Mechanism of Semantic Processing of Lexicalized and Novel Compound Words: An Eye Movement Study

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Materials, analysis code and raw data can be found in osf (https://osf.io/tyr62/).

Abstract

The integration of semantic information of compound words with context is a crucial aspect of reading comprehension. In two eye-tracking experiments, we used two-character and four-character Chinese lexicalized and novel compound words to investigate how Chinese readers integrate semantic information of compound words with contexts in the present study. By manipulating the temporary plausibility of the first constituent through varying the preceding verb, we aimed to investigate how readers process semantic information of compound words during normal reading. A significant plausibility effect pattern in the first constituent region was observed for the four-character novel words, but not for the lexicalized compound words and two-character novel compound words. However, for both two-character and four-character novel compound words, a reverse plausibility effect was found in the second constituent region. This was not the case for lexicalized compound words. These results indicate that novel compound words are integrated with context in a decompositional manner, while lexicalized compound words are integrated holistically.

***Key words**:* semantic integration, lexicalized compound words, novel compound words, reading, eye movement

Introduction

Compound word is a common word type in many languages, formed by combining two or more morphemes. For example, “football” is combined by “foot” and “ball.” While some compound words are familiar to readers, others may be novel to some degree. The former is referred as a lexicalized compound word (e.g., “雪人” in Chinese or “snowman” in English), whereas the latter is referred as a novel compound word (e.g., “雪猫” in Chinese or “snowcat” in English; Hyönä et al., 2020; Pollatsek et al., 2011). Lexicalized compound words are stored in readers’ mental lexicon. Although novel compound words[1] are not stored in readers’ mental lexicons, readers can easily comprehend the meanings of these words (Hyönä et al., 2020).

The question of whether compound words are processed by first identifying their constituents is a key research question in psycholinguistics in history. Three types of models have been proposed to address this question. Supra-lexical models assume that compound words are processed holistically and do not require access to their constituents (Diependaele et al., 2005; Giraudo & Grainger, 2001). In contrast, sub-lexical models claim that access to constituents is necessary before identifying compound words, which means that compound words are processed in a decompositional manner (Taft & Forster, 1975, 1976). Dual-route models propose that holistic and decompositional routes work simultaneously during compound word processing (Pollatsek et al., 2000), and which route would win depends on word

[1] Novel compound words in this paper are also considered phrases in written Chinese. In the present study, we only focus on nominal phrases, in which both the constituents and whole words are nouns.

properties like word length and word frequency. For instance, some researchers have suggested that long words are more likely to be processed in a decomposiontal manner, while shorter words are more likely to be processed in a holistic manner (Bertram & Hyönä, 2003). Given that evidence has been found to support both holistic and decompositional processing, it seems that answers to the question may not be simply binary or ternary. Instead, it is possible that readers use different strategies in compound word processing depending on words' properties. Therefore, studies should be designed to investigate the conditions under which we see evidence of more holistic vs. more decompositional processing. Since Chinese has more compound words than English (McBride-Chang & Liu, 2011), it is essential to investigate how readers process compound words in Chinese.

Chinese Word Identification

Many studies have investigated how Chinese compound words are identified in isolation and the results were mixed.

Some studies have shown significant effects of the characteristics of the compound constituents on the processing of compound words. For example, in studies using lexical decision tasks and manipulating the frequency of constituent characters within compound words, researchers have observed shorter response time for compound words containing high-frequency characters than those containing low-frequency characters (Peng et al., 1999; Wang & Peng, 1999). This constituent frequency effect has usually been interpreted as evidence for the activation of constituents within compound words, implying that compound words can be accessed through a

decompositional way. One mega-study also investigated the roles of both word and character frequencies in processing compound words (Tse & Yep, 2018). Results showed significant word frequency effect and character frequency effect. What is more important, an interaction between word and character frequency was observed. Further analysis showed that character frequency effect was larger for low-frequency words than high-frequency words. This study suggested that Chinese compound words can be identified using both decompositional and holistic ways. Low-frequency words are more likely to be identified through a decompositional way than high-frequency words.

Studies using the priming paradigm also showed that semantic information of components is activated during compound word processing. Zhou and Marslen-Wilson (2000) found a facilitative priming effect when the prime and target words shared the same first morpheme. Furthermore, Tsang and Chen (2014) found that the morphemic meaning of a character was activated when the character was embedded in an opaque compound word (the meaning of its constituent character is unrelated to the meaning of the whole word). For example, given an opaque compound word “雷达” (means radar), which is not semantically related to the target word “闪电” (means flash), it produced a semantic priming effect to the processing of the target word because its first constituent “雷” (means thunder) is semantically related to the target word. With other paradigms like meaning generation, Tang and his colleagues also found strong evidence that semantic information of morphemes or constituents can be activated during compound word identification (Tsang & Chen, 2013a; 2013b; Tsang et al., 2014).

However, other studies supported the view that compound words are identified in a holistic way. Using a partial report task, Mok (2009) found that even fully transparent compound words (defined as both constituents are semantically related to the whole compound word) produced a word superiority effect. In other words, character reporting accuracy was significantly higher when the character was within a word than when it was in a nonword. The results implied that fully transparent words can be processed as a whole.

Another study showed that different type of compound words may be identified in a different way. Cui et al. (2018) used a priming lexical decision paradigm to study whether subordinate compound words and coordinate compound words are processed in a similar way. For subordinate compound words, the first character modifies the second character (e.g., "雪球", means snowball). For coordinate compound words, both constituents contribute equally to the word meaning (e.g., "风雨", wind and rain, means storm). The key manipulation was whether the prime words shared the same word structure with the target words. The authors argued that both constituents need to be accessed to derive the structure and meaning of the word. Thus, structure priming effect can be seen as a symbol of decomposition identification. The structure priming effect was only significant for subordinate compound words but not for coordinate compound words. Therefore, the results suggest that while subordinate compound words can be processed by decomposition, coordinate words are more likely to be identified as whole units.

In summary, previous studies on isolated word processing in Chinese have

produced mixed results, with some findings supporting decompositional processing and others supporting holistic processing. These mixed results might be due to two factors: (1) The identification of compound words is a task dependent process; (2) The properties of a compound word affect how it is processed. As discussed earlier, whether a compound word is processed holistically or decompositionally depends on its semantic transparency (one of the most prominent factors investigated in compound processing) and its grammatical structure (e.g., Cui et al., 2018).

A recent computational model, the Chinese Reading Model, offers a framework for how Chinese lexicalized compound words are identified (CRM, Li & Pollatsek, 2020). According to CRM, all characters within the perceptual span are activated in parallel. These activated characters then activate all the corresponding words at the word level. These activated words compete for a winner. Once the activation of a word reaches the threshold, the word wins the competition, and it is segmented and identified at the same time. For a compound word, both the compound word and its constituents are activated and they compete with each other. Since the compound word receives activation from more characters than its constituents, the whole word usually wins the competition (simulation showed that more than 99% two-character words win the competition, while less than 1% constitute words win the competition). In summary, CRM assumes that constitutes of a lexicalized compound word are activated during reading, but the whole compound word is usually processed as a whole during reading. Although CRM provides a reasonable solution on how Chinese compound words are identified, further studies are necessary to test its validity.

Word Integration During Sentence Reading

During sentence reading, readers need to group contiguous characters into words of different lengths (Li & Pollatsek, 2020) and then incrementally integrate newly perceived information into the current sentence representation to understand a sentence (Yang et al., 2009a). Words have to be first identified and then integrated into context. Since compound word can be identified either by combing constituents or as a whole unit, researchers have been interested in whether the constituents of compound words or the whole compound words would be integrated with context during online sentence reading (e.g., Staub et al., 2007; Yang et al., 2012).

Evidence from English has indicated that readers tend to integrate the initial noun of a spaced noun-noun compound with the previous context immediately (Staub et al., 2007). In this study, spaced noun-noun novel and familiar compounds (e.g., “cafeteria manager” and “mountain lion”, respectively) were used. While the whole compounds were plausible in the sentences, the initial noun was either a plausible or implausible object of a previous verb (e.g., “visited” in the plausible condition and “talked to” in the implausible condition for the novel compound “cafeteria manager”). Fixation durations for the modifier noun “cafeteria” were significantly shorter when it was preceded by “visited” than “talked to”, suggesting that the modifier noun had been immediately integrated with the context. Although the plausibility effect was smaller in number for familiar compounds, the overall patterns for both novel and familiar compounds were the same. There were no significant effects in the second constituent (head noun) region.

However, using a similar paradigm, researchers found a different pattern of results in reading Chinese. Yang et al. (2012) used two-character Chinese compound words and manipulated the plausibility of the first character (constituent) by varying the verb prior to the compound. They also included one-character words, which were the first character (constituent) of the compound words, as a control condition (see examples 1a-1d). All sentences were plausible, except those in the single-word implausible conditions (e.g., example 1d). The results showed that the plausibility effect was found only for single-character words but not for two-character compound words. Specifically, no significant plausibility effect was observed in either the whole two-character words or the first character of the two-character words. This study indicated that the whole compound word, rather than the first constituent, was integrated with the previous verb.

1a. Plausible-plausible	围观的人看着他踢打**门卫**却无动于衷
	People were inattentive when he kicked the **gate-keeper.**
1b. Plausible-implausible	围观的人看着他哀求**门卫**却无动于衷
	People were inattentive when he entreated the **gate-keeper**.
1c. Plausible	围观的人看着他踢打**门**却无动于衷
	People were inattentive when he kicked the **door.**
1d. Implausible	围观的人看着他哀求**门**却无动于衷
	People were inattentive when he entreated the **door**.

Furthermore, Zhou and Li (2021) replicated the findings of Yang et al. (2012) using

a similar paradigm to investigate whether three-character compound words are integrated into sentence context as a whole. In Zhou and Li, the first two characters of the three-character compound words constitute another word， and these two-character words were target words in the two-character word condition. No significant plausibility effect was found in the three-character word condition for either the whole word region or the first two-character word region. The plausibility effect was observed only in the two-character word condition. Again, these results suggested that Chinese readers treated compound words as whole units and integrated them with sentence contexts.

The compound words used in these two studies (Yang et al., 2012; Zhou & Li., 2021) were all lexicalized compound words. Regarding how novel compound words are integrated with context in Chinese reading, Yao et al. (2022) used novel four-character noun-noun Chinese compound words to examine this question. They manipulated the temporary plausibility of the first noun by varying the classifier before the compound word (see examples 2a-2b, the word space is only for illustration and is not presented in the original study). They found shorter gaze durations and higher skipping rates in the plausible condition than in the implausible condition in the first noun region. In addition, they found a reversed plausibility effect in the second noun region, where gaze duration and total time were significantly longer in the plausible condition than in the implausible condition. The results of Yao et al. (2022) suggest that Chinese novel compound words are integrated with previous contexts in a decompositional manner.

2a. Plausible 柜子 里的 那 一 件 **毛衣** 外套 是 妈妈 新买的。

(Translation of each word) Wardrobe inside that one Cl_piece **sweater** coat is Mom new buy

(Translation of the whole sentence) That sweater coat in the wardrobe was newly bought by Mom.

2b. Implausible 柜子 里的 那 一 件 **羊毛** 外套 是 妈妈 新买的。

(Translation of each word) Wardrobe inside that one Cl_piece **wool** coat is Mom new buy

(Translation of the whole sentence) That woolen coat in the wardrobe was newly bought by Mom.

To make a brief summary, previous studies showed that Chinese readers usually integrate two- and three-character lexicalized compound words at the whole word level instead of the constituent level. For novel compound words, readers tended to immediately integrate the first constituents with contexts. While these findings enhance our understanding of compound word processing in Chinese, some important questions need to be answered.

First, does word length influence the semantic integration of compound words? Although previous studies have shown that two-character words and three-character words were integrated as a whole in Chinese reading (Yang et al., 2012; Zhou & Li, 2021), this processing might be different for longer compound words like four-character words, since the perceptual span in reading Chinese is 3-4 characters (1 character to the

left and 2-3 characters to the right of a fixation, Inhoff & Liu, 1998). Because four-character words are longer, they are less likely to fall entirely within the perceptual span and more likely to be processed incrementally. In addition, two-character words that are embedded in four-character words may have some advantage because they are the most common type of words in Chinese. Therefore, some Chinese readers may prefer to identify the embedded two-character word and integrate it with the context when they process a four-character compound word in a sentence.

Second, although Yao et al. (2022) shed some light on the semantic integration of novel compound words, much less is known about the processing of novel compound words compared to lexicalized compound words. Yao et al.'s (2022) finding might not reflect the general processing of novel compound words when we consider the word length issue mentioned above (i.e., two-character novel compounds word may show a different pattern of results). Moreover, Yao et al. (2022) used classifiers to manipulate the plausibility of the first constituent, which is hard to compare their results with previous studies that used verbs for this manipulation (Staub et al., 2007; Yang et al. 2012; Zhou & Li, 2021).

The Present Study

The present study was designed to address two questions related to compound word integration in Chinese reading: (1) Are the constituents of compound words integrated with context as independent words? We compared lexicalized and novel compound words using a within-subject design so that we could investigate whether their integration with context is similar or different. (2) Whether word length moderates the

probability that the constituents of compound words integrated with context as independent words? In Experiment 1, we used two-character novel and lexicalized compound words and manipulated the plausibility of the first constituents of compound words by varying the verb before them (see the Methods section for details). The manipulation in Experiment 2 was the same as in Experiment 1, except that the compound words were four-characters long. For both experiments, if constituents of compound words are immediately integrated, there should be a plausibility effect in the first constituent, regardless of whether the compound is novel or lexicalized. Otherwise, there should be no plausibility effect of the first constituent. However, if lexicalized compound words and novel compound words are integrated with contexts in different ways (i.e., novel compound words are integrated immediately and lexicalized compound words are integrated in a holistic way), a different pattern should be observed for these two kinds of compound words. If word length can moderate the pattern of integration, we should find different result patterns between these two experiments.

Although the paradigm we used in the present study focuses on whether the components are integrated immediately, it can also shed light on how lexicalized compound word is identified. As we reviewed above, lexicalized compound words can be identified through either a holistic way or decompositional way. If lexicalized compound words are identified as whole units, they must be integrated as whole units. Therefore, if the present study shows that the first constituent of a lexicalized compound word is integrated with context immediately, it provides strong evidence against the argument that lexicalized compound word is identified holistically. In contrast, if the

results show whole compound words are integrated with context as a whole, it can be more complex, which will be discussed further in General Discussion.

Experiment 1

Methods

Participants

Forty-three native Chinese speakers from universities near the Institute of Psychology, Chinese Academy of Sciences (age: M = 23.27, SD = 2.00; 16 male) participated in Experiment 1. They received a small amount of monetary compensation. All of them had either normal or corrected-to-normal vision and were naïve to the purpose of the experiment. Three participants were excluded from the analysis because more than one-third of the trials had more than five blinks.

The number of participants was estimated using the *simr* package (Green & Macleod, 2016) in *R* statistical software (R Development Core Team, 2018). To do this, we tested eight participants in a pilot study and analyzed the gaze duration in the first constituent region using a linear mixed model. Since the plausibility effect for the novel compound words was the effect of our interest, we used the planned contrast method (see more details in the analysis section). We then investigated how power changed with the number of participants. The results showed that the power reached 85% for 41 participants. Thus, 43 participants were recruited for Experiment 1 to guarantee sufficient power.

Materials

Forty-eight pairs of novel and lexicalized two-character compound words were selected as materials. Both the novel and lexicalized compound words were combinations of two familiar Chinese characters (hereafter referred to as the first constituent and second constituent, respectively), which are single-character words by themselves. For example, "火棍" (means "firestick") for the novel compound word condition was combined by "火" (means "fire") and "棍" (means "stick"); and "火柴," (means "match") for the lexicalized compound word condition was combined by "火" (means "fire") and "柴" (means "firewood"). "火," "棍," and "柴" are single-character words in Chinese. While lexicalized compound words are listed as words in the *Modern Chinese Dictionary* (Dictionary Editorial Office, Institute of Linguistics, Chinese Academy of Social Sciences, 2016), novel compound words are not. In each pair of stimuli, the first constituents were identical (which is "火" in the previous example). The character frequency and number of strokes of the second constituents were matched between the lexicalized compound words and novel compound words ($t(94)=0.76$ for character frequency; $t(94)=-0.25$ for strokes, $ps>.1$; see Table 2). The frequency data was obtained from *the Lexicon of common words in contemporary Chinese* (Lexicon of Common Words in Contemporary Chinese Research Team, 2008).

Each pair of compound words was embedded in an identical sentence frame. We varied the verb prior to the compound words so that the plausibility of the first constituent of the compound word was manipulated. In the plausible condition, the combination of the verb and first constituent of the compound words was plausible. For example, the combination of the verb "点燃" (means "light") and the first constituent

of the compound word “火” was “点燃火” (means “light the fire”), which was plausible. However, this combination was not plausible in the implausible condition. For instance, the combination of the verb “折断” (means “break”) and the first constituent of the compound word “火” was “折断火” (means “break the fire”), which was implausible. The combinations of verbs and whole compound words were always plausible (as shown in Table 1).

Table 1

Examples of Materials in Experiment 1

Type of word	Context plausibility	Example sentences	Combination of verb and first constituent
Novel	Plausible	淘气的小孩再次***点燃*** **火棍** 时被妈妈看到了。 (When the naughty child ***lit*** the **firesticks** again, his mother saw this scene.)	点燃火 (lit the fire)
Novel	Implausible	淘气的小孩再次***折断*** **火棍** 时被妈妈看到了。 (When the naughty child ***broke*** the **firesticks** again, his mother saw this scene.)	折断火 (broke the fire)
Lexicalized	Plausible	淘气的小孩再次***点燃*** **火柴** 时被妈妈看到了。 (When the naughty child ***lit*** the **matches** again, his mother saw this scene.)	点燃火 (lit the fire)
Lexicalized	Implausible	淘气的小孩再次***折断*** **火柴** 时被妈妈看到了。 (When the naughty child ***broke*** the **matches** again, his mother saw this scene.)	折断火 (broke the fire)

Note. Italic and bold fonts were only used for illustration and did not appear during the experiment.

The temporary plausibility of the first constituent of the compound word within a sentence was assessed by 30 participants, and each verb-first constituent combination

was assessed by 15 participants. For each pair of combinations, the participants saw the sentences in only one condition (either plausible or implausible). Participants read the sentence fragments until the first constituent of the compound words, and they judged plausibility on a seven-point scale, with 1 indicating totally implausible and 7 indicating totally plausible. The plausibility was lower than four in the implausible condition, while the plausibility was higher than four in the plausible condition (see Table 2 for details). Plausibility scores were significantly higher in the plausible than in the implausible condition ($t(94)=17.14$, $p < .001$).

Table 2

Properties of Materials Used in Experiment 1

	Lexicalized compound		Novel compound	
	Plausible	Implausible	Plausible	Implausible
Plausibility of the first constituent	5.39 (0.78)	2.73 (0.73)	5.39 (0.78)	2.73 (0.73)
Predictability	0.00 (0.01)	0.01 (0.02)	0.00 (0.00)	0.00 (0.02)
Naturalness	5.93 (0.52)	5.80 (0.41)	5.88 (0.43)	5.83 (0.45)
Frequency of verb	34 (71)	32 (118)	34 (71)	32 (118)
Character frequency of the second constituent	515 (709)	515 (709)	405 (696)	405 (696)
Stroke number of the second constituent	8.75 (2.80)	8.75 (2.80)	8.92 (3.55)	8.92 (3.55)

Notes. 1) SD values are given in parentheses. 2) The units of word frequency and character frequency are occurrences per million.

The naturalness of the sentences was assessed by 60 participants, with 15

participants in each condition. Participants saw only one condition per sentence frame. The naturalness of all sentences was higher than four, and there was no significant difference among the conditions ($F(3,191)= 0.91, p > .1$). The predictability of the target words was assessed by another 15 participants, and the results showed that they were close to zero, and there was no significant difference between the conditions ($F(3,191)= 0.81, p > .1$).

Apparatus

The materials were presented on a 21-inch CRT monitor (Sony Multiscan G520) with a resolution of 1,024 × 768 pixels and a refresh rate of 150 Hz. Each sentence was displayed on a single line in Song 20-point font in white (RGB: 255, 255, 255) on a black background (RGB: 0, 0, 0). The participants' eyes were positioned approximately 58 cm from the computer monitor. At this viewing distance, each character subtends a visual angle of approximately 1°. Eye movements were monitored using an Eyelink 1000 eye-tracking system (SR Research, Mississauga, Ontario, Canada) with a sampling rate of 1,000 Hz. The participants placed their chins on a chin rest and leaned their foreheads against the forehead rest to minimize head movements. Participants read sentences binocularly, but only their right eye was monitored.

Procedure

The eye tracker was calibrated at the beginning of the experiment and again as needed. A three-point calibration procedure was performed. The maximum calibration error was 0.5. Participants were asked to read silently at their normal speed and answer comprehension questions following one-third of the sentences. The questions were used

to ensure that the participants continued to concentrate on the reading task. Each sentence appeared after the participants fixated on a character-sized box at the location of the first character of each sentence. After reading a sentence or answering a comprehension question, participants were asked to press a response button to start the next trial. Each participant read 48 experimental sentences (12 sentences in each of the four conditions) and 48 filler sentences.

Data Analysis

We analyzed eye-movement data on the pre-target verb, the first and second constituents of the compound words, and the whole compound words. The following eye-movement measures are reported for each area of interest: first fixation duration (the duration of the first first-pass fixation on the target regions), gaze duration (the sum of all first-pass fixations on the target regions before moving to other regions), go-past time (the sum of duration starting when entering the target regions until their right boundary was crossed), and skipping probability (the probability that the target regions were skipped).

We analyzed the above eye-movement measures for all the areas of interest using *linear mixed models* for continuous variables and *generalized linear mixed models* for dichotomous variables (Baayen et al., 2008) using *R* statistical software (R Development Core Team, 2018). We reported the regression coefficients (*b*), standard errors (SE), and test statistics (*t* values for linear mixed models or *z* values for generalized linear mixed models with a logit link function). Although the Wald statistics are interpretable directly, we also estimated p values using the *lmerTest* package. Since

the plausibility effects for the novel compound word condition and lexicalized compound word condition were our main interests, following Schad et al. (2020), we used the following three customized contrasts: (1) a contrast that tests the main effect of type (novel compound word vs. lexicalized compound word, coded as 0.5 and -0.5); (2) a contrast that tests the plausibility effect (implausible vs. plausible, coded as 0.5 and -0.5) for the novel compound word condition; and (3) a contrast that tests the plausibility effect for the lexicalized compound word condition. We fitted a maximum model that included random slopes for all fixed factors (see Barr et al., 2013) and random intercepts for participants and items. A maximum convergent model was used. To achieve this, a model with a maximum random factor structure was constructed. When the maximum model failed to converge, we used the zero-correlation parameter model and removed random constituents that produced the least variance. Materials, analysis code and data are available in osf (Wang, 2022).

Results

The average accuracy for the comprehension questions was high (mean=95.7% [range: 80%-100%], SD=4.3%), indicating that the participants understood the sentences well. Trials were removed if there was a blink within the critical four-character region (verbs and two-character compound words). A total of 121 trials (6.30% of all trials) were excluded. Fixations shorter than 80 ms or longer than 1000 ms were removed (0.8%). Trials with fixations beyond three standard deviations for each condition and participant were also excluded from the analyses (14 data points). The means and SEs for each eye-movement index in all regions are summarized in Table 3.

Pre-Target Verb and the First Constituent of the Compound Word

No significant effects were found in the two regions (*p*s > .1). For completeness, we included conditional means for these two regions in Table 3, but will not discuss them further.

Second Constituent of the Compound Word

The first fixation duration (b = 15.41, SE = 7.76, t = 1.99, p = .053) and gaze duration (b = 23.86, SE = 7.52, t = 3.17, p = .003) were longer in the novel compound word condition than in the lexicalized condition, although only gaze duration reached significant. Skip probability in the novel compound word condition was lower than in the lexicalized compound condition, but it was only close to significant (b = -0.17, SE = 0.10, t = -1.70, p = .089). More importantly, for novel compound words, the reversed plausibility effects (longer fixation duration in the plausible condition than in the implausible condition) were significant for the first fixation duration (b = -19.77, SE = 8.77, t = -2.25, p = .024) and gaze duration (b = -27.92, SE = 10.06, t = -2.78, p = .011).

Whole Compound Words

Gaze duration was longer in the novel compound word condition than in the lexicalized compound word condition (b =29.85, SE = 9.99, t = 2.99, p =.005). There was a trend of a plausibility effect for novel compound words in skipping probability, with higher skipping probability for the lexicalized compound words, but this effect was not significant (b = -0.30, SE = 0.15, t = -1.95, p = .051). No other significant effects were observed in this region.

Table 3

Eye Movement Measures in Experiment 1

	Lexicalized compound word		Novel compound word	
Eye Movement Measures	**Plausible**	**Implausible**	**Plausible**	**Implausible**
		Pre-target verb Region		
First fixation duration	278 (7)	287 (7)	281 (7)	284 (8)
Gaze duration	338 (13)	344 (12)	345 (11)	359 (15)
Go-past time	399 (16)	439 (25)	430 (17)	446 (21)
Skipping probability	0.12 (0.02)	0.13 (0.02)	0.14 (0.03)	0.10 (0.02)
		First constituent region		
First fixation duration	287 (9)	270 (8)	296 (13)	282 (7)
Gaze duration	293 (9)	276 (9)	310 (14)	292 (9)
Go-past time	372 (20)	387 (20)	389 (19)	423 (29)
Skipping probability	0.52 (0.03)	0.48 (0.03)	0.51 (0.03)	0.50 (0.02)
		Second constituent region		
First fixation duration	267 (7)	272 (9)	294 (8)	280 (6)
Gaze duration	270 (7)	273 (9)	307 (9)	285 (6)
Go-past time	370 (24)	387 (26)	414 (24)	394 (22)
Skipping probability	0.45 (0.03)	0.49 (0.03)	0.43 (0.03)	0.43 (0.02)
		Compound word region		
First fixation duration	281 (8)	274 (7)	291 (8)	283 (6)
Gaze duration	324 (11)	322 (12)	362 (14)	344 (10)
Go-past time	430 (20)	440 (20)	472 (23)	445 (21)
Skipping probability	0.13 (0.02)	0.13 (0.02)	0.11 (0.02)	0.09 (0.02)

Note. 1) First-fixation duration, gaze duration and go-past time were measured in milliseconds. 2) SE values are given in parentheses.

Discussion

The major result of Experiment 1 showed that reading times for whole compound words were longer for novel compound words than for lexicalized compound words. We did not observe any plausibility effects in the first constituent region. In the second constituent region, for novel compound words, a reversed plausibility effect was observed for first fixation duration and gaze duration.

These results suggested that lexicalized and novel compound words were processed differently. That is, lexicalized compound words were likely to be integrated with context holistically because no significant effects were observed in either the first or second constituent regions. This pattern is consistent with the findings of Yang et al. (2012), who used lexicalized two-character compound words as targets and failed to observe plausibility effects on the first constituent of the compound word. In contrast, novel compound words were likely to be integrated with contexts in a decompositional manner, as evidenced by the reverse plausibility effect on the second constituent region of the novel compound words. This reversed plausible effect may be caused by the correction procedure of the previous integration between the verb prior to the compound word and the first constituent of the compound word. If the first constituent is plausible within the sentence context, readers may integrate the first constituent into a sentence. Later, when they found that the first constituent was not an independent word but part of a compound word, they had to correct the integration so that it took a longer time. In contrast, if the first constituent is implausible within the sentence context, readers will not integrate it into a sentence but will integrate the whole compound word into the sentence context. Therefore, readers are not required to correct incorrect word segmentation or information integration.

Experiment 2

In Experiment 1, we replicated Yang et al. (2012) for two-character lexicalized compound words' holistic integration pattern. However, how long compound words, including both lexicalized and novel compound words, are integrated with context is

still unclear. Thus, in Experiment 2, we investigated how long compound words are integrated during reading.

Method

Participants

We calculated the number of participants with the same method as in Experiment 1. The results showed that the power reached 80% for 18 participants. Consistent with Experiment 1, forty-four native Chinese speakers from the same participant pool as in Experiment 1 (age: M= 22.57, SD= 2.55; 12 men) participated in Experiment 2. None of the participants participated in Experiment 1. All of them had either normal or corrected-to-normal vision and were naïve to the purpose of the experiment. Four participants were excluded because of too many blinks (there were more than three blinks in each trial in more than one-third of trials).

Materials

Forty-eight pairs of four-character novel and lexicalized compound words were used. All the compound words were constructed using two commonly used two-character words (referred to as constituents in the following section). While novel compound words are not listed in the Modern Chinese Dictionary, lexicalized compounds are. For each pair, the first constituent was identical. The word frequency of the second constituent words (t(94)=1.23, p>.1), the character frequencies (t(94)=1.13, p>.1 for the third character; t(94)=1.40, p>.1 for the fourth character), and the number of strokes of both characters (t(94)=-0.83, p>.1 for the third character; t(94)=-7.53, p>.1 for the fourth character) of the second constituent words were

matched between the novel and lexicalized compound word conditions (see Table 4). The frequency data was obtained from *the Lexicon of common words in contemporary Chinese* (Lexicon of Common Words in Contemporary Chinese Research Team, 2008).

Table 4

Example Sentences in Experiment 2

Word novelty	Context plausibility	Example sentences	Combination of verb and first constituent
Novel	Plausible	我国的人们***保护*** **海洋植物** 有较长的历史了。 (People in our country have a long history of ***protecting*** **sea plant**.)	保护海洋 (protect the sea)
Novel	Implausible	我国的人们***食用*** **海洋植物** 有较长的历史了。 (People in our country have a long history of ***eating*** **sea plant**.)	食用海洋 (eat the sea)
Lexicalized	Plausible	我国的人们***保护*** **海洋生物** 有较长的历史了。 (People in our country have a long history of ***protecting*** **sea life**.)	保护海洋 (protect the sea)
Lexicalized	Implausible	我国的人们***食用*** **海洋生物** 有较长的历史了。 (People in our country have a long history of ***eating*** **sea life**.)	食用海洋 (eat the sea)

Note. Italic and bold fonts were only used for illustration and did not appear during the experiment.

Each pair of compound words was embedded in a sentence frame. Similar to Experiment 1, two-character verbs before the target word were manipulated so that the

first constituents were plausible in the sentence context in half of the trials, whereas the first constituents were implausible in the other half of the trials. As in Experiment 1, we asked participants to assess the predictability of the key compound words (30 participants), plausibility of the combination (30 participants), and naturalness of the whole sentences (60 participants). The plausibility score was significantly higher in the plausible condition than in the implausible condition ($t(94)=16.56$, $p < .001$). There were no significant differences among the conditions for the other assessments ($F(3,191)=1.00$, $p>.1$ for predictability; ($F(3,191)=0.71$, $p>.1$ for naturalness). The average scores for each assessment in the four conditions are listed in Table 5.

Table 5

Properties of Materials Used in Experiment 2

	Lexicalized compound		Novel compound	
	Plausible	Implausible	Plausible	Implausible
Plausibility	5.14 (0.70)	3.03 (0.52)	5.14 (0.70)	3.03 (0.52)
Predictability	0.00 (0.00)	0.00 (0.01)	0.00 (0.00)	0.00 (0.00)
Naturalness	5.38 (0.61)	5.48 (0.51)	5.33 (0.57)	5.37 (0.51)
Word frequency of verb	67 (76)	48 (60)	67 (76)	48 (60)
Word frequency of the second constituent	102 (148)	102 (148)	69 (117)	69 (117)
Character frequency of the third character	1471 (1711)	1471 (1711)	1118 (1282)	1118 (1282)
Strokes of the third character	8.02 (3.18)	8.02 (3.18)	8.58 (2.99)	8.58 (2.99)
Character frequency of the fourth character	1589 (1917)	1589 (1917)	1117 (1284)	1117 (1284)
Strokes of the fourth character	7.88 (2.93)	7.88 (2.93)	8.33 (2.97)	8.33 (2.97)

Note. 1) SD values are given in parentheses. 2) The units of word frequency and character frequency are occurrences per million.

Apparatus and procedure

The apparatus and procedure were the same as in Experiment 1.

Data Analysis

The analysis was similar to that of Experiment 1 except that the areas of interest were changed. In Experiment 2, the first and second constituent regions were two-character words. Materials, analysis code and data are available in osf (https://osf.io/tyr62/).

Results

The average accuracy of the comprehension question was high (mean=94.3% [range: 83.0%-100.0%], SD=4.4%), indicating that the participants understood the sentences well. Trials were removed if there was a blink within the critical six-character region (pre-target verbs and compound words). A total of 258 trials (13.43% of all trials) were excluded. Fixations shorter than 80 ms or longer than 1000 ms were removed (0.9%). Data points with more than three standard deviations from the mean (calculated within participants and conditions) were also removed (8 data points). The means and SEs for each eye movement index in all regions are summarized in Table 6.

Pre-Target Verb

We did not observe any significant effect in the verb region, *p*s > .1.

First Constituent

We found significant plausibility effects for novel compound words in the first fixation duration (b = 14.85, SE = 5.84, t = 2.50, p = .017) and gaze duration (b = 25.99, SE = 10.30, t = 2.52, p = .016), with longer durations in the implausible condition than in the plausible condition. In contrast, this effect was not significant for lexicalized compound words (first fixation duration: b = -4.76, SE = 5.92, t = -0.79, p = .430; gaze duration: b = 3.27, SE = 9.14, t = 0.36, p = .720). We also found that go-past time was longer in the novel compound word condition than that in the lexicalized compound word condition (b = 35.49, SE = 14.43, t = 2.46, p = .018). No other effects were significant (*p*s > .1).

Second Constituent

All fixation measures showed a significant main effect of word novelty (first fixation duration: $b = 20.47$, $SE = 4.47$, $t = 4.58$, $p < .001$; gaze duration: $b = 38.10$, $SE = 8.02$, $t = 4.75$, $p < .001$; go-past time: $b = 42.54$, $SE = 19.66$, $t = 2.16$, $p = .037$), with longer fixation durations in the novel compound word condition than in the lexicalized compound word condition. Skipping probability was lower in the novel compound word condition than in the lexicalized compound word condition ($b = -0.26$, $SE = 0.12$, $t = -2.13$, $p = .033$). There was a trend of reversed plausibility effects in the novel compound word condition for the first fixation duration ($b = -11.97$, $SE = 6.50$, $t = -1.84$, $p = .072$) and gaze duration ($b = -20.07$, $SE = 11.26$, $t = -1.78$, $p = .084$), with longer fixation durations in the plausible condition than in the implausible condition. However, the trends were only close to being significant. No other effects were significant in this region.

Whole Compound Word

A significant word-type effect was observed in gaze duration ($b = 48.32$, $SE = 11.37$, $t = 4.25$, $p < .001$) and go-past time ($b = 58.63$, $SE = 17.44$, $t = 3.36$, $p = .002$), as they were longer in the novel compound word condition than in the lexicalized compound word condition. We also observed a close-to-significant plausibility effect for novel compound words in the first fixation duration ($b = 9.41$, $SE = 5.39$, $t = 1.75$, $p = .089$), which was longer in the implausible condition than in the plausible condition.

Table 6

Eye Movement Measures in Experiment 2

	Lexicalized compound word		Novel compound word	
Eye Movement Measures	**Plausible**	**Implausible**	**Plausible**	**Implausible**
		Pre-target verb Region		
First fixation duration	241 (7)	252 (7)	242 (6)	247 (7)
Gaze duration	276 (12)	281 (10)	269 (10)	277 (10)
Go-past time	364 (21)	354 (19)	330 (14)	340 (16)
Skipping probability	0.22 (0.04)	0.24 (0.03)	0.20 (0.03)	0.20 (0.03)
		First constituent region		
First fixation duration	250 (7)	246 (6)	244 (6)	259 (7)
Gaze duration	272 (9)	275 (8)	272 (9)	296 (10)
Go-past time	348 (14)	349 (14)	394 (21)	366 (18)
Skipping probability	0.20 (0.03)	0.21 (0.03)	0.21 (0.03)	0.20 (0.03)
		Second constituent region		
First fixation duration	234 (5)	233 (6)	261 (7)	249 (7)
Gaze duration	254 (7)	242 (7)	296 (10)	276 (9)
Go-past time	326 (20)	316 (18)	372 (20)	360 (21)
Skipping probability	0.26 (0.03)	0.26 (0.03)	0.20 (0.03)	0.23 (0.03)
		Compound word region		
First fixation duration	252 (7)	244 (6)	249 (6)	258 (6)
Gaze duration	408 (17)	409 (18)	449 (20)	465 (20)
Go-past time	512 (19)	521 (23)	583 (27)	565 (29)
Skipping probability	0.03 (0.01)	0.03 (0.01)	0.03 (0.01)	0.02 (0.01)

Note. 1) First-fixation duration, gaze duration and go-past time were measured in milliseconds. 2) The SEs are given in parentheses.

Discussion

Experiment 2 was similar to Experiment 1 except that two-character compound words were replaced by four-character words. The reversed plausibility effect for the novel compound words in the second constituent region paralleled the pattern of results in Experiment 1, although it was just close to significant. More importantly, we observed a significant plausibility effect in the novel compound word condition for first fixation duration and gaze duration in the first constituent region. Fixation durations were significantly longer in the implausible condition than in the plausible condition. However, no such effect was found for lexicalized compound words. These results

implied that the novel compound words were partially integrated with context during Chinese reading.

General Discussion

In the present study, we investigated how readers process lexicalized and novel compound words of different lengths during Chinese reading. In both experiments, we found that readers spent more time processing novel compound words than lexicalized ones. Most importantly, the temporary plausibility manipulation of the first constituent region of the compound words yielded a different pattern of plausibility effects for the novel and lexicalized compound words. While no plausibility effects were found in any region of interest for lexicalized compound words in the two experiments, reliable effects from this plausibility manipulation were observed for novel compound words, although there were differences between the two experiments. In Experiment 1, where the target words were two-character words, we observed a reversed plausibility effect of first fixation duration and gaze duration on the second constituent of novel compound words. In Experiment 2, where the target words were four-character words, we observed a significant plausibility effect of the first fixation duration and gaze duration in the first constituent region of novel compound words. We also observed a trend of a reversed plausibility effect in the second constituent region of the novel compound words (ps = .072 and .084 for the first fixation duration and gaze duration, respectively).

The different findings between novel and lexicalized compound words indicate that the two kinds of compound words are integrated with context using different mechanisms. For novel compound words, we observed plausibility effects on the first

constituents for four-character words. Reversed plausibility effects on the second constituent were observed for two-character words, and a similar trend of reversed effect was also observed for four-character words, but the effect was not significant. These results suggest that Chinese readers integrated the first constituent of novel compound words with context as independent words when they first encountered them. In the implausible condition, when they try to integrate the first constituent into the sentence context, they have some difficulty, so they need a longer time. In contrast, we did not observe any plausibility or reversed plausibility effects in any region of the two- or four-character lexicalized compound words. This suggests that lexicalized compound words are integrated with context as a whole unit so that whether their constituents are plausible within the sentence context does not affect eye movements during reading.

The current results that readers immediately integrate the first constituent of the novel compound words support the view that the semantic integration of Chinese novel compound words in sentences is highly incremental (Rayner et al., 2006). Considering that Chinese is an unspaced script (no visual cues between words), the immediate plausibility effect observed on the first constituents of novel compounds is interesting. Staub et al. (2007) observed an immediate integration of the first noun constituent of the spaced noun-noun compounds with its previous verb. One may argue that Staub et al. (2007) used spaced noun-noun compounds, which made readers more likely to treat the first noun as the object of the verb before it. Indeed, Juhasz et al. (2005) indicated that spaces in compound words can be beneficial in identifying constituents. The

findings of the present study showed that inter-word spaces may not be the determining factor that causes immediate integration. Since there are no spaces between words in Chinese, Chinese readers have to decide where the word boundaries are using other mechanisms (Li et al., 2009; Li & Pollatsek, 2020). Once Chinese readers segment a word from its context, they immediately integrate it with context. For novel compound words, Chinese readers initially segment the first component of a novel compound word as a word, and then integrate it into the verb prior to it.

The finding observed in the present study that the lexicalized compound words are integrated with sentence context as a whole unit seems inconsistent with previous semantic priming studies that showed semantic activation of morphemes in lexicalized compound words (e.g., Tsang & Chen, 2013a; 2013b). This might be because these studies focused on different stages of word processing. To be specific, Tsang and Chen (2013a) focused on word identification and demonstrated that different meanings of an ambiguous morpheme could be activated at the early stage of word identification. However, in the present study, we focused on word integration and did not find evidence that the constitutes of the lexicalized compound words are integrated with sentence context. CRM could also explain the different patterns of semantic activation across these studies. That is, the lexicalized compound word and its constituent words are activated at the early stage of word processing. Later, as the whole word dominates the competition, the activation of constituent words is inhibited.

While our results showed strong evidence that lexicalized compound words were integrated in a holistic manner with the sentence context, they provide less evidence

regarding how the constituents of compound words were identified before semantic integration. In other words, there are two possibilities: First, lexicalized compound words were identified as whole units, thus they can only be integrated as whole units. This possibility is consistent with the prediction of CRM as discussed above. Second, lexicalized compound words could be identified through a decompositional manner, and readers combined their constituents into a bigger unit before integrating it with context. As the main purpose of the current study was on semantic integration of compound words, we will not discuss how compound words were identified before integration. Future studies are needed to distinguish these two possibilities. When comparing the results of Experiments 1 and 2, we found that word length was not the major factor that determines whether a compound word is integrated with the sentence context as a whole. Regardless of word length, lexicalized compound words are integrated with contexts in a holistic way, and novel compound words are not integrated into the sentence context as a whole.

Nevertheless, word length did affect the pattern of plausibility effects across two experiments. Specifically, we only observed plausibility effects in the first constituent region for four-character words, but not for two-character words. This may be because the two-character words were short and close to foveal vision when the eyes were fixating on the verb prior to the target word. It has been reported that Chinese readers can obtain preview information from at least two characters to the right of fixation, regardless of whether they form a word (Yang et al., 2009b). Therefore, even when readers processed two-character novel compound words in a decomposed manner, this

processing occurred so rapidly that the plausibility effect was not found in the first constituent regions in Experiment 1.

In the present study, we only considered the impact of word length and word novelty in the semantic integration of compound words during sentence reading. Several other factors might also have influences. A study found that Italian compound words, which can be used as both transparent and opaque words, showed a different pattern of constituent frequency effect in different sentence contexts (Amenta et al., 2015). In the context supporting transparency meaning, reading fixation showed a facilitation effect for constituent frequency, while in the context supporting opaque meaning, an inhibition constituent frequency effect was observed. This indicated an interaction between sentence context and semantic transparency on the processing of compound words. However, it is still under investigation how word properties, including semantic transparency and word structure, can influence integration between compound words and sentence contexts.

Conclusion

In conclusion, the present study showed that novel compound words and lexicalized compound words are integrated with sentence context in different ways. For novel compound words, we observed plausibility effects of the first constituent, suggesting that Chinese readers integrated the first constituent of novel compound words with context as independent words when they first encountered them. In contrast, lexicalized compound words are integrated with context in a holistic way so that we did not observe any plausibility of the first compound, regardless of word length.

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