The Quarterly Journal of Experimental Psychology

ISSN: 1747-0218 (Print) 1747-0226 (Online) Journal homepage: http://www.tandfonline.com/loi/pqje20

The processing of Chinese compound words with ambiguous morphemes in sentence context

Wei Shen, Xingshan Li & Alexander Pollatsek

THE QUARTERLY JOURNAL OF EXPERIMENTAL PSYCHOLOGY, 2016
http://dx.doi.org/10.1080/17470218.2016.1270975

The processing of Chinese compound words with ambiguous morphemes in sentence context

Wei Shen[a,b], Xingshan Li[a] and Alexander Pollatsek[c]

[a]CAS Key Laboratory of Behavioral Science, Institute of Psychology, Beijing, China; [b]School of Humanities, University of Chinese Academy of Sciences, Beijing, China; [c]Department of Psychology, University of Massachusetts, Amherst, MA, USA

ABSTRACT

We employed a boundary paradigm to investigate how Chinese two-character compounds (i.e., compound words) are processed during reading. The first character of the compound was an ambiguous morpheme that had a dominant and subordinate meaning. In Experiment 1, there were three previews of the second character: identical to the target character; the preview provided subordinate biasing information (the subordinate condition); the preview provided dominant biasing information (the dominant condition). An invisible boundary was inserted between the two characters. We found that gaze durations and go-past times on the compounds were longer in the subordinate condition than those in the dominant or identical conditions. In Experiment 2, the semantic similarity between target and preview words in the dominant condition was manipulated to determine whether the differences in fixation durations in Experiment 1 resulted from the semantic similarity between the preview and target words. There were significant fixation duration differences on the target word between the dominant and subordinate conditions only when the preview and target words were semantically related. This finding indicated that the whole-word meaning plays an important role in processing Chinese compounds and that the whole-word access route is the principal processing route in reading two-character compounds in Chinese.

ARTICLE HISTORY
Received 28 April 2016
Accepted 27 November 2016

KEYWORDS
Boundary paradigm; Chinese reading; Compound words; Eye movements

Compound words, which are composed of at least two morphemes, exist across different languages. In the last few decades, a large number of studies have focused their research interests on how compound words are represented in the mental lexicon. The central focus of many of these studies is whether compound words are stored in the mental lexicon as whole-word forms (see Lukatela, Gligorijević, Kostić, & Turvey, 1980) or are constructed from their constituent morphemes (see Taft & Forster, 1975, 1976). In the present study, we investigated how Chinese compound words are processed during sentence reading.

There is a considerable amount of empirical evidence from studies conducted on alphabetical languages showing that lexical morphemes are activated during the recognition of compound words (Duñabeitia, Perea, & Carreiras, 2007; Juhasz, Starr, Inhoff, & Placke, 2003; Pollatsek, Hyönä, & Bertram, 2000). Most studies conducted on this issue used constituent frequency as a diagnosis tool, and the observation of a constituent frequency effect on the recognition time for the compound word is treated as evidence for the activation of the constituents. By this method, researchers found that the recognition of a compound word was influenced by the constituent frequency via the observations of shorter lexical decision times (Andrews, 1986; Juhasz et al., 2003), naming latencies (Juhasz et al., 2003), and fixation times (Andrews, Miller, & Rayner, 2004; Hyönä & Pollatsek, 1998; Juhasz et al., 2003) on compound

CONTACT Xingshan Li lixs@psych.ac.cn CAS Key Laboratory of Behavioral Science, Institute of Psychology, 16 Lincui Road, Beijing, China
Supplemental material is available via the "Supplemental" tab on the article's online page (http://dx.doi.org/10.1080/17470218.2016.1270975).

words with high-frequency constituents. These findings provided strong evidence that the compound words are recognized via the constituent morphemes during processing at least some of the time.

Later evidence from eye-movement studies, however, showed that the decompositional route is not the only way that compound words are recognized. That is, there is also a direct access route where the whole-word form of a compound word can be looked up directly from the mental lexicon (Bertram & Hyönä, 2003; Duñabeitia et al., 2007; Pollatsek et al., 2000). For example, Pollatsek et al. (2000) manipulated the whole-word frequency of Finnish compound words and matched the frequency of the first and second constituents and found a significant whole-word frequency effect. More importantly, the whole-word frequency effect was observed on gaze duration, which was almost at the same time point of observing a morpheme effect of the second morpheme. This finding indicated that the whole-word access can occur virtually simultaneously with the access of the second morpheme. On the basis of these findings, Pollatsek et al. (2000) proposed a dual-route race model in which there are two parallel processing routes, a decompositional route and a direct access route, during the recognition of compound words. These two processing routes can be carried out simultaneously and overlap in the time course of processing.

A subsequent study conducted by Bertram and Hyönä (2003) further showed that the length of the compound word can modulate which route is more likely to dominate the processing. They found that the whole-word access route takes priority in the access of shorter Finnish compound words while the decompositional route plays a larger role in the identification of longer words. This is presumably because all the letter information can be perceived and processed in a single fixation for short compound words, whereas more than one fixation is needed for processing long compound words due to visual acuity limitations.

In sum, the processing mechanism of compound words in alphabetical languages appears to be rather straightforward: The first constituent is decomposed and accessed first followed by the access of the second constituent with attempted access of the whole word occurring in parallel with the activation of the constituents. The process of identifying the whole word appears to be a "race" between the two processes, with the winner of the race determined by factors such as the length of the compound word. However, the mechanism underlying the processing of compound words in non-alphabetical languages is less clear. For example, unlike one-word compounds in alphabetical languages, Chinese compounds are composed of visually salient characters. In Chinese, however, a character can often represent more than one distinct meaning in different words. For example, the character 青(/qing1/) has the meaning of "cyan colour" in the word 青菜 (/qing1cai4/, vegetables) but "young age" in the word 青春 (/qing1chun1/, youth). In addition, because more than 70% of words in Chinese are two-character words (Zhou & Marslen-Wilson, 2000), word length variability is smaller than that in alphabetical languages. These cross-language differences indicate that compound words in Chinese may be processed differently from compound words in alphabetical languages.

Studies conducted on Chinese compound words have also found that both characters and words are activated in compound word processing by manipulating both character frequency and whole-word frequency. In an eye-tracking study, Yan, Tian, Bai, and Rayner (2006) found significant word frequency and character frequency effects on the fixation times on two-character words: There were longer fixation times on low-frequency words than on high-frequency words and on words with low-frequency characters than on words with high-frequency characters. However, the character frequency effects were limited to the low-frequency words, which were very low frequency (about 1 per million words). Thus, it is possible that composing Chinese words serially from characters only occurs when the direct word identification process is extremely slow.

However, some other studies that adopted different paradigms also showed that the whole-word access route appears to be the dominant processing route for two-character Chinese compound words. Using a priming technique, Liu and Peng (1997) presented participants with compound words as targets which were preceded by primes. The primes were semantically related either to the whole word or to one of the morphemes of the target word. All target words were presented immediately after the primes disappeared. There was a larger facilitation from whole-word-related primes on target words in both short (43 ms, 86 ms) and long (143 ms) stimulus onset asynchrony (SOA) conditions, while the morphemic priming effect was only observed in the long SOA condition. This finding suggests that the whole-word representation was activated earlier than the representation at the character level, suggesting a dominant role of the whole-word access route in Chinese. Consistent with this, using the logic of the Reicher (1969) paradigm, researchers have also consistently found that the recognition of a character was more efficient when it belonged to a real Chinese word than when it was presented by itself (e.g., Cheng, 1981; Mattingly & Xu, 1994; Shen & Li, 2012). These studies all show that the whole-word route has an important role in the processing of Chinese compound words in spite of the visual transparency of their constituent structure.

There is also a study that argued that the processing of compound word is flexible. Cui et al. (2013) investigated the processing of characters in Chinese compound words in an eye movement study using the boundary paradigm. An invisible boundary was inserted between the first and second characters, and the previews of the second character were manipulated to be identical, semantically related to the second character, semantically unrelated to the second character, or a pseudocharacter. They also manipulated the second character to be either predictable or unpredictable given the first character. They found that an incorrect preview of the second character increased fixation duration on the first character. Moreover, this finding was only observed when the second character was predictable. On the basis of these results, the authors argued that the relationship between two characters (e.g., whether the second character is predictable or not) can affect how a compound word is processed.

The goal of this study was to further examine the role of constituents of two-character Chinese compound words using the boundary paradigm (Rayner, 1975). There was a display change in a single target word of interest in the sentence when the reader's eyes crossed an invisible boundary in the sentence. In both experiments, the boundary was placed between the first and second characters of the two-character target word. Furthermore, only the second character of the target word changed: from the preview character that appeared before the boundary was crossed to the target character that appeared after the boundary was crossed. This allows a closer look at the time-course of the processing of the characters in the compound word.

A key feature of both experiments was that the sentences were constructed so that the preview words fit in the sentence well at the point that the target word appeared although they were often anomalous with the sentence after more words had been read. One purpose of this part of the design was to assess the extent to which effects at the time of fixating the target word region were due to semantic processing of the preview word. That is, if the meaning of preview word was encoded, one would expect little in the way of "boggle" effects in the region of the target word because the preview would fit into the sentence reasonably at that point; instead, such effects should occur later in the sentence when the preview word did not fit.

In Experiment 1, the first character of the target word had two morphemic meanings: a dominant meaning and a subordinate meaning (based on relative meaning frequency). Critically, the previews of the second character were manipulated to bias either the dominant or a subordinate meaning of the first character. Thus, if the morphemic meaning of the first character was activated during processing the preview word, we would observe longer fixation times in the subordinate condition than in the dominant condition.

Experiment 1

Method

Participants

Thirty-six native Chinese speakers aged from 19 to 28 years ($M = 22.5$) were recruited to participate in the experiment. They were undergraduate students from universities near the Institute of Psychology, Chinese Academy of Social Sciences, and were paid RMB 25 (approximately US$ 3.8) after the experiment. All participants had normal or corrected-to-normal vision and were unaware of the purpose of the experiment.

Apparatus

Eye movements were collected by an EyeLink1000 tracker (SR Research Ltd. Canada). Experimental materials were presented on a 21″ CRT monitor (SONY G520) with 1024×768 pixel resolution and a refresh rate of 150 Hz. The eye-tracking system was sampled at 1000 Hz. Participants placed their chins on a chinrest and heads on a headrest to minimize head movements during the experiment. Although viewing was binocular, eye movement data were collected only from the right eye. Participants were seated 58 cm from the video monitor. Each character was presented in Song 30-point font in white (RGB: 255, 255, 255) on a black background (RGB: 0, 0, 0), and each character subtended a visual angle of approximately 1.5°.

Materials and design

One hundred and fifty characters containing potentially ambiguous morphemes were selected initially from the *Modern Chinese Dictionary* (Chinese Academy of Social Sciences, 2012; see Supplemental Material). Fifteen participants (none participated in the main reading experiment) were recruited to judge the meaning dominance of each ambiguous morpheme by writing down the first meaning coming into their minds for each morpheme. Seventy-two ambiguous Chinese characters[1] having morphemes with a dominant ($M = .86$, $SD = .10$) and a subordinate meaning ($M = .03$, $SD = .05$) were selected as the first characters of the compound words.

Each of these first characters was paired with another character to construct three real two-character Chinese compounds. During reading, an invisible boundary was inserted between the first and the second character. The preview of the second character was manipulated to provide either the dominant or the subordinate biasing information of the first character. There were three previews of the second character: (a) identical to the character in the target word (the identical condition); (b) a character that provided subordinate biasing information for the first character (the subordinate condition); (c) a character that provided dominant biasing information for the first character (the dominant condition). The previews in the identical and dominant conditions provided dominant biasing information of the first character, but these were two different Chinese characters. (See Table 1 for experimental examples.) The character frequency (ranging from 2.42 to 2206.73 occurrences per million; Chinese Linguistic Data Consortium, 2003), the number of strokes of the second character, and the whole-word frequency were carefully matched across the three conditions ($ps > .10$). (See Table 2 for the lexical properties of the experimental stimuli.)

All target words were embedded into a neutral sentence context. Fifteen participants (none participated in the main experiment) were presented with the sentences prior to the target words and were asked to think of a two-character word that would follow. None of the preview words (including the target words) were predicted. There was also a plausibility rating task in which 15 participants were presented with the sentence portions up through the target (preview) words and were asked to judge the extent to which they were plausible on the basis of the preceding context on a 5-point scale (1 = very implausible, 5 = very plausible). The mean ratings for the identical, dominant, and subordinate conditions were 4.19, 4.04, and 4.15, respectively, $F(2, 141) = 1.06$, $p = .34$. Another 10 participants were asked to rate the naturalness of all the entire sentences in the identical condition on a 7-point scale (1 = not natural at all, 7 = very natural). The mean score of the rating was 6.3, indicating that these sentences were all very natural.

Table 1. Example experimental sentences for Experiment 1.

Conditions	Example sentences
Identical	墨西哥曾是中美洲树林**(forests)**砍伐最严重的国家之一 (Before boundary crossing) 墨西哥曾是中美洲树林**(forests)**砍伐最严重的国家之一 (After boundary crossing)
Dominant	墨西哥曾是中美洲树胶**(gums)**砍伐最严重的国家之一 (Before boundary crossing) 墨西哥曾是中美洲树林**(forests)**砍伐最严重的国家之一 (After boundary crossing)
Subordinate	墨西哥曾是中美洲树敌**(making enemies)**砍伐最严重的国家之一 (Before boundary crossing) 墨西哥曾是中美洲树林**(forests)**砍伐最严重的国家之一 (After boundary crossing)

Note: Words in bold are the words in the target region, and English translations were given in the parentheses. The English translation of identical condition is: *Mexico was once one of central American counties where **forests** were destroyed most seriously*. As indicated in the text, the sentences did not always make sense at the end if the target word was encoded with the preview character but they did make sense until the position of the target word.

Procedure

After the participants entered the lab, they were given a brief introduction to the eye tracker and instructions for the experiment. The eye tracker was calibrated and validated at the beginning of the experiment, and a drift check was performed at the beginning of each

Table 2. Some characteristics of the stimuli used in Experiment 1.

	Conditions		
Measure	Identical	Dominant	Subordinate
Word frequency	3.86	3.75	3.58
Character frequency of 2nd character	413	432	341
Number of strokes of 2nd character	8.40	8.55	9.25

Note: Word frequency and character frequency are measured in occurrences per million.

trial. Participants performed this procedure through a three-point calibration, and the validation error was smaller than 0.5° of visual angle. At the beginning of each trial, participants were required to look at a white square located at the left of the screen. Once the eye tracker detected the fixation on the white square, the sentence was presented. During reading, when participants' eyes crossed the invisible boundary, the preview character changed into the target character (see Figure 1). A set of nine practice trials was presented before the experimental trials. Participants were asked to read sentences for comprehension, and comprehension questions were given after about one third of the trials. Each participant read 72 experimental and 72 filler sentences. All the sentences were presented in a random order, and the entire experiment lasted approximately 30 min.

Results

The mean accuracy for the comprehension questions was 96%, indicating that participants understood these sentences. Trials with more than three blinks and any blinks in the target word region or pre-target word region were discarded from the analysis, resulting in 10% of the trials being excluded. Fixations shorter than 80 ms or longer than 1000 ms were also excluded from our analyses. In addition, all trials with early and late changes were excluded from the analysis, resulting in the deletion of about another 20% of the trials. Finally, data trimming was conducted beyond three standard deviations for each participant and each condition.

We report four eye movement indicators: (a) first-fixation duration (FFD, the duration of the first fixation on a region during first-pass[2] reading); (b) gaze duration (GAZE, the sum of all first-pass fixations on a word before moving to another word); (c) go-past time (GO PAST), the sum of fixations on the whole compound word region from first going into it to first going past it); (d) total time (TT, the sum of all fixations on a word, including regressions). Of greatest interest are planned contrasts between fixation times in the subordinate and dominant conditions (both participant and item analysis were performed and reported as t_1 and t_2, respectively). Table 3 shows the measures on the whole compound words and the two characters in each condition.

（1）墨西哥曾是中美洲树|敌砍伐最严重的国家之一。
*

（2）墨西哥曾是中美洲树|林砍伐最严重的国家之一。
*

Figure 1. An illustration of the boundary paradigm in the subordinate condition. In Sentence 1, the preview of the second character was "敌" before the eye crossed the boundary. When the eye crossed the invisible boundary "|", the preview character "敌" in Sentence 1 changed into the target character "林" in Sentence 2. The asterisks under the sentences represent eye fixations.

Eye movement measures on whole compounds

GAZEs on the whole compounds were longer in the subordinate condition than those in the dominant condition [$t_1(35) = 1.98$, $p = .05$; $t_2(71) = 2.20$, $p = .03$], as were GO PASTs [$t_1(35) = 2.76$, $p = .009$; $t_2(71) = 2.24$, $p = .03$] and TTs [$t_1(35) = 3.53$, $p = .001$; $t_2(71) = 2.71$, $p = .008$].

Eye movement measures on characters

We also analysed the fixation durations on the first character to examine whether there were effects of the preview character before the boundary was crossed. There was almost literally no preview effect on either FFD or GAZE on the first character (ts < 1), indicating that early processing of the first character (i.e., processing before the boundary change) was not influenced by the preview.

In addition, fixation durations on the second character in the subordinate condition were significantly longer than those in the identical condition on FFDs [$t_1(35) = 4.00$, $p < .001$; $t_2 = 4.16$, $p < .001$] and GAZEs [$t_1(35) = 4.30$, $p < .001$; $t_2(71) = 4.77$, $p < .001$], as were fixation durations in the dominant condition for both FFDs [$t_1(35) = 2.21$, $p = .034$; $t_2(71) = 3.56$, $p = .001$] and GAZEs [$t_1(35) = 1.88$, $p = .06$; $t_2(71) = 2.92$, $p = .005$]. These results are typical preview benefit effects indicating that the display change disrupts

Table 3. Experiment 1: Eye movement measures for the first character, the second character, and the whole target words.

		Conditions		
Region	Measures	Identical	Dominant	Subordinate
Whole word	GAZE	306 (10)	322 (12)	342 (14)
	GO PAST	324 (10)	341 (14)	378 (14)
	TT	442 (17)	519 (24)	570 (28)
1st character	FFD	247 (7)	248 (8)	245 (8)
	GAZE	250 (7)	252 (8)	248 (8)
2nd character	FFD	256 (7)	274 (10)	282 (8)
	GAZE	267 (9)	288 (13)	309 (15)

Note: All eye-movement indicators were measured in milliseconds, and standard errors from subject analyses are reported in parentheses. GAZE = gaze duration; GO PAST = go-past time; FFD = first-fixation duration; TT = total time.

reading. However, the differences between the subordinate and dominant conditions were not reliable for the second character for FFD [$t_1(35) < 1$; $t_2(71) = 1.19$, $p = .24$] and only marginally reliable for GAZE [$t_1(35) = 2.16$, $p = .04$; $t_2(71) = 1.72$, $p = .09$].

Discussion

In Experiment 1, we manipulated the preview of the second character to provide either dominant or subordinate biasing information. We found that the fixation durations on the whole compound were longer in the subordinate condition than those in the dominant condition.

Traditionally, this finding would be interpreted as the compound words were initially decomposed into individual morphemes, and the dominant meaning of the first character was also activated at the same time. In the subordinate condition, the preview of the second character presumably increased the activation level of the subordinate meaning. Thus it looks like the competition between the two morphemic meanings made meaning integration of the preview of the compound word with the target word harder in the subordinate condition than in the dominant condition. However, there is another possible explanation for the results observed in Experiment 1. In Chinese, two words sharing the same meaning of the first character are also likely to be semantically closer at the whole-word level. For example, the words "树林" (forests) in the identical condition and "树胶" (gum) in the dominant condition are not only morphemically related (sharing the same meaning of the first character) but also semantically related at the whole-word level. However, the word "树敌" (making enemies) in the subordinate condition was semantically unrelated with "树林" (forests) at both the morphemic and whole-word levels. To check this possibility, we recruited 15 participants to judge how semantically related the words in the dominant and subordinate conditions were to the words in the identical condition using the numbers 0 (unrelated) or 1 (related). The words in the identical condition were indeed semantically closer to those in the dominant condition ($M = .71$) than with those in the subordinate condition ($M = .04$). Therefore, it was possible that the difference in fixation durations between the dominant and subordinate conditions was due to the words in the dominant condition being semantically closer to the words in the identical condition than the words in the subordinate condition. Experiment 2 was conducted to test this possibility.

Experiment 2

In Experiment 2, we manipulated the preview word in the dominant condition to be either semantically related or unrelated with the target word with the aim of examining whether whole-word similarity was responsible for the fixation duration difference in Experiment 1. If the data pattern observed in Experiment 1 was due to semantic activation occurring at the morphemic level, then fixation durations in dominant conditions should be shorter than those in the subordinate condition irrespective of semantic relatedness. Otherwise, shorter fixation durations would only be observed in the dominant condition when it was semantically related to the target word, and this should be viewed as evidence that whole-word similarity played the primary role during processing.

Method

Participants

Experiment 2 had 36 participants aged 19–28 years ($M = 23.70$) recruited from the same pool as those of Experiment 1. None of them had participated in Experiment 1. All participants had normal or corrected-to-normal vision and were paid RMB 25 (approximately US $3.8) after the experiment.

Materials and design

The experimental design was almost identical to that of Experiment 1 with the following exceptions: The whole-word semantic relatedness between the target word and preview word in the dominant condition was manipulated to be either semantically related (dominant biasing and semantically related condition, hereafter the dominant-related condition) or semantically unrelated (dominant biasing and semantically unrelated condition, hereafter the dominant-unrelated condition). Thus, together with the identical and subordinate conditions, there were four conditions in Experiment 2. Fifteen participants were recruited to judge whether word pairs were semantically related or not (0 for unrelated, 1 for related). Each word in the identical condition was paired respectively with words in the dominant-related, dominant-unrelated, and subordinate conditions to construct three word pairs. The semantic relatedness between the words in the identical and dominant-related conditions ($M = .92$) was significantly higher than that between words in the identical and subordinate conditions ($M = .03$), $t(79) = 51.17$, $p < .001$, and that between the words in the identical and dominant-unrelated conditions ($M = .05$), $t(79) = 48.07$, $p < .001$. However, there was little difference between the latter two conditions, $t(79) = 1.08$, $p > .10$. (See Table 4 for experimental examples.) The character frequency (ranging from .54 to 5204.67 occurrences per million; Chinese Linguistic Data Consortium, 2003), number of strokes of the second character, and the whole-word frequency were closely matched across the three conditions ($ps > .20$). (See Table 5 for the lexical properties of the stimuli in Experiment 2.)

All target words were embedded into a neutral context sentence. The same procedures for obtaining predictability, naturalness, and plausibility ratings were performed as those in Experiment 1. The mean predictability rating was 0. The mean score of naturalness rating was 6.4, indicating that the whole sentences were all natural. The mean plausibility rating scores for the identical, dominant-related, dominant-unrelated, and subordinate conditions were 4.47, 4.41, 4.49, and 4.53, respectively, $F(3, 316) = 1.24$, $p = .29$, indicating that the words in all conditions were equally plausible when they appeared in the sentence.

Table 4. Example experimental sentence for Experiment 2.

Conditions	Example sentences
Identical	一位专家介绍说风向**(wind direction)**的变化会引起洋流的季节性变化 (Before boundary crossing) 一位专家介绍说风向**(wind direction)**的变化会引起洋流的季节性变化 (After boundary crossing)
Dominant related	一位专家介绍说风力**(wind power)**的变化会引起洋流的季节性变化 (Before boundary crossing) 一位专家介绍说风向**(wind direction)**的变化会引起洋流的季节性变化 (After boundary crossing)
Dominant unrelated	一位专家介绍说风衣**(wind coat)**的变化会引起洋流的季节性变化 (Before boundary crossing) 一位专家介绍说风向**(wind direction)**的变化会引起洋流的季节性变化 (After boundary crossing)
Subordinate	一位专家介绍说风趣**(humour)**的变化会引起洋流的季节性变化 (Before boundary crossing) 一位专家介绍说风向**(wind direction)**的变化会引起洋流的季节性变化 (After boundary crossing)

Note: Words in bold are words in the target location, and English translations are given in the parentheses. The English translation of identical condition is: *An expert said that the change of **wind direction** drives the seasonal changes of ocean current*. As indicated in the text, the sentences did not always make sense at the end if the target word was encoded with the preview character but they did make sense until the position of the target word.

Apparatus

The apparatus was identical to that used in Experiment 1.

Procedure

Most of the procedure was identical to that in Experiment 1 except that participants read 80 experimental sentences with 20 sentences in each condition together with 80 filler sentences. All sentences were presented in a random order, and the entire experiment lasted approximately 40 min.

Results

The mean accuracy for the comprehension questions was 95%, indicating that participants could understand these sentences well. Trials with blinks in the target word region or pre-target word region, or with more than three blinks were discarded from the analysis, resulting in 5% of trials being excluded. Fixations shorter than 80 ms or longer than 1000 ms were also excluded from our analyses. In addition, trials with all early and late changes were excluded from the analysis, resulting in about 15.8% trials being deleted. (Table 6 shows the eye movement measures in each condition in Experiment 2.) The data analysis was identical to that used in Experiment 1.

Eye movement measures on the whole compound words

Fixation times on the whole compounds were over 20 ms longer in the subordinate condition than those in the dominant-related condition on GAZE [$t_1(35) = 2.76$, $p = .009$; $t_2(79) = 2.24$, $p = .03$], GO PAST [$t_1(35) = 1.98$, $p = .05$; $t_2(79) = 2.22$, $p = .03$], and TT [$t_1(35) = 3.01$, $p = .005$; $t_2(79) = 3.23$, $p = .002$]. However, no difference between the dominant-unrelated condition and subordinate condition was close to significant on any of these eye movement measures ($ts < 1$). In addition, fixation times in the dominant-related condition were shorter than those in the dominant-unrelated condition on GAZE [$t_1(35) = 4.50$, $p < .001$; $t_2(79) = 2.56$, $p = .01$], GO PAST [$t_1(35) = 3.34$, $p = .002$; $t_2(79) = 2.05$, $p = .04$], and TT [$t_1(35) = 3.78$, $p = .001$; $t_2(79) = 3.05$, $p = .003$].

Eye movement measures on characters

The processing of the first character was not affected by the previews as indicated by both FFD and GAZE ($ts < 1$), indicating that there was no preview effect

Table 5. The characteristics of the preview stimuli used in Experiment 2.

	Conditions			
Measure	Identical	Dominant related	Dominant unrelated	Subordinate
Word frequency	4.51	3.58	3.23	3.55
Character frequency of 2nd character	642	753	487	708
Number of strokes of 2nd character	7.77	7.57	8.18	8.00
Semantic relatedness with words in the identical condition	—	0.92	0.08	0.03

Note: Word frequency and character frequency are measured in occurrences per million.

of the second character on the first character. This finding was similar to that in Experiment 1. However, significant preview benefits were observed on the second character, and the fixation times in all non-identical conditions were significantly longer than those in the identical condition on FFD and GAZE ($ts > 2.06$, $ps < .05$). In addition, although fixation times in the dominant-related condition were numerically shorter than those in the subordinate condition, the differences did not reach statistical significance on either FFD [$t_1(35) = 1.46$, $p = .15$; $t_2(79) = 1.41$, $p = .16$] or GAZE [$t_1(35) = 1.18$, $p = .25$; $t_2(79) = 1.37$, $p = .17$]. No difference was observed between the dominant-unrelated condition and subordinate condition on FFD or GAZE ($ts < 1$).

Discussion

In Experiment 2, we manipulated the semantic relatedness of the whole word between the words in the identical condition and preview words. The main result was that there were large fixation duration differences when the preview words were semantically related to the target words: Fixation durations in the dominant-related condition were shorter than those in the dominant-unrelated and subordinate conditions whereas no fixation duration difference between the dominant-unrelated condition and subordinate condition was close to significant.

These findings cannot be easily explained by serial processing of the two characters of the stimulus in the target region to form the meaning of the target word. If the morphemes were decomposed first, and the morphemic meanings were also activated, then fixation durations in both dominant conditions should be shorter than those in the subordinate condition. On the contrary, these results indicated that only the semantic similarity of the whole preview word to the target word played a significant role in processing of the target compound word. Thus, during processing, the whole-word representation of the preview word must have been activated very early, and the meaning similarity to the target word resulted in the shorter fixation durations in the dominant-related condition than in either the dominant-unrelated or subordinate condition.

General discussion

In the present study, we investigated how compound words in Chinese are processed in sentence reading. Using a boundary paradigm, an invisible boundary was inserted between the first and second characters of a compound word with the preview of the second character being manipulated to provide either dominant or subordinate biasing information. In Experiment 1, we observed that fixation durations on the whole word in the subordinate condition were longer than those in the dominant condition. However, after we explicitly manipulated the semantic relatedness between the preview word and the target word, we found that only preview words that were

Table 6. Eye movement measures for the first character, second character, and the whole target words in Experiment 2.

		Conditions			
Region	Measures	Identical	Dominant related	Dominant unrelated	Subordinate
Whole word	GAZE	305 (13)	320 (14)	355 (16)	343 (16)
	GO PAST	317 (14)	339 (14)	369 (19)	360 (19)
	TT	425 (21)	494 (27)	567 (31)	551 (28)
1st character	FFD	247 (8)	251 (7)	251 (9)	258 (8)
	GAZE	248 (8)	254 (7)	255 (10)	264 (9)
2nd character	FFD	258 (8)	279 (9)	290 (10)	293 (11)
	GAZE	269 (10)	294 (11)	310 (11)	306 (13)

Note: All eye-movement indicators were measured in milliseconds, and standard errors from subject analyses are reported in parentheses. GAZE = gaze duration; GO PAST = go-past time; FFD = first-fixation duration; TT = total time.

semantically related to the target words elicited shorter fixation durations than those in the subordinate condition.

The current findings thus indicate that the whole-word properties play the key role in preview effects in on-line Chinese compound word processing in reading, suggesting that two-character Chinese compound words are more likely to be initially accessed through a whole-word access route. This finding is in contrast with those in alphabetical languages (i.e., English, Finnish) for which most compounds are accessed via the constituents serially. One possible reason may be word length. According to the visual acuity limitation account proposed by Bertram and Hyönä (2003), word length can modulate the extent to which the decompositional or the whole-word route can dominate the processing. As mentioned before, in Chinese, most compound words are two characters long (as were those in the present experiments). Hence, all of their characters when they are first fixated are likely to fall into foveal vision, thus making it possible that the representation of the whole word is activated more efficiently.

However, as our fixation time data on the first character in the target word indicated (where there were virtually no differences between any of the conditions in either experiment), this apparently full processing of the whole target word had not reached the point of conscious awareness. Otherwise, one would presumably expect that fixation times after crossing the boundary in all the display-change conditions would be significantly longer than those in the identical condition. It is also worth noting that because the preview words all fit equally well into the sentence at that point in the sentence (and as well as the target word) that it was unlikely that the pattern of differences among conditions in first-pass measures was due to recognition that the preview word in one condition fitted in less well with the prior sentence than the preview word in another condition. However, the considerably longer total time measures in the non-identical conditions indicated that the participants did occasionally encode the target word with the preview character and then needed to reread the sentence when the latter part of the sentence indicated that this did not fit in.

Another factor that would promote whole-word processing of shorter Chinese compound words is that if skilled Chinese readers realize that the first unprocessed character is likely to be a constituent of a larger linguistic unit with the next character. We calculated the likelihood of the first character being a one-character word following the practice used by Zang et al. (2016) and found that the likelihoods were low (i.e., 29% and 33% in Experiments 1 and 2, respectively) indicating that the first characters are more likely to be a part of a larger linguistic unit with another character. Therefore, it was likely that readers would first try to combine the two characters into a single linguistic unit to process rather than process them character by character. These findings converge with previous findings of Zang et al. (2016), Liu and Peng (1997), and the word superiority effect in Chinese.

Yan et al. (2006) found that Chinese high-frequency words are more likely to be accessed through a whole-access route while low-frequency words are more likely to be processed via individual constituents. However, the word frequency of the low-frequency words in their study was 1 per million, which was extremely low. The means of target word frequency were 3.86 and 4.51 per million in our Experiments 1 and 2, respectively. Based on a Chinese Linguistic Data Consortium (2003), the percentage of words more frequent than 3.86 per million is 16%, and the percentage of words more frequent than 4.51 per million is 14%. Therefore, the words used in the current study were not all that low frequency in Chinese making it plausible that the words were initially accessed via the whole-word access route.

In conclusion, our current findings suggest that the whole-word access route dominates the reading of two-character compound words in Chinese. It is clearly an open question whether this route is dominant for longer Chinese compounds.

Notes

1. Of all the items, 21 items were selected from Tsang and Chen (2013).
2. First-pass means the first time the word or region is fixated when entering the word or region from the left.

Acknowledgements

We thank four anonymous reviewers for their helpful comments on earlier version of the manuscript.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This research was supported by grants from the National Natural Science Foundation of China [grant numbers 31571125, 61621136008]; and was supported by Beijing Advanced Innovation Center for Imaging Technology [grant number BAICIT-2016018].

References

Andrews, S. (1986). Morphological influences on lexical access: Lexical or nonlexical effects? Journal of Memory and Language, 25(6), 726–740.

Andrews, S., Miller, B., & Rayner, K. (2004). Eye movements and morphological segmentation of compound words: There is a mouse in mousetrap. European Journal of Cognitive Psychology, 16(1–2), 285–311.

Bertram, R., & Hyönä, J. (2003). The length of a complex word modifies the role of morphological structureEvidence from eye movements when reading short and long Finnish compounds. Journal of Memory and Language, 48(3), 615–634.

Cheng, C. M. (1981). Perception of Chinese characters. Acta Psychologica Taiwanica, 23, 137–153.

Chinese Academy of Social Sciences. (2012). 现代汉语词典(第六版) [Modern Chinese words dictionary] (6th ed.). Beijing, China: the Commercial Press.

Chinese Linguistic Data Consortium. (2003). 现代汉语通用词表 [Chinese lexicon] (CLDC-LAC-2003-001). Beijing, China: Tsinghua University, State Key Laboratory of Intelligent Technology and Systems, and Chinese Academy of Sciences, Institute of Automation.

Cui, L., Yan, G., Bai, X., Hyönä, J., Wang, S., & Liversedge, S. P. (2013). Processing of compound-word characters in reading Chinese: An eye-movement-contingent display change study. The Quarterly Journal of Experimental Psychology, 66(3), 527–547.

Duñabeitia, J. A., Perea, M., & Carreiras, M. (2007). The role of the frequency of constituents in compound words: Evidence from Basque and Spanish. Psychonomic Bulletin & Review, 14(6), 1171–1176.

Hyönä, J., & Pollatsek, A. (1998). Reading Finnish compound words: Eye fixations are affected by component morphemes. Journal of Experimental Psychology: Human Perception and Performance, 24(6), 1612–1627.

Juhasz, B. J., Starr, M. S., Inhoff, A. W., & Placke, L. (2003). The effects of morphology on the processing of compound words: Evidence from naming, lexical decisions and eye fixations. British Journal of Psychology, 94(2), 223–244.

Liu, Y., & Peng, D-L. (1997). Meaning access of Chinese compounds and its time course. In H-C. Chen (ed.), Cognitive *pro*cessing of Chinese and *r*elated *A*sian *l*anguages (pp. 219–232). Hong Kong: The Chinese University Press.

Lukatela, G., Gligorijević, B., Kostić, A., & Turvey, M. T. (1980). Representation of inflected nouns in the internal lexicon. Memory & Cognition, 8(5), 415–423.

Mattingly, I. G., & Xu, Y. (1994). Word superiority in Chinese. In H-W. Chang, J-T. Huang, C-W. Hue & O. J. L. Tzeng (Eds.), Advances in the study of Chinese *language processing*, Vol I: Selected Writing from *the sixth international symposium on cognitive aspects* of the Chinese *l*anguage (pp. 101–111). Taipei: Department of Psychology, National Taiwan University.

Pollatsek, A., Hyönä, J., & Bertram, R. (2000). The role of morphological constituents in reading Finnish compound words. Journal of Experimental Psychology: Human Perception and Performance, 26(2), 820–833.

Rayner, K. (1975) The perceptual span and peripheral cues in reading. *Cognitive Psychology*, 7(1), 65–81.

Reicher, G. M. (1969) Perceptual recognition as a function of meaningfulness of stimulus material. *Journal of Experimental Psychology, 81*(2), 275–280.

Shen, W., & Li, X. (2012) The uniqueness of word superiority effect in Chinese reading (in Chinese). Chinese Science Bulletin (Chinese Version), 57(35), 3414–3420.

Taft, M., & Forster, K. I. (1975). Lexical storage and retrieval of prefixed words. Journal of Verbal learning and Verbal Behavior, 14(6), 638–647.

Taft, M., & Forster, K. I. (1976). Lexical storage and retrieval of polymorphemic and polysyllabic words. Journal of Verbal Learning and Verbal Behavior, 15(6), 607–620.

Tsang, Y. K., & Chen, H. C. (2013). Early morphological processing is sensitive to morphemic meanings: Evidence from processing ambiguous morphemes. Journal of Memory and Language, 68(3), 223–239.

Yan, G., Tian, H., Bai, X., & Rayner, K. (2006). The effect of word and character frequency on the eye movements of Chinese readers. British Journal of Psychology, 97(2), 259–268.

Zang, C., Wang, Y., Bai, X., Yan, G., Drieghe, D., & Liversedge, S.P. (2016). The use of probabilistic lexicality cues for word segmentation in Chinese reading. *The Quarterly Journal of Experimental Psychology*, 69(3), 548–560.

Zhou, X., & Marslen-Wilson, W. D. (2000). Lexical representation of compound words: Cross-linguistic evidence. Psychologia, 43, 47–66.