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The Effects of Lexical and Sentence Level Contextual Cues on Chinese Word Segmentation

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Abstract

The present study investigated whether and how the lexical-level contextual cue influences word segmentation when reading Chinese. Chinese readers' eye movements were recorded as they read sentences containing an overlapping ambiguous string (OAS). The OAS consists of three characters (ABC) whose middle character can form a distinct word with both the character on its left (word AB) and on its right (word BC). In the semantically related condition, the pre-OAS context contained a word that was semantically related to the left-side word AB, while this word was replaced by an unrelated control word in the semantically unrelated condition. In the high-constraint context, only the right-side word A-BC structure was preferred by the context, while the context did not provide any constraint on word segmentation in the low-constraint context. The results showed that there was a facilitation effect of the lexical-level contextual cue in the low-constraint context, reflected by lower regression-out probabilities in the semantically related condition than the semantically unrelated condition. However, in the high-constraint context, the facilitation effect of the lexical-level contextual cue was replaced with an inhibitory effect, reflected by higher regression-out probabilities in the semantically related condition than the semantically unrelated condition. These results suggest that Chinese readers use the lexical-level contextual cue when segmenting words, and words supported by this information are more likely to be segmented as words than words not supported by this information. Moreover, when both the lexical-level and

the sentence-level contextual cues are available, the lexical-level contextual cue is used earlier or simultaneously than the sentence-level contextual cue.

Keywords: Chinese reading, eye-tracking, word segmentation, semantic relatedness, context constraints

The Effects of Lexical and Sentence Level Contextual Cues on Chinese Word Segmentation

Unlike alphabetic languages such as English, there are no inter-word spaces to demarcate words in Chinese texts. Hence, Chinese readers must use other available information to help them with word segmentation (i.e., grouping continuous characters into words) to achieve successful reading comprehension (Ma et al., 2014; Yen et al., 2012). One important question in this regard is understanding what kind of information Chinese readers use to segment words and how they use it. In the present study, we investigated whether Chinese readers use the lexical-level contextual cue to segment words, and how they jointly use the lexical-level contextual cue and the sentence-level contextual cue when segmenting words.

Previous studies have shown that Chinese readers use word frequency, the relative position of words, and sentence context to help with word segmentation. Ma et al. (2014) investigated how Chinese readers segment words during sentence reading using *overlapping ambiguous strings* (OASs). OASs are one type of word boundary ambiguity (Luo et al., 2002). An OAS usually consists of three characters (ABC, denoting the characters from left to right), with the first two characters constituting a word (i.e., word AB), and the last two characters constituting another word (i.e., word BC). Taking the OAS "从小吃" as an example, the first two characters constitute the word "从小" (meaning *from childhood*), while the last two characters constitute another word "小吃" (meaning *snack*). Each OAS can be segmented into a left-side word AB-C structure (e.g., "从小-吃," meaning *eat from childhood*) or a right-side

word A-BC structure (e.g., "从-小吃," meaning *from snack*). Ma et al. (2014) embedded OASs into sentences and found that when the post-OAS disambiguating information was consistent with a segmentation favoring the higher frequency word, second-pass reading times were shorter and regression-in probabilities were lower than those in an inconsistent situation. Thus, word frequency is essential to word segmentation, and words with higher frequencies are more likely to be segmented as words. Moreover, since the reading direction of Chinese is from left to right, left-side words (AB) are more likely to be segmented as words when other factors being equal (Ma et al., 2014; Huang & Li, 2020). Finally, sentence context also affects word segmentation, with words that are favored by the sentence context being more likely to be segmented as words (Huang et al., 2021).

How do Chinese readers segment words using the information introduced above? According to a recent computational model (*Chinese reading model,* CRM), all characters within the perceptual span are activated, and all words composed by these characters are activated (Li et al., 2009; Li & Pollatsek, 2020). Spatially overlapping words such as words AB and BC that are spatially overlap (such as character B in this example) compete with each other, and only one word can win the competition. Once a word wins the competition, it is recognized and segmented from the text simultaneously. Therefore, the CRM assumes that word segmentation and word identification are a unified process during Chinese reading, without one happening earlier than the other. It should be noted that CRM did not have a semantic component, but it can successfully simulate many important findings about word

segmentation, including the left-side word advantage and the word frequency effect.

What remains unknown in the literature is whether Chinese readers use the lexical-level contextual cue to segment words. During sentence reading, the processing of a target word is sometimes affected by a word appearing in the prior context, which is semantically related to it. This word appearing in the prior context is considered to provide a lexical-level contextual cue for the target word. The lexical-level contextual cue is considered important for sentence comprehension, and its facilitation effect on word processing has been found in RSVP naming experiments, eye-movement sentence reading studies, and ERP studies (Duffy et al., 1989; Hoeks et al., 2004; Van Petten, 1993). For instance, in a study by Morris (1994), reading times on a verb (e.g., trim) were shorter when prior context contained a semantically related noun (e.g., barber), compared to a condition where the semantically related noun was replaced by a semantically unrelated noun (e.g., person).

Although many studies have been conducted to understand how lexical-level contextual cue affects word processing and reading comprehension, its impact on Chinese word segmentation remains unclear. This was the first question we asked in the present study. To answer this question, we focused on a specific situation, which is whether readers will use the lexical-level contextual cue to segment words when they can correctly segment words without using it. One possibility is that readers use all available information to segment words, so they use the lexical-level contextual cue to segment words. Alternatively, due to limited working memory resources, readers might only use necessary information to segment words, so they do not use

the lexical-level contextual cue to help with word segmentation.

In the present study, we also manipulated sentence-level contextual cue to compare the time course of the effects of the lexical-level and sentence-level contextual cues on word segmentation. As mentioned above, the lexical-level contextual cue was manipulated by containing a word semantically related to target word or not, thus this information worked at the lexical level. In contrast, for the sentence-level contextual cue, the prior context was manipulated to either constrain the segmentation structure of OAS or not. Huang and Li (2020) found that readers could use context constraint information to segment words. The first possibility is that readers use the lexical-level contextual cue later than the sentence-level contextual cue. Therefore, readers might already have segmented words using the sentence-level contextual cue when the lexical-level contextual cue becomes available to them. Consistent with this possibility, previous studies have shown that the semantically related words contained in the prior context can only facilitate the processing of the target word when the sentence-level contextual information is consistent with the target word (Morris, 1994). For example, in the sentence "The gardener talked as the barber trimmed the mustache after lunch", the facilitation effect of lexical-level contextual cue on "mustache" was found, while this effect was not found in the sentence "The gardener talked to the barber and trimmed the mustache after lunch", in which the sentence context was not consistent with the meaning of "mustache" (as gardeners usually trim branches, not mustaches), despite the same lexical content. However, these results cannot be directly generalized to Chinese word segmentation.

The second possibility is that readers can use the lexical-level contextual cue earlier than the sentence-level contextual cue. Therefore, readers might use the lexical-level contextual cue at the early stage of word segmentations, and then use the sentence-level contextual cue during the integration stage. Analogy to this possibility, the checking model (Norris, 1986) make similar assumptions that semantically related concepts or associative relationships can exert an earlier effect on reading compared to the sentence-level context.

To explore these issues, we conducted an eye-movement study in which readers read sentences containing OASs. The lexical-level contextual cue and the sentence-level contextual cue were orthogonally manipulated. For the lexical-level contextual cue, the pre-OAS context contained a word (e.g., "日本", meaning *Japanese*) that was semantically related to word AB (e.g., "和服", meaning *kimono*) in the semantically related condition, while this word was replaced by an unrelated control word (e.g., "上海", meaning *Shanghai*) in the semantically unrelated condition.

Unlike the lexical-level contextual cue, the sentence-level contextual cue involved manipulation of the prior context to form constraints on the subsequent continuation. Specifically, these constraints were primarily imposed by the words immediately preceding the OAS region. In the high-constraint condition, only the A-BC structure was plausible given the prior context. For example, the A-BC structure was preferred following the prior context ("这位日本游客不需要休息和-服用…," meaning *This Japanese tourist does not need to rest and take…*). In contrast, in the low-constraint condition, the prior context did not provide any constraint on word

segmentation, making any segmentation structure plausible given the prior context. For example, the AB-C and A-BC structures were both plausible given the prior context ("这位日本游客不知道购买和服-用/和-服用…," meaning *This Japanese tourist does not know what … to use to buy kimono/to buy and take…*).

The post-OAS texts indicated that the correct segmentation of OASs was the A-BC structure in all conditions. As shown, readers could correctly segment the OAS "和服用" as the A-BC structure"和-服用" without considering the lexical-level contextual cue (i.e., "日本," meaning *Japanese*), but could not correctly segment words without using the sentence-level contextual cue.

Different hypotheses make different predictions regarding reading times and regression-out probabilities of the OAS region during first-pass reading. If readers use only necessary information to assist them with word segmentation, they will not use unnecessary lexical-level contextual cue; hence, the lexical-level contextual cue should not affect any eye-movement behavior. By contrast, if readers use the lexical-level contextual cue, they can quickly resolve ambiguities related to word boundaries and perform a word segmentation. Consequently, in a low-constraint context where ambiguity in word boundary exists, there should be shorter reading times and lower regression-out probabilities in the semantically related condition compared to the semantically unrelated condition.

Now, let us return to the issue of whether the lexical-level contextual cue or the sentence-level contextual cue is used earlier. If the lexical-level contextual cue is used earlier than the sentence-level contextual cue, readers initially perform an AB-C

segmentation based on the lexical-level contextual cue in the semantically related condition, which conflicts with the A-BC segmentation based on the sentence-level contextual cue in the high-constraint condition. Therefore, in a high-constraint context, there should be longer reading times and higher regression-out probabilities in the semantically related condition than in the semantically unrelated condition. However, if the lexical-level contextual cue is used later than the sentence-level contextual cue, readers can initially perform an unambiguous segmentation based on high-constraint contexts. Thus, in a high-constraint context, there should be no significant difference between the semantically related and unrelated conditions.

Method

Participants

Forty-eight college students (16 males and 32 females; age range 18–30 years, *M* = 23.31 years, *SE* = 0.31) participated in the experiment. To determine the ideal number of participants, we estimated the priori power of the study by using the *powerSim* and *powerCurve* functions of the *simr* package (Green & MacLeod, 2018) within the *R* Environment for Statistical Computing (R Development Core Team, 2020). First, we conducted a pilot study with 12 participants and analyzed the data using a linear mixed-effects model (as described in the Data Analysis section), in which second-pass reading time on the OAS region was the dependent variable. Then, based on the pilot data, we explored how the power varies as a function of the number of participants. The results indicated that the power estimate of 45 participants was 81%; therefore, 48 participants were suitable for a well-powered within-subjects

design (Brysbaert & Stevens, 2018; Cohen, 2013). The observed effect size from the pilot study was utilized for the power simulations. However, it should be acknowledged that the observed effect size may have been an overestimate of the true effect, which could potentially result in an underestimation of the required number of participants to attain the targeted power level. All participants were native Chinese speakers with normal or corrected-to-normal vision.

Materials

We took three-character OASs (ABC) as targets whose first two characters constituted a word (i.e., word AB) and whose last two characters constituted another word (i.e., word BC). A total of 56 OASs were selected, in which the left-side words AB and right-side words BC were medium-frequency words (Lexicon of Common Words in Contemporary Chinese Research Team, 2008). Word frequency ($t(110) = 0.68$, $p = .501$) and stroke number ($t(110) = -0.30$, $p = .762$) were comparable between words AB and BC (see Table 1).

Table 1

Properties of Word AB and Word BC

	Word AB	Word BC
Word frequency (log-transformed)	0.89 (0.06)	0.83 (0.06)
Stroke number	14.38 (0.43)	14.57 (0.48)

Note. Standard errors are given in parentheses. The unit of word frequency is the number of occurrences per million.

Each OAS was embedded into four sentences (see Table 2 for examples). Regarding the lexical-level contextual cue, the prior context contained a word

semantically related to the left-side word AB in the semantically related condition, while this word was replaced by an unrelated control word in the semantically unrelated condition. As for the sentence-level contextual cue, only the A-BC structure was preferred, given the prior context in the high-constraint condition, whereas no specific segmentation structure was preferred in the low-constraint condition. Therefore, the segmentation result based on semantically related words (supporting word AB) conflicts with the high-constraint context (supporting the A-BC structure). The study design was a 2 (lexical-level contextual cue: semantically related vs. semantically unrelated) × 2 (sentence-level contextual cue: high-constraint vs. low-constraint) within-participants design. The post-OAS texts indicated that the correct segmentation of all OASs was the A-BC structure. As mentioned above, Chinese readers could correctly segment words without using the lexical-level contextual cue, but they could not correctly segment words without the sentence-level contextual cue. Taking the OAS "和服用" (pronounced *he fu yong*) as an example (see Table 2 for details), it has a AB-C structure "和服-用" (meaning *kimono using*) and a A-BC structure "和-服用" (meaning *and take*). In the semantically related and high-constraint condition, the prior context "这位日本游客不需要休息…" (meaning *This Japanese tourist does not need to rest…*) contained a word "日本" (meaning *Japanese*) semantically related to the word AB "和服" (meaning *kimono*); moreover, the A-BC structure was preferred following the prior context ("这位日本游客不需要休息和-服用…," meaning *This Japanese tourist does not need to rest and take…*), while the AB-C structure was not preferred ("这位日本游客不需要休息和服-用…,"

meaning *This Japanese tourist does not need to rest kimono using…*). However, in the semantically related and low-constraint condition, the prior context did not have a particular preference for the AB-C structure ("这位日本游客不知道购买和服-用," meaning *This Japanese tourist does not know what … to use to buy kimono…*) or the A-BC structure ("这位日本游客不知道购买和-服用…," meaning *This Japanese tourist does not know what … to buy and take…*). For the corresponding semantically unrelated conditions of the high-constraint and low-constraint conditions, the semantically related word "日本" (meaning *Japanese*) was replaced by the semantically unrelated word "上海" (meaning *Shanghai*). To avoid the influence of parafoveal information on foveal processing, disambiguation information appeared after at least two characters following the OAS region. As is shown, readers could correctly segment the OAS "和服用" as "和-服用" without considering the semantic related word (i.e., "日本," meaning *Japanese*), but could not correctly segment the word without considering the high-constraint context constraint. Therefore, the lexical-level contextual cue of the present stimuli was unnecessary for word segmentation.

Table 2

Material Examples Across Conditions

Instruction	Example/Translation
Semantically related and high-constraint	
Stimuli	这位日本游客不需要休息**和-服用**什么药就能适应高原反应
The whole sentence	This Japanese tourist does not need to rest **and take** any medicine to adapt to altitude sickness
Prior context + AB-C	This Japanese tourist does not need to rest **kimono using**…
Prior context + A-BC	This Japanese tourist does not need to rest **and take**…
Semantically unrelated and high-constraint	
Stimuli	这位上海游客不需要休息**和-服用**什么药就能适应高原反应
The whole sentence	This Shanghai tourist does not need to rest **and take** any medicine to adapt to altitude sickness
Prior context + AB-C	This Shanghai tourist does not need to rest **kimono using**…
Prior context + A-BC	This Shanghai tourist does not need to rest **and take**…
Semantically related and low-constraint	
Stimuli	这位日本游客不知道购买**和-服用**什么药才能缓解高原反应
The whole sentence	This Japanese tourist does not know what medicine to buy **and take** to relieve altitude sickness
Prior context + AB-C	This Japanese tourist does not know what … to **use** to buy **kimono**…
Prior context + A-BC	This Japanese tourist does not know what … to buy **and take**…
Semantically unrelated and low-constraint	
Stimuli	这位上海游客不知道购买**和-服用**什么药才能缓解高原反应
The whole sentence	This Shanghai tourist does not know what medicine to buy **and take** to relieve altitude sickness
Prior context + AB-C	This Shanghai tourist does not know what … to **use** to buy **kimono**…
Prior context + A-BC	This Shanghai tourist does not know what … to buy **and take**…
Question: 上述句子是否出现“和服”这个词？(Translation: Did the word *kimono* appear in the above sentence?)	

Note. For experimental stimuli, the OASs are in bold, and the semantically related and unrelated words are underlined. Note, however, that the characters were not bolded or underlined in the experiment. The “-” symbols are added for illustrative purposes. For the corresponding translations, the AB-C and A-BC structures are in bold, and the semantically related and unrelated words are underlined.

We recruited 20 participants who did not participate in the eye-movement experiment to evaluate the degree of relatedness between semantically related words and words AB and BC, as well as the degree of relatedness between semantically unrelated words and words AB and BC on a 7-point scale (1 = *highly unrelated in*

meaning, 7 = *highly related in meaning*). The results showed that the semantic relatedness degree between words AB and semantically related words (M = 5.47, SE = 0.08, range 4.10−6.60) was greater than that of the other three pairs (words AB and semantically unrelated words: M = 2.65, SE = 0.08, range 1.30−3.70; words BC and semantically related words: M = 2.59, SE = 0.10, range 1.40−3.80; words BC and semantically unrelated words: M = 1.95, SE = 0.08, range 1.20−3.90; $F(3, 220)$ = 345.60, $p < .001$). We recruited 40 participants who did not participate in the formal experiments to evaluate the effectiveness of the sentence-level contextual cue. They read texts consisting of content from the beginning of the sentence to two characters following the OAS and were asked to segment the OAS. Compared with the low-constraint condition, participants were more likely to segment the OAS as an A-BC structure in the high-constraint condition (see Table 3 for details). In addition, we asked another 40 participants to evaluate the plausibility of the whole sentences, and another 40 participants to evaluate the predictability of the OASs. Sentence plausibility was evaluated on a 7-point scale (1 = *very implausible*, 7 = *very plausible*). The results showed that all sentences were plausible (the mean plausibility rating was above 5.5 for all conditions), and the plausibility of sentences was comparable across conditions (Table 3). To evaluate the predictability of OASs (including words A, AB and BC), participants were asked to write down the three characters they predicted after reading the preceding context up to but not including the OAS, and were informed that the characters they wrote may not necessarily complete the sentence. Predictability was very low (less than 0.02) in all conditions.

Table 3

Properties of the Stimuli

	High-constraint		Low-constraint		Lexical-level contextual cue	Sentence-level contextual cue	Interaction
	Semantically related	Semantically unrelated	Semantically related	Semantically unrelated			
Plausibility of the whole sentence	5.92 (0.08) Range: 4.00−6.90	5.96 (0.09) Range: 4.20−6.80	5.77 (0.10) Range: 4.20−6.90	5.83 (0.09) Range: 4.00−6.90	$F(1, 55) = 0.42$, $p = .519$	$F(1, 55) = 2.78$, $p = .101$	$F(1, 55) = 0.03$, $p = .859$
Predictability	.02 (.01)	.02 (.01)	.01 (.003)	.01 (.005)	$F(1, 55) = 0.05$, $p = .821$	$F(1, 55) = 2.43$, $p = .125$	$F(1, 55) = 0.60$, $p = .444$
The probability of A-BC structure [a]	.63 (.03)	.63 (.03)	.31 (.03)	.39 (.03)	$F(1, 55) = 2.76$, $p = .103$	$F(1, 55) = 84.03$, $p < .001$	$F(1, 55) = 2.29$, $p = .136$

Note. Standard errors are given in parentheses.

[a] The probability of the A-BC structure reflects the results of A-BC segmentation, which was based on texts consisting of content from the sentence beginning to two characters following the OAS. Participants were provided three options to segment the OAS: AB-C structure, A-BC structure, or both.

Apparatus

Participants' eye movements were recorded using an SR Research Eyelink 1000 eye-tracking system with a sampling rate of 1,000 Hz. The materials were presented on a 21-inch cathode-ray tube monitor (resolution: 1024 × 768 pixels; refresh rate: 150 Hz) connected to a Dell personal computer. Each sentence was displayed on a single line in Song 20-point font, and the characters were shown in black (RGB: 0, 0, 0) on a gray background (RGB: 128, 128, 128). A chin rest and forehead rest were employed to minimize head movement during the entire experiment. Participants were seated 58 cm from the computer screen; at this distance, one character subtended a visual angle of approximately 0.7°. For each participant, the viewing was binocular, but only the right eye was monitored. The experiment was programmed with the *EyeTrack* software developed by the UMASS Eye Tracking Lab.

Procedure

Upon entering the lab, participants were given the experimental instructions and a brief description of the apparatus. The eye tracker was calibrated at the beginning of the experiment and again during the experiment as needed. A three-point calibration and validation procedure was followed, and the maximal error of validation was below 0.5° for the visual angle. Next, participants were asked to read the sentences silently and answer the provided questions. Each participant read six sentences for practice, followed by 56 experimental sentences and 56 filler sentences in a random order. Each sentence appeared after participants fixated on a character-sized box at the location of the first character of each sentence. There was a question after each

sentence: “上述句子是否出现‘XX’这个词” (meaning “Did the word ‘XX’ appear in the above sentence”). For the experimental sentences, “XX” denoted the left-side words AB of the OASs in the sentence; for filler sentences, “XX” denoted two-character words that appeared or did not appear in the sentence, with a proportion of 50% each. We set this question to investigate whether semantically related words and low-constraint context would lead readers to incorrectly segment the OAS as an AB-C structure. Participants responded by pressing a button on a button box.

One may argue that the question setting can encourage participants to pay attentional attention to the OAS region, thereby affecting the observed results in eye-movement measures and question answering. However, readers may not usually notice the existence of OASs or consider multiple segmentation options, so they only perform one type of segmentation. Additionally, since there are many words in the sentence, readers may not know in advance which word is expected to be reported. The presence of filler sentences in half of the trials also weakens potential task-driven effects. If the task is solely responsible for the observed effects, we expect to see similar word segmentation across all four conditions, as the question setting is the same for all conditions. In this case, we should only find the effect of the sentence-level contextual cue, where word AB is not plausible in high-constraint contexts, resulting in longer reading times and higher regression-out probabilities than in low-constraint contexts. Nevertheless, this is not consistent with our findings (see Results section).

Data Analysis

The following eye-movement measures were analyzed: (1) *first fixation duration* (FFD) is the duration of the first fixation on the OAS region during the first-pass reading, (2) *first-pass reading time* (FP) is the summed duration of all first-pass fixations on the OAS region before moving to another region, (3) *go-past time* (GP) is the summed duration starting when entering the OAS region until this region's right boundary is crossed, (4) *regression-out probability* (RO) is the percentage of regressions made from the OAS region to earlier areas before leaving the OAS region in a forward direction, (5) *second-pass reading time* (SP) is the summed duration of all fixations on the OAS region following the first-pass reading (including zero times when the OAS region is not fixated, see Clifton et al., 2007), and (6) *regression-in probability* (RI) is the percentage of regressions made back to the OAS region from the right region after passing it.

In addition, we also analyzed the probabilities of "Yes" answers to questions following experimental sentences. The question after each experimental sentence was "上述句子是否出现'XX'这个词" (meaning "Did the word 'XX' appear in the above sentence"). A higher probability of "Yes" answers might indicate that readers were more likely to segment the OAS as an AB-C structure incorrectly.

Data were analyzed using *linear mixed-effects models* (LMMs) for continuous variables and *generalized linear mixed-effects models* (GLMMs) for binary dependent variables. Lexical-level contextual cue, sentence-level contextual cue, and their interaction were entered as fixed effects, specifying the participants and items as crossed random effects, including intercepts and slopes (Baayen et al., 2008).

Following Barr et al. (2013), we used the maximal model that could converge. We first constructed a model with a maximal random factor structure. When the maximal model failed to converge, we used a zero-correlation parameter model and dropped the random components that generated the smallest variances. The *lmer* and *glmer* functions from the *lme4* package (Bates et al., 2015) were used. We report the regression coefficients (*b*s, which estimate the effect size), standard errors (*SE*s), *t*-values (for durations), *z*-values (for binary dependent variables), and corresponding *p*-values. We estimated and reported the *p*-values for the effects using the *summary* function of the *lmerTest* package (Kuznetsova et al., 2017). Under the circumstance of a significant interaction, we conducted simple effect analyses using the *emmeans* package (Lenth et al., 2018). Fixation duration measures were log-transformed, except for SP, which included zero time.

The mean accuracy on the questions following filler sentences was 95.06%, indicating that the participants understood the sentences well. Noisy blinks resulted in the exclusion of 3.87% of the trials. Fixations with durations longer than 1,000 ms or shorter than 80 ms (approximately 0.55%) were also excluded from the analysis. Because we used a three-point calibration and validation procedure, the *EyeTrack* software automatically corrected for vertical drift.

Results

The main effects of the lexical-level contextual cue and sentence-level contextual cue and their interaction were not significant for FFD or FP (see Table 4 for details). For GP and RO, the non-significant main effects were modulated by a

strong interaction between the lexical-level contextual cue and the sentence-level contextual cue (see Table 5 for detailed statistics). In the high-constraint context, longer GP ($b = -0.08$, $SE = 0.04$, $t = -2.00$, $p = .048$) and higher RO ($b = -0.28$, $SE = 0.14$, $z = -1.99$, $p = .047$) were observed in the semantically related condition than in the semantically unrelated condition. However, in the low-constraint condition, the inhibitory effect of the lexical-level contextual cue was eliminated for GP ($b = 0.06$, $SE = 0.04$, $t = 1.51$, $p = .134$) or replaced with a faciliatory effect for RO ($b = 0.36$, $SE = 0.15$, $z = 2.42$, $p = .016$). The high-constraint context had shorter SP and lower RI (SP: $M = 686$ ms, $SE = 26$; RI: $M = .62$, $SE = .02$) than the low-constraint context (SP: $M = 839$ ms, $SE = 30$; RI: $M = .68$, $SE = .01$), as supported by the main effect of the sentence-level contextual cue. None of the other effects was significant for SP and RI.

The probabilities of "Yes" answers to experimental sentences were higher in the semantically related condition ($M = .35$, $SE = .01$) than in the semantically unrelated condition ($M = .32$, $SE = .01$), and were higher in the low-constraint condition ($M = .35$, $SE = .01$) than in the high-constraint condition ($M = .32$, $SE = .01$), as supported by the main effects of the lexical-level contextual cue and the sentence-level contextual cue. The interaction was not significant.

Table 4

Eye-Movement Measures on the OAS Region and Question Answers for Experimental Sentences

	High-constraint		Low-constraint	
Measures	Semantically related	Semantically unrelated	Semantically related	Semantically unrelated
First fixation duration (ms)	305 (5)	303 (5)	307 (5)	307 (5)
First-pass reading	579 (16)	575 (16)	588 (17)	596 (17)

time (ms)				
Go-past time (ms)	952 (31)	842 (27)	848 (27)	906 (30)
Regression-out probability	.28 (.02)	.23 (.02)	.19 (.02)	.24 (.02)
Second-pass reading time (ms)	709 (38)	662 (35)	873 (45)	804 (39)
Regression-in probability	.62 (.02)	.63 (.02)	.69 (.02)	.67 (.02)
Probabilities of "Yes" answers	.33 (.02)	.30 (.02)	.37 (.02)	.33 (.02)

Table 5

Results of the (Generalized) Linear Mixed-Effects Models

Measures	Fixed effect	Estimate	SE	*t/z*	*p*
First-fixation duration	Lexica-level contextual cue	−0.003	0.02	−0.19	.848
	Sentence-level contextual cue	0.001	0.02	0.08	.937
	Interaction	−0.002	0.03	−0.08	.939
First-pass reading time	Lexica-level contextual cue	0.01	0.02	0.40	.689
	Sentence-level contextual cue	0.02	0.02	0.73	.468
	Interaction	-0.00	0.05	-0.001	1.00
Go-past time	Lexica-level contextual cue	−0.01	0.03	−0.33	.742
	Sentence-level contextual cue	−0.04	0.04	−0.98	.331
	Interaction	**0.14**	**0.05**	**2.65**	**.011**
Regression-out probability	Lexica-level contextual cue	0.04	0.10	0.38	.706
	Sentence-level contextual cue	−0.23	0.13	−1.84	.066
	Interaction	**0.64**	**0.20**	**3.16**	**.002**
Second-pass reading time	Lexica-level contextual cue	−66.33	31.10	−1.62	.115
	Sentence-level contextual cue	**151.66**	**50.92**	**2.98**	**.004**
	Interaction	−14.75	78.34	−0.19	.852
Regression-in probability	Lexica-level contextual cue	−0.02	0.10	−0.17	.867
	Sentence-level contextual cue	**0.29**	**0.12**	**2.50**	**.013**
	Interaction	−0.14	0.19	−0.73	.466
Probabilities of "Yes" answers	**Lexica-level contextual cue**	**−0.39**	**0.15**	**−2.57**	**.010**
	Sentence-level contextual cue	**0.34**	**0.14**	**2.42**	**.016**
	Interaction	0.02	0.28	0.08	.937

Note. Significant effects are indicated in bold.

Discussion

We conducted an eye-tracking experiment to investigate whether and how the

lexical-level contextual cue affects word segmentation when reading Chinese. The lexical-level contextual cue and the sentence-level contextual cue were orthogonally manipulated. We found that in the low-constraint context, the semantically related condition had lower RO than the semantically unrelated condition. However, in the high-constraint context, the semantically related condition had longer GP and higher RO than the semantically unrelated condition. The probabilities of reporting word AB were higher in the low-constraint context than in the high-constraint context, and were higher in the semantically related condition than in the semantically unrelated condition.

Unnecessary but Count: Effect of Lexical-level Contextual Cue

As summarized above, RO, GP, and probability of reporting word AB were all affected by the lexical-level contextual cue. These findings suggest that readers use the lexical-level contextual cue to segment words. As mentioned in the previous sections, the lexical-level contextual cue was not necessary for word segmentation with respect to the stimuli of the present study, and readers could ignore this information. However, we found that readers still used the lexical-level contextual cue during the word segmentation process, even if they did not need to do so, suggesting that the use of the lexical-level contextual cues might be inevitable.

An interesting finding is that even after reading the whole sentences, the lexical-level contextual cue continued to influence readers' answers to offline questions. These results suggest that readers may adopt a good enough processing strategy for reading. Contrary to the traditional view that language processing is carried out in a

perfect manner, the good-enough theory holds that language processing is sometimes only partial, shallow, or incomplete, a viewpoint that has received support from several studies (Christianson, 2016; Ferreira et al., 2002; Slattery et al., 2013; Swets et al., 2008; Traxler, 2014).

As mentioned in the Method section, the effect of the lexical-level contextual cue observed may be driven by the task used in the current study. Based on this possibility, we should only find the effect of the sentence-level contextual cue. However, we also observed a significant effect of the lexical-level contextual cue on GP, RO, and the probabilities of "Yes" answers, suggesting that the lexical-level contextual cue also affected word segmentation.

In summary, readers used the lexical-level contextual cue to help them with word segmentation, even though this information was not necessary for word segmentation. In addition to online reading, the lexical-level contextual cue also affected offline question answering.

Lexical-level vs. Sentence-level Contextual Cue

The present findings might shed some light on the relative time course of the effects of the lexical-level contextual cue and the sentence-level contextual cue. We observed an inhibitory effect of the lexical-level cue on GP and RO in the high-constraint contexts. These results suggest that readers can use the lexical-level contextual cue earlier than the sentence-level contextual cue. To recapitulate the logic laid out in the Introduction, if the lexical-level contextual cue is used later than the sentence-level contextual cue, there should be no effect of the lexical-level contextual

cue in the high-constraint condition. Readers might have already made an unambiguous and correct segmentation based on high-constraint information, and word AB supported by the lexical-level contextual cue will not be segmented at all; hence, it will not affect reading times at all. On the contrary, if readers can use the lexical-level contextual cue earlier than the lexical-level contextual cue, word AB supported by the lexical-level contextual cue should be segmented as a word more often than word BC. According to the design, the AB-C segmentation structure is implausible in a high-constraint context. As a result, readers need to correct the segmentation, leading to longer reading times. The results of this study evidently show that Chinese readers used the lexical-level contextual cue earlier than the sentence-level contextual cue when segmenting words. This finding is consistent with the checking model (Norris, 1986). In the checking model, the semantic relationships between words are checked quickly for contextual plausibility, while sentence-level context requires more time to check the plausibility of words, suggesting an earlier effect of the lexical-level contextual cue than the sentence-level contextual cue.

Although we found that readers used the lexical-level contextual cue for word segmentation earlier than the sentence-level contextual cue, the effect of the lexical-level contextual cue might still occur in the integration stage. Different eye movement measures are considered to reflect different underlying cognitive processes in reading. The probability of making a leftward saccade from the fixated region (i.e., RO) may indicate some difficulties with integrating a word or detecting errors caused by integration failure (Clifton et al., 2007). In the present study, a reliable effect of the

lexical-level contextual cue was observed in the RO, suggesting that the lexical-level contextual cue influences the integration stage of processing.

While we compared the relative time course of using the lexical-level contextual cue and the sentence-level contextual cue, the effects of these information on word segmentation may not have particular orders. According to CRM, spatially overlapping words compete with each other for a single winner that will be segmented and recognized. The lexical-level contextual cue and the sentence-level contextual cue might affect word competition simultaneously. In the high-constraint contexts, word BC was activated by the sentence-level contextual cue. When word AB was activated by the lexical-level contextual cue, it competed with word BC, resulting more processing difficulties than when word AB was not activated. Therefore, in the high-constraint contexts, there was an inhibitory effect of the lexical-level contextual cue on RO and GP. The situation was different in the low-constraint contexts where no particular word segmentation was supported by the sentence-level contextual cue. When word AB was activated by the lexical-level contextual cue, it could win the competition easily, while readers needed additional time to segment word when neither word AB or word BC was favored. Therefore, the inhibitory effect of the lexical-level contextual cue was either eliminated or replaced by a facilitation effect in low-constraint contexts. The current results cannot distinguish between the competition and lexical-level priority possibilities.

Conclusion

The present study showed that Chinese readers use the lexical-level contextual

cue when segmenting words, and words supported by the lexical-level contextual cue are more likely to be segmented as words than words not supported by the lexical-level contextual cue. Moreover, when both the lexical-level contextual cue and the sentence-level contextual cue are available, the lexical-level contextual cue is used earlier or simultaneously than the sentence-level contextual cue.

Declarations

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Conflicts of interest/competing interests

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Ethics approval

This project was approved by the Institutional Review Board of the Institute of Psychology of Chinese Academy of Science.

Consent to participate

Informed consent was obtained from all individual participants included in the study.

Consent for publication

The participant has consented to the submission of their data to the journal.

Availability of data and materials

The original data and materials are available from https://osf.io/tky9z/.

Code availability

The R code is available from https://osf.io/tky9z/.

Authors' contributions

Linjieqiong Huang: Conceptualization, Methodology, Software, Investigation, Formal analysis, Visualization, Writing-Original draft preparation

Xingshan Li: Conceptualization, Methodology, Formal analysis, Visualization, Supervision, Writing-Reviewing and Editing, Funding acquisition

Reference

Baayen, R. H., Davidson, D. J., & Bates, D. M. (2008). Mixed-effects modeling with crossed random effects for subjects and items. *Journal of Memory and Language*, *59*(4), 390–412. https://doi.org/10.1016/j.jml.2007.12.005

Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language*, *68*(3), 255–278. https://doi.org/10.1016/j.jml.2012.11.001

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, *67*(1), 1–48. https://doi.org/10.18637/jss.v067.i01

Brysbaert, M., & Stevens, M. (2018). Power analysis and effect size in mixed effects models: A tutorial. *Journal of Cognition*, *1*(1), 9.

Cohen, J. (2013). Statistical power analysis for the behavioral sciences. Routledge.

Christianson, K. (2016). When language comprehension goes wrong for the right reasons: Good-enough, underspecified, or shallow language processing. *Quarterly Journal of Experimental Psychology*, *69*(5), 817–828. https://doi.org/10.1080/17470218.2015.1134603

Clifton Jr, C., Staub, A., & Rayner, K. (2007). Eye movements in reading words and sentences. *Eye Movements*, 341–371. https://doi.org/10.1016/B978-008044980-7/50017-3

Cohen, J. (2013). *Statistical power analysis for the behavioral sciences*. Routledge.

Duffy, S. A., Henderson, J. M., & Morris, R. K. (1989). Semantic facilitation of

lexical access during sentence processing. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15*(5), 791–801. https://doi.org/10.1037/0278-7393.15.5.791

Ferreira, F., Bailey, K. G., & Ferraro, V. (2002). Good-enough representations in language comprehension. *Current Directions in Psychological Science*, *11*(1), 11–15. https://doi.org/10.1111/1467-8721.00158

Green, P., & MacLeod, C. J. (2016). simr: An R package for power analysis of generalised linear mixed models by simulation. *Methods in Ecology and Evolution*, *7*(4), 493–498.

Hoeks, J. C., Stowe, L. A., & Doedens, G. (2004). Seeing words in context: the interaction of lexical and sentence level information during reading. *Cognitive Brain Research*, *19*(1), 59–73. https://doi.org/10.1016/j.cogbrainres.2003.10.022

Huang, L., & Li, X. (2020). Early, but not overwhelming: The effect of prior context on segmenting overlapping ambiguous strings when reading Chinese. *Quarterly Journal of Experimental Psychology*, *73*(9), 1382–1395. https://doi.org/10.1177/1747021820926012

Huang, L., Staub, A., & Li, X. (2021). Prior context influences lexical competition when segmenting Chinese overlapping ambiguous strings. *Journal of Memory and Language*, *118*, 104218. https://doi.org/10.1016/j.jml.2021.104218

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). lmerTest package: Tests in linear mixed effects models. *Journal of Statistical Software*, *82*(13), 1–26. https://doi.org/10.18637/jss.v082.i13

Lenth, R., Singmann, H., Love, J., Buerkner, P., & Herve, M. (2018). *emmeans: Estimated Marginal Means, aka Least-Squares Means*. R package version 1.3.0. https://CRAN.R-project.org/package=emmeans.

Lexicon of Common Words in Contemporary Chinese Research Team. (2008). *Lexicon of common words in contemporary Chinese*. Commercial Press.

Li, X., Rayner, K., & Cave, K. (2009). On the segmentation of Chinese words during reading. *Cognitive Psychology*, *58*(4), 525–552. https://doi.org/10.1016/j.cogpsych.2009.02.003

Li, X., & Pollatsek, A. (2020). An integrated model of word processing and eye-movement control during Chinese reading. *Psychological Review*, *127*(6), 1139–1162. http://doi.org/10.1037/rev0000248

Luo, X., Sun, M., & Tsou, B. K. (2002). Covering ambiguity resolution in Chinese word segmentation based on contextual information. In *Proceedings of the 19th international conference on computational linguistic* (Vol. 1., pp. 1–7). Association for Computational Linguistics.

Ma, G., Li, X., & Rayner, K. (2014). Word segmentation of overlapping ambiguous strings during Chinese reading. *Journal of Experimental Psychology: Human Perception and Performance*, *40*(3), 1046–1059. https://doi.org/10.1037/a0035389

Morris, R. K. (1994). Lexical and message-level sentence context effects on fixation times in reading. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *20*(1), 92–103. https://doi.org/10.1037/0278-7393.20.1.92

Norris, D. (1986). Word recognition: Context effects without priming. *Cognition*, *22*, 93–136. https://doi.org/10.1016/S0010-0277(86)90001-6

R Development Core Team. (2020). *R: A language and environment for statistical computing* (Version 4.0.0) [Computer software]. R Foundation for Statistical Computing. https://www.R-project.org

Slattery, T. J., Sturt, P., Christianson, K., Yoshida, M., & Ferreira, F. (2013). Lingering misinterpretations of garden path sentences arise from competing syntactic representations. *Journal of Memory and Language*, *69*(2), 104–120. https://doi.org/10.1016/j.jml.2013.04.001

Swets, B., Desmet, T., Clifton, C., & Ferreira, F. (2008). Underspecification of syntactic ambiguities: Evidence from self-paced reading. *Memory & Cognition*, *36*(1), 201-216. https://doi.org/10.3758/MC.36.1.201

Traxler, M. J. (2014). Trends in syntactic parsing: Anticipation, Bayesian estimation, and good-enough parsing. *Trends in Cognitive Sciences*, *18*(11), 605–611. https://doi.org/10.1016/j.tics.2014.08.001

Van Petten, C. (1993). A comparison of lexical and sentence-level context effects in event-related potentials. *Language and Cognitive Processes*, *8*(4), 485–531. https://doi.org/10.1080/01690969308407586

Yen, M.-H., Radach, R., Tzeng, O. J.-L., & Tsai, J.-L. (2012). Usage of statistical cues for word boundary in reading Chinese sentences. *Reading and Writing*, *25*(5), 1007–1029. https://doi.org/10.1007/s11145-011-9321-z