorter tend to be the recipients of shorter fixations).

Although comparable experiments to investigate the dissociation between visual encoding versus orthographic processing have not been conducted in Chinese, there is evidence that visual processing may play an even more significant role in reading this language. For example, Liversedge et al. (2014; see also Yang & McConkie, 1999) manipulated both the frequency and complexity (i.e., number of strokes) of single-character target words in text and found longer fixation durations on low-frequency complex characters. And although both variables also influenced saccade targeting, with both high-frequency characters and simple characters being more likely to be skipped than either low-frequency or complex characters, there was no interactive effect of these two variables on where readers looked. This pattern of findings was interpreted as providing evidence consistent with the dissociation between "decisions" about when versus where to move the eyes during reading (e.g., see Rayner & Pollatsek, 1981), as well as demonstrating an important role of visual processing that is not well described by current models of eye movement control during reading (e.g., *E-Z Reader*: Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Pollatsek, & Rayner, 2012; *SWIFT*: Engbert, Nuthmann, Richter, & Kliegl, 2005; Schad & Engbert, 2012). If this interpretation is correct, then one prediction that follows is that it should be possible to demonstrate an effect of character complexity even in subjects who cannot read Chinese because the effects should not be dependent upon lexical processing or having representations of Chinese characters in memory. And if the visual encoding of words plays a more significant role in Chinese than alphabetic languages, then another prediction might be that character complexity should influence both *where* (e.g., as with the visual-length effect in alphabetic languages) and *when* the eyes move. The purpose of this article and the experiments reported next was to test these predictions.

Experiment 1

Experiment 1 employed a visual-search task in which English speakers (with no significant exposure to Chinese) scanned Chinese text to locate specific target characters. The logic of this experiment is thus simple: to demonstrate that skipping rates and fixation durations on individual characters are modulated by their complexity, even in subjects who have no representations of those characters (thus precluding an explanation of the effect based on lexical processing).

Method

Participants. 27 English speakers who indicated no experience with speaking or reading Chinese took part in this experiment at the University of Southampton. All the participants had normal or corrected-to-normal vision.

Materials and Design. 14 short narrative passages from Chinese primary school texts (grades 5 and 6) were used in the experiment. The passages were displayed as multi-line pages on the monitor, with one of three possible target characters being displayed at the top of each page (see Figure 1). The participants' task was to search for the target character and indicate via button presses the number of times it appeared on each given paragraph of text (0-5 times). Target characters were matched for frequency (453 per million on average based on *Chinese Character Information Dictionary*) but varied in visual complexity: (1) low complexity ("火 ", 4 strokes); (2) medium complexity ("神 ", 9 strokes); and high complexity ("算 ", 14 strokes). The three target characters were presented in separate blocks of trials, and the order of these blocks was counterbalanced across participants. The target characters were randomly embedded in the text.

Figure 1

Apparatus and Procedure. Eye movements were measured with an SR Research EyeLink 1000-Plus system with a 1,000 Hz sampling rate. A chin rest and forehead rest were used to minimize head movements. The display monitor was a 24-inch Asus VG248QE monitor with a refresh rate of 144 Hz and a screen resolution of 1,920 × 1,080 pixels. The distance between the monitor and participant was approximately 93 cm, so that each character subtended 0.5° of visual angle. Although viewing was binocular, only participants' right eyes were tracked. A 9-point calibration was used in the experiment. Following calibration, average gaze-position error was less than 0.5º.

At the beginning of a trial, participants were required to fixate on a small fixation dot and to press a button. This triggered the text to appear on the screen. The fixation dot was centered horizontally, and it was located one degree of visual angle above the top line in the paragraph of text that was subsequently displayed on the screen. To remind the participants which target character to search for, the target character was shown above the paragraph of text (in the same location as the fixation dot at the start of the trial). To end the trial, participants pressed a button to indicate the number of times the target appeared in the paragraph of text (0-5 times). The participants received feedback at the end of the trial to indicate if their response was accurate or inaccurate.

Results and Discussion

Search Accuracy. Participants correctly indicated the number of target-character occurrences on 88% of the trials (chance performance = 20%), thus demonstrating that they were engaged in the search task.

Eye-Movement Measures. All the characters in the texts were treated as interest areas. Because there were very few characters having fewer than 3 or more than 16 strokes, these characters were excluded from our analyses. (Table 1 shows the percentage of characters containing different number of strokes in the passages.) Interest areas with first-fixation durations shorter than 80 ms or longer than 1,000 ms were also excluded, resulting in 3.4% of the interest areas being excluded from our analyses. Three dependent measures were analysed: (1) *first-fixation duration*, or the duration of the initial fixation on a character, including those initially fixated after a regression; (2) *dwell time*, or the sum of all fixation durations on a character; and (3) *skipping rate*, or the proportion of characters that were not fixated.

Table 1

Figure 2 shows the mean first-fixation durations, dwell times, and skipping rates on 3-16 stroke characters as a function of target-character complexity. Linear regression analyses were carried out separately for each level of target complexity. When searching for the high-complexity target, there were significant linear relationships between character complexity and all three dependent measures [first-fixation durations: $R^2 = 0.61$, $F(1,12) = 18.62$, $p < 0.005$; dwell times; $R^2 = 0.70$, $F(1,12) = 27.52$, $p < 0.001$; skipping rates: $R^2 = 0.76$, $F(1,12) = 38.36$, $p < 0.001$], with complex characters being fixated longer and skipped less often than simple characters. The same pattern was also evident when searching for the medium-complexity target [first-fixation durations: $R^2 = 0.83$, $F(1,12) = 59.52$, $p < 0.001$; dwell times: $R^2 = 0.37$, $F(1,12) = 6.92$, $p < 0.05$; skipping rates: $R^2 = 0.43$, $F(1,12) = 9.11$, $p < 0.05$]. However, when searching for the low-complexity target, this pattern was limited to skipping rates [$R^2 = 0.91$, $F(1,12) = 61.38$, $p < 0.001$], with complex characters being skipped more often than simple characters. Thus, the complexity of both the fixated characters and the characters being search for modulated the decisions about whether to look at a character, and if so, for how long.

Figure 2

Table 2 shows the mean first-fixation durations, dwell times, and skipping rates as a function of target-character complexity. A repeated-measures Analysis of Variance (*ANOVA*) was conducted for each dependent measure using target complexity (low vs. medium vs. high) as a within-participant factor and participants as a random factor. These analyses indicated significant effects of target complexity for first-fixation durations [$F(2, 52) = 29.61$, $p < 0.001$], dwell times [$F(2, 52) = 15.62$, $p < 0.001$], and skipping rates [$F(2, 52) = 43.08$, $p < 0.001$]. Paired-contrasts using *t*-tests indicated that first-fixation durations were longer when searching for the medium- than the high-complexity target [$t(26) = 3.34$, $p < 0.005$] and longer when searching for the high- than the low-complexity target [$t(26) = 4.32$, $p < 0.005$]. The same pattern was evident for dwell times [$t(26) = 2.21$, $p < 0.05$; $t(26) = 4.88$, $p < 0.001$]. And consistent with these findings, skipping rates were higher when searching for the low- than the high-complexity target [$t(26) = 5.87$, $p < 0.001$] and for the high- than the medium-complexity target [$t(26) = 3.16$, $p < 0.005$]. Search difficulty was thus influenced by target-character complexity, being most difficult for the medium-complexity target and easiest for the low-complexity target.

Table 2

Finally, to examine the possible confound between character complexity and frequency, all non-target characters were divided into high- vs. low-frequency groups (using median splits) for each level of character complexity (3-16 strokes). *t*-tests indicated no effects of character frequency on first-fixation durations [$t(754) = 0.40$, $p =$

0.69], dwell times [$t(754) = 1.43$, $p = 0.15$] , or skipping rates [$t(754) = 1.51$, $p = 0.13$], as would be expected given that the participants had no knowledge of Chinese characters.

Experiment 2

Experiment 2 used the same paradigm and materials as Experiment 1 but with native speakers of Chinese as participants. The goal of this experiment was to replicate character-complexity effects in participants with knowledge of Chinese characters to allow direct comparison of these effects to those observed in Experiment 1.

Method

Participants. 18 native Chinese speakers took part in this experiment at Ludong University. All participants had normal or corrected-to-normal vision.

Materials and Design. Same as Experiment 1.

Apparatus and Procedure. An SR Research EyeLink 1000-Plus eye-tracker with a 1,000 Hz sampling rate was used to collect the data. The display monitor was 19-inch CRT monitor with a refresh rate of 100 Hz and a screen resolution of 1,024 × 768 pixels. The distance between the participants was approximately 70 cm, so that each character subtended 0.9° of visual angle. Viewing was binocular but only the right eye was tracked. A 9-point calibration was used in the experiment. Following calibration, average gaze-position error was less than 0.5º. All other aspects of the apparatus and procedure were identical to Experiment 1.

Results and Discussion

Search Accuracy. Participants correctly indicated the number of target-character occurrences on 87% of the trials.

Eye-Movement Measures. The same exclusion criteria were used as in Experiment 1, resulting in 3.7% of the interest areas being excluded.

Figure 3 shows the mean first-fixation durations, dwell times, and skipping rates on 3-16 stroke characters as a function of target-character complexity. Regression analyses indicated significant linear relationships between character complexity and all three dependent measures when searching for both the high-complexity target [first-fixation durations: $R^2 = 0.38$, $F(1,12) = 7.21$, $p < 0.05$; dwell times: $R^2 = 0.51$, $F(1,12) =$

12.68, $p < 0.005$; skipping rates: $R^2 = 0.95$, $F(1,12) = 233.80$, $p < 0.001$] and the medium-complexity target [first-fixation durations: $R^2 = 0.77$, $F(1,12) = 41.08$, $p < 0.001$; dwell times: $R^2 = 0.67$, $F(1,12) = 24.16$, $p < 0.001$; skipping rates: $R^2 = 0.83$, $F(1,12) = 57.55$, $p < 0.001$], with complex characters being fixated longer and skipped less often than simple characters. However, when searching for the low-complexity target, character complexity only correlated with the two fixation measures [first-fixation duration: $R^2 = 0.37$, $F(1,12) = 7.09$, $p < 0.05$; dwell times: $R^2 = 0.33$, $F(1,12) = 5.97$, $p < 0.05$]. Thus, as was observed in Experiment 1 with English speakers, the complexity of both the fixated and target characters influenced fixation durations and probabilities.

Figure 3

Table 2 shows the mean first-fixation durations, dwell times, and skipping rates as a function of target-character complexity. Repeated-measures ANOVAs using target complexity (low vs. medium vs. high) as a within-participant factor and participants as a random factor indicated significant target-complexity effects for first-fixation durations [$F(2, 34) = 3.94$, $p < 0.05$], dwell times [$F(2, 34) = 6.64$, $p < 0.005$], and skipping rates [$F(2, 34) = 16.68$, $p < 0.001$]. Paired *t*-tests were indicated that both first-fixation durations and dwell times were longer when searching for the high- than the low- or the medium-complexity target [all *t*s > 1.86, all *p*s < 0.08]. Skipping rates were also higher when searching for the low- than the medium-complexity target [$t(17) = 2.92$, $p < 0.01$] and for the medium- than the high-complexity target [$t(17) = 2.42$, $p < 0.05$]. The overall influence of target-character complexity thus appears different for English-speaking versus Chinese-speaking participants: Whereas the former participants had the most difficulty looking for the medium-complexity target, the latter participants had the most difficult looking for the high-complexity target.

To further examine possible differences between English- and Chinese-speaking participants, a 3-way mixed-effect ANOVA was completed for each dependent measure, using target complexity (low vs. medium vs. high) and complexity of fixated characters (3-9 strokes vs. 10-16 strokes) as within-participant factors, and experiment (Experiment 1 vs. Experiment 2) as a between-participants factor. For first-fixation durations, the main effects of target character complexity, fixated character complexity, and experiment were all significant (all Fs > 19.56, all ps < 0.001). In comparison with the Chinese speakers, the English speakers spent more time fixating the characters, which is consistent with previous findings (e.g., see Rayner, Li, Williams, Cave, & Well, 2007). Both the Character Complexity × Target Complexity and Target Complexity × Experiment interactions were significant [both Fs > 17.54, ps < 0.001], as was Character Complexity × Target Complexity × Experiment interaction [$F(2, 86) = 4.03$, $p < 0.05$]. Simple effect tests showed that, for English-speaking participants, the target-complexity effect was significant regardless of the fixated character complexity [both Fs > 25.64, ps < 0.001], while for Chinese-speaking participants, the target-complexity effect was only significant for characters containing 10-16 strokes [$F(2, 86) = 4.58$, $p < 0.05$]. A similar pattern of results was observed for dwell times and skipping rates (i.e., all three main effects, both two-way interactions, and the three-way interaction were significant; all Fs > 2.92, ps < 0.06), but with the Character Complexity × Experiment interaction also being significant for skipping rates [$F(1, 43) = 18.64$, $p < 0.001$]. These interactions suggest that knowledge of Chinese characters made the search task easier for Chinese-speaking participants, although it must be acknowledged that between-experiment differences in the apparatus (e.g., differences in the computer monitors that were used) may have also contributed.

Finally, all non-target characters were divided into high- vs. low-frequency groups (using median splits) for each level of character complexity (3-16 strokes) to examine possible effects of character frequency. No such effects were observed for any of the three dependent measures [first-fixation durations: $t(754) = 0.19$, $p = 0.85$; dwell times: $t(754) = 0.14$, $p = 0.89$; skipping rates: $t(754) = 0.52$, $p = 0.60$], consistent with Rayner and Fischer's (1996) findings that word-frequency effects are absent or attenuated when participants search for target words in English text.

Experiment 3

Experiment 3 used the same materials as the previous two experiments but a different task: Native speakers of Chinese were instructed to simply read the text for comprehension (while ignoring the extra target characters that had been inserted into the text to make the search task viable in the first two experiments). The goal of this experiment was thus to allow a direct comparison of character-complexity effects in visual search versus reading.

Method

Participants. 18 native Chinese speakers from Ludong University who did not participate in Experiment 2 participated in Experiment 3. All participants had normal or correct-to-normal vision.

Materials and Design. The participants' tasks were to read and comprehend the passages, and to answer 18 two-alternative comprehension questions about the text. Participants were also explicitly instructed to ignore the "odd" characters embedded in the passages (i.e., the search-task targets) which were retained so that the stimuli would be identical across Experiments 1-3.

Apparatus and Procedure. The apparatus and procedure were the same as Experiment 2, with the exception that participants were instructed to read for comprehension and the target characters were no longer displayed above each paragraph. After reading each paragraph, the participants pressed a button to end the trial. Two-alternative comprehension questions were presented after approximately 35% of trials, with immediate feedback about response accuracy.

Results and Discussion

Comprehension Accuracy. Participants correctly answered 79% of the text comprehension questions (chance performance = 50%), thus demonstrating that they understood the text.

Eye-Movement Measures. 5.7% of the interest areas were excluded due to first fixations that were shorter than 80 ms or longer than 1,000 ms.

Figure 4 shows the mean first-fixation durations, dwell times, and skipping rates on 3-16 stroke characters as a function of target-character complexity. Regression analyses indicated a significant linear relationship between character complexity and first-fixation durations [$R^2 = 0.64$, $F(1,12) = 21.80$, $p < 0.005$], dwell times [$R^2 = 0.87$, $F(1,12) = 78.00$, $p < 0.001$], and skipping rates [$R^2 = 0.86$, $F(1,12) = 72.66$, $p < 0.001$].

The observed effects of character complexity on fixation durations and locations thus generalized across both visual search and reading.

Figure 4

Table 2 shows the mean first-fixation durations, dwell times, and skipping rates as a function of target-character complexity. Although participants were reading and not searching for specific target characters, to ensure the target characters embedded in the passages did not cause any obvious disruptions, the pages in which participants searched for the different targets used in Experiments 1 and 2 were assigned to those targets and used as a within-participant factor ("low" vs. "medium" vs. "high") in repeated-measures ANOVAs. As expected, these analyses indicated no significant effects for first-fixation durations [$F(2, 34) = 0.85$, $p = 0.44$], dwell times [$F(2, 34) = 0.10$, $p = 0.91$], or skipping rates [$F(2, 34) = 0.79$, $p = 0.46$], which confirms that it is the characteristics of the text on these pages (rather than the target characters per se) that contributed to the observed differences in the three dependent measures in this experiment. Additionally, the fact that the embedded target characters had no discernable effect in Experiment 3 but has marked effects in Experiments 1 and 2 further supports our conclusion that differences in target-character complexity influenced fixation durations and locations in search but not reading.

Finally, relative to what was observed when Chinese-speaking participants searched for target characters (i.e., Experiment 2), dwell times were inflated [$t(34) = 2.88$, $p < 0.01$] and skipping rates were reduced [$t(34) = 3.27$, $p < 0.005$] during reading. And after controlling for character complexity, there were character-frequency effects for all measures [first-fixation durations: $t(502) = 1.86$, $p = 0.062$; dwell times: $t(502) = 2.74$, $p < 0.01$; skipping rates: $t(502) = 2.47$, $p < 0.05$], adding additional support for the conclusion that the word-frequency effects that are ubiquitous during normal reading are absent or attenuated during search (Rayner & Fischer, 1996).

General Discussion

The results of Experiments 1-3 can be summarized as follows. Experiment 1 showed that English speakers searching for specific target characters in Chinese text made longer fixations on and were less likely to skip characters of increasing complexity. Additionally, fixation durations and skipping rates were modulated by the complexity of the target character, with longer fixations and less skipping when searching for the medium-complexity character. Experiment 2 replicated these findings with native Chinese speakers, but with longer fixations and less skipping when searching for the high-complex target. Finally, Experiment 3 extended these results to natural reading, showing that native Chinese speakers both make longer fixations on and are less likely to skip complex characters. This overall pattern provides clues about the nature of lexical processing in Chinese reading, and how it might differ from lexical processing of alphabetic languages like English.

The fact that the participants in Experiment 1 were English speakers with no prior experience with Chinese significantly curtailed how they might have performed the character-search task: On each trial, participants had to first study the target character so that it might be actively maintained in working memory, to be used as a "template" against which each fixated character might then be compared. How this comparison was done is suggested by two key findings. First, the main effect of the target-character complexity indicates that the relative ease of representing a target in working memory so that it could be compared to each fixated character was differentially influenced by the target's complexity (although this might reflect factors other than the number of strokes; e.g., similarity to known shapes, differences in distinctiveness, etc.). This interpretation is consistent with Rayner and Fisher's (1987a, 1987b) findings that fixation durations in visual search increase as the similarity between targets and distractors increases. This interpretation therefore suggests that the medium-complexity target may have been more difficult to locate than the low- or the high-complexity target because of its greater overall similarity to the characters in the text. This hypothesis is supported by an analysis using the *RadicalLocator* software (Yu, Reichle, Jones, & Liversedge, 2015) to quantify the mean similarity between target and non-target characters: The medium-complexity target was more similar to non-target characters (similarity value = 1.24) than was either the low- (2.48) or the high- (2.22) complexity target (where smaller numbers indicate greater similarity).

The second key finding is the effect of the fixated character's complexity, which indicates that the comparisons were also likely influenced by variables that might be expected to co-vary with complexity (e.g., lateral masking due to visual crowding). Importantly, this latter result per definition must reflect the visual processing of each fixated character and/or the process of comparing it to the target character because the participants had no prior knowledge of Chinese characters to draw upon in performing the task. However, we must acknowledge that this account of Experiment 1 remains tentative pending further investigation.

Next consider the participants in Experiment 2, who were native Chinese speakers performing the same search task. Because participants had extensive knowledge of Chinese, the effort required to actively maintain the target character in working memory was likely reduced by drawing upon representations already in long-term memory. This conjecture is supported by the overall reduction in fixation durations (indicating that comparisons between the target and each fixated character were less effortful; cf., Figures 2 vs. 3) and by the different ordering of the target-character complexity effects observed in Experiment 2 (e.g., where dwell times increased from the low- to the medium- to the high-complexity target) than Experiment 1 (e.g., where dwell times were longest for the medium-complexity target). Again, the effect of the fixated character's complexity might reflect each fixated character's visual processing and/or its comparison to the target character.

Finally, the participants in Experiment 3 were native Chinese speakers who read the same passages of text used in Experiments 1 and 2. The fact that participants accurately answered the text comprehension questions in conjunction with longer fixation durations in this experiment relative to the previous two (see Rayner & Fischer, 1996) indicates that participants were engaged in normal reading. Importantly, despite the absence of any secondary requirement of having to decide whether or not a given character matched some pre-specified target, there was still an effect of the fixated character's complexity, suggesting that the effect reflects whatever visual processing is necessary to identify a character.

Putting all of these findings together, one might posit that, in contrast to alphabetic writing systems in which the visual features of individual letters can be rapidly converted into abstract lexical codes, the processing of Chinese characters is much more reliant upon whatever visual (e.g., configural) processing is required to generate those codes. And because these lexical codes require time to generate, their generation is apparently affected by their complexity to a greater degree than is true with English, perhaps because the process of converting individual strokes into the representations of radicals and characters is done in a serial or capacity-limited parallel manner (see Townsend, 1972). Although this is speculative and runs counter to models of alphabetic word identification in which letters are processed in parallel (e.g., McClelland & Rumelhart, 1981; Plaut, McClelland, Seidenberg, & Patterson, 1996), there is some theoretical precedent for the serial assembly of sub-lexical codes even in alphabetic languages like English (e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Davis, 2010; Whitney, 2001).

From a computational perspective, the hypothesis that visual processing plays a more pronounced role in Chinese than alphabetic languages makes sense if one considers two main differences between the writing systems. The first is that words written in English are comprised of configurations of 26 unique letters, whereas words written in Chinese are comprised of 1-36 strokes arranged into a hierarchy of radicals and/or characters. The second is that the letters in English words are arranged along a single spatial dimension, whereas the strokes, radicals, and characters in Chinese words are arranged along two spatial dimensions. These differences are shown schematically in Figure 5. As shown, the visual features of English words can be readily converted into lexical code because of their relatively simplicity (or invariance) and because their relative spatial positions are represented along only one dimension. In contrast, the visual features of Chinese words have to be converted into a series of intermediate representations that require the preservation of their relative positions in two spatial dimensions. These differences are schematically shown in Figure 5 by the black arrows indicating the visual processing needed to convert visual features into lexical codes. Although the visual processing needed to generate the correctly ordered orthographic codes for the letters in "cat" might be less than what is required to do the same for the letters in "gray", this difference is fairly small and—with alphabetic languages like English—will always be confounded with visual acuity (i.e., "gray" extends further from the center of vision than "cat"). In contrast, the visual processing needed to generate the lexical codes for the two Chinese words are markedly different (i.e., 6 vs. 12 strokes), and these differences are propagated up through the levels of radicals and characters.

Figure 5

Although this hypothesis about the role of visual processing plays in Chinese is admittedly speculative, it is consistent with at least one model of Chinese word identification (Perfetti, Liu, & Tan, 2005). The hypothesis also suggests that differences in writing systems can fundamentally influence how the perceptual and cognitive "machinery" that supports reading may have to be configured to support lexical processing. And perhaps just as interestingly, the hypothesis suggests that—at least within certain limits—the perceptual and cognitive processes that are engaged during reading can be readily adapted to support highly skilled comprehension of text despite of the profound differences between languages and writing systems (Liversedge et al., 2016).

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Table 1. The percentage of unique characters (i.e., types) and total characters (i.e., tokens) in the text containing 1-21 strokes.

# Strokes	% Character Types	% Characters Tokens
1	0.2	1.8
2	1.0	3.0
3	2.8	5.5
4	5.2	7.5
5	6.6	9.5
6	10.6	13.6
7	11.9	12.3
8	12.4	14.6
9	13.3	9.7
10	9.5	7.9
11	8.6	4.9
12	7.2	4.3
13	4.0	2.3
14	2.4	1.0
15	1.6	0.8
16	1.4	1.0
17	0.7	0.2
18	0.3	0.1
19	0.3	0.1
20	0.3	0.1
21	0.1	0.0

Table 2. Mean first-fixation durations, dwell times, and skipping rates as a function of target-character complexity for Experiments 1-3. (Standard deviations are in parentheses.)

Experi-ment	First-Fixation Durations (ms)				Dwell Times (ms)				Skipping Rates			
	High	Med-ium	Low	*M*	High	Med-ium	Low	*M*	High	Med-ium	Low	*M*
1	247 (31)	255 (31)	233 (35)	245 (34)	346 (93)	374 (121)	292 (87)	337 (107)	0.43 (0.14)	0.40 (0.15)	0.59 (0.14)	0.47 (0.17)
2	221 (33)	215 (30)	215 (32)	217 (30)	264 (43)	248 (44)	245 (54)	252 (48)	0.59 (0.13)	0.63 (0.12)	0.69 (0.11)	0.64 (0.13)
3	216 (36)	221 (39)	215 (35)	217 (37)	284 (72)	287 (71)	282 (59)	284 (67)	0.56 (0.10)	0.57 (0.11)	0.56 (0.10)	0.56 (0.10)

Figure Captions

Figure 1. An example of stimuli in Experiment 1 and 2. The target shown at the top of the example is the low-complexity character. (See the text for the medium- and the high-complexity character.)

Figure 2. Experiment 1: Mean first-fixation duration (A), dwell time (B), and skipping rate (C) as a function of target-character complexity (low, medium, high) and fixated character complexity (3-16 strokes) for target-character search by English-speaking participants.

Figure 3. Experiment 2: Mean first-fixation duration (A), dwell time (B) and skipping rate (C) as a function of target-character complexity (low, medium, high) and fixated character complexity (3-16 strokes) for target-character search by Chinese-speaking participants.

Figure 4. Experiment 3: Mean first-fixation duration (A), dwell time (B) and skipping rate (C) as a function of target-character complexity (low, medium, high) and fixated character complexity (3-16 strokes) by Chinese-speaking participants during reading. (Note that target-character complexity in this reading task denotes those pages in which participants searched for low-, medium-, or high-complex targets in Experiments 1 and 2.)

Figure 5. Schematic diagram showing possible roles of visual (black arrows) and lexical (gray arrows) processing in English (A) versus Chinese (B). Note that the individual radicals in the Chinese characters have been differentially shaded for illustrative purposes, and that another possible layer of representation—corresponding to multi-character words—has not been shown in the Chinese examples to keep them simple.

Figure 1.

火

科学家经过反复研究，终于解开了蝙蝠能在夜间火飞行

的秘密。蝙蝠一边飞，一边从嘴里发出一种叫做超声波

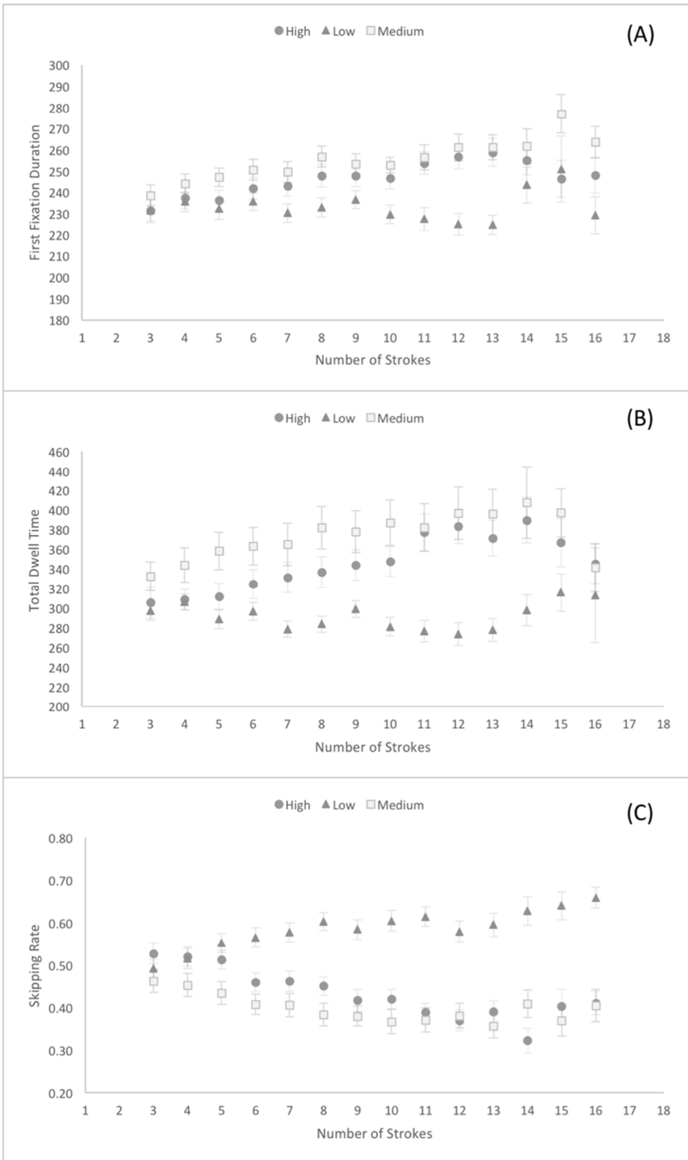
的声音，人们的耳朵听不见这种波蝙蝠的耳朵却能听见。

超声波像波浪一样向前推进，遇到障碍物就反火射回来，

传到蝙蝠的耳朵里。听到波后蝙蝠立刻改变飞行的方向。

科学家模仿蝙蝠探路的方法，给飞机装上雷达。

Figure 2.



High Low Medium
(A)
First Fixation Duration
Number of Strokes
(B)
Total Dwell Time
Number of Strokes
(C)
Skipping Rate
Number of Strokes

Figure 3.

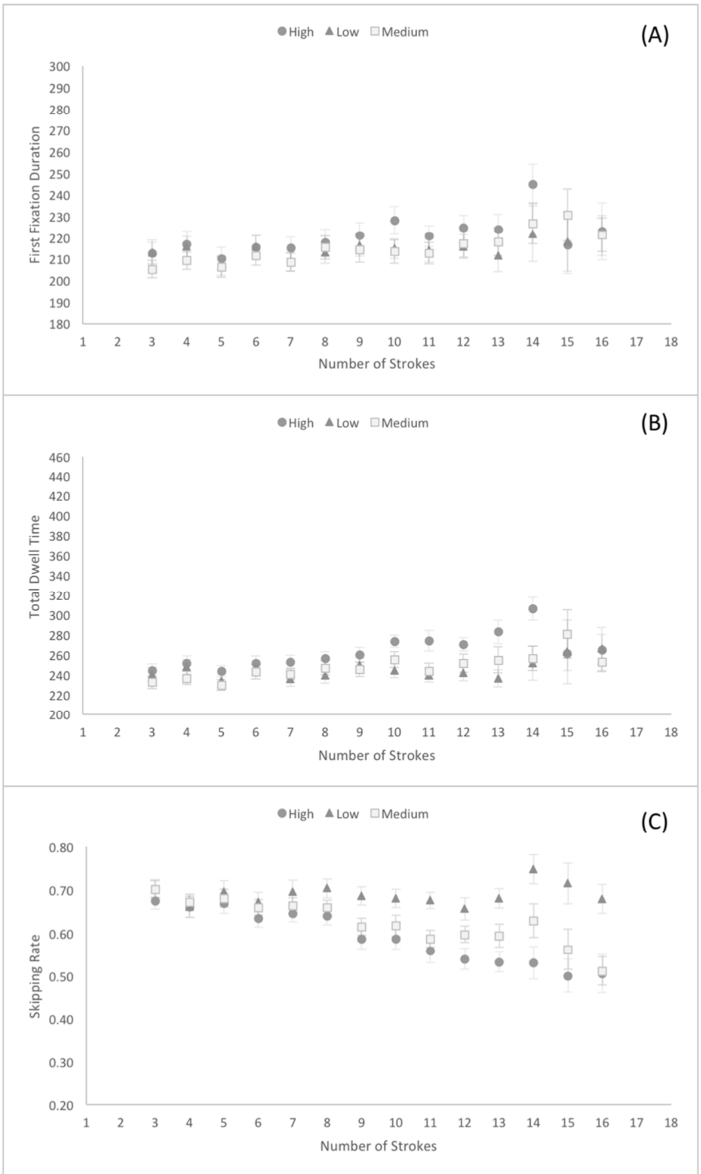

High
Low
Medium
(A)
First Fixation Duration
Number of Strokes
(B)
Total Dwell Time
Number of Strokes
(C)
Skipping Rate
Number of Strokes

Figure 4.

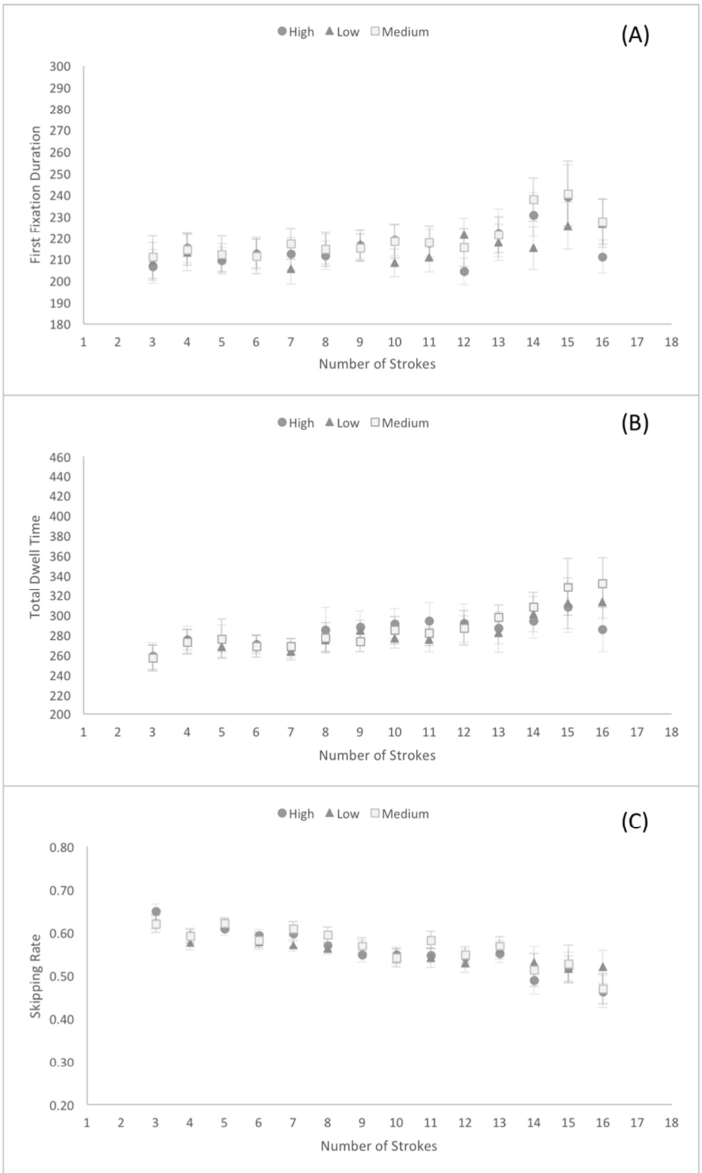
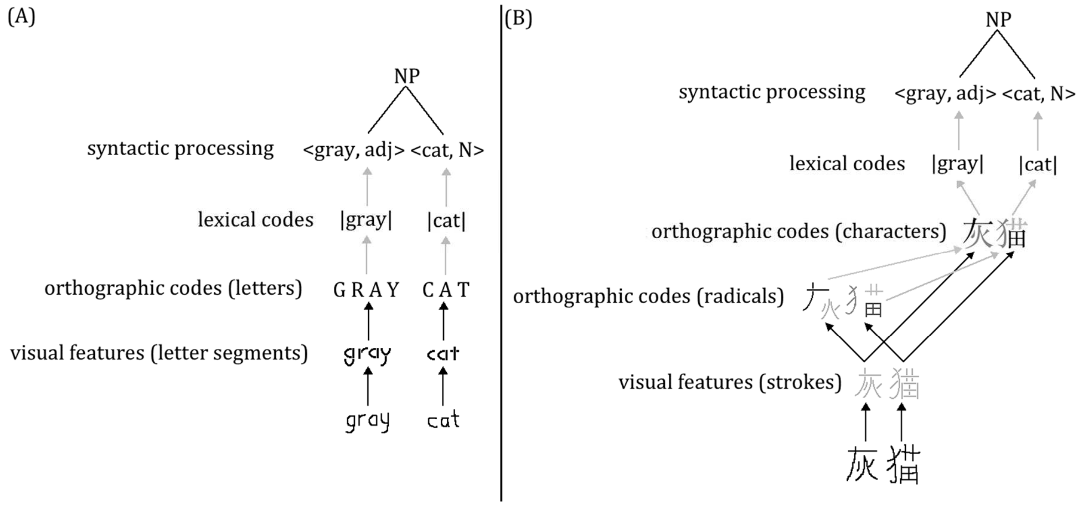

High
Low
Medium
(A)
First Fixation Duration
300
290
280
270
260
250
240
230
220
210
200
190
180
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Number of Strokes
(B)
Total Dwell Time
460
440
420
400
380
360
340
320
300
280
260
240
220
200
Number of Strokes
(C)
Skipping Rate
0.80
0.70
0.60
0.50
0.40
0.30
0.20
Number of Strokes

Figure 5.


(A)
NP
syntactic processing
<gray, adj> <cat, N>
lexical codes
|gray| |cat|
orthographic codes (letters)
G R A Y C A T
visual features (letter segments)
gray cat
gray cat
(B)
NP
syntactic processing
<gray, adj> <cat, N>
lexical codes
|gray| |cat|
orthographic codes (characters)
灰猫
orthographic codes (radicals)
visual features (strokes)
灰猫
灰猫