

Prosodic Boundaries Delay the Processing of Upcoming Lexical Information During Silent Sentence Reading

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Prosodic boundaries can be used to guide syntactic parsing in both spoken and written sentence comprehension, but it is unknown whether the processing of prosodic boundaries affects the processing of upcoming lexical information. In 3 eye-tracking experiments, participants read silently sentences that allow for 2 possible syntactic interpretations when there is no comma or other cue specifying which interpretation should be taken. In Experiments 1 and 2, participants heard a low-pass filtered auditory version of the sentence, which provided a prosodic boundary cue prior to each sentence. In Experiment 1, we found that the boundary cue helped syntactic disambiguation after the cue and led to longer fixation durations on regions right before the cue than on identical regions without prosodic boundary information. In Experiments 2 and 3, we used a gaze-contingent display-change paradigm to manipulate the parafoveal visibility of the first constituent character of the target word after the disambiguating position. Results of Experiment 2 showed that previewing the first character significantly reduced the reading time of the target word, but this preview benefit was greatly reduced when the prosodic boundary cue was introduced at this position. In Experiment 3, instead of the acoustic cues, a visually presented comma was inserted at the disambiguating position in each sentence. Results showed that the comma effect on lexical processing was essentially the same as the effect of prosodic boundary cue. These findings demonstrate that processing a prosodic boundary could impair the processing of parafoveal information during sentence reading.

Keywords: prosodic boundary, sentence reading, eye movements, parafoveal processing, wrap-up process

To understand a spoken sentence, a hearer needs to know the meaning of its constituent words, to analyze its syntactic structure, and to attend to its prosodic structure. For instance, the sentence “The reporter interviewed the squatter and the policeman” may describe an event with two objects. But if a break is heard between

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tion can keep listeners from entertaining unnecessary syntactic structures (e.g., Cutler, Dahan, & van Donselaar, 1997; Frazier, Carlson, & Clifton, 2006; Lu, 2003; Marslen-Wilson, Tyler, Warren, Grenier, & Lee, 1992) and provides them with the initial domains for semantic analysis (Schafer, 1997). In the case of reading, although there is no acoustic input during reading, readers may experience "inner speech" mirroring the intonation pattern of external speech (i.e., implicit prosody; Fodor, 2002). Behavioral evidence has shown that the implicit "intonational break" generated by readers is used to resolve syntactic ambiguity such as the attachment preference of relative clauses (Fodor, 2002; Jun, 2003) or dative noun phrases (Hwang & Schafer, 2009), with the break signaling when to close off a clause (Allbritton, McKoon, & Ratcliff, 1996; Nicol, 1996; Snedeker & Trueswell, 2003; Speer, Kjølgaard, & Dobroth, 1996; Warren, Grabe, & Nolan, 1995). Punctuation marks, which often reflect some major aspects of a writer's prosodic intent, also facilitate reading by conveying effectiveness of speech (Chafe, 1988), by informing syntactic structures (Hill & Murray, 2000), and by supporting memory systems to process lexical information and semantic associations (Cohen, Douaire, & Elsabbagh, 2001).

A recent study by Hirotani, Frazier, and Rayner (2006) investigated readers' eye movements during the reading of sentences with and without punctuation. Except for nonrestrictive relative clauses, punctuation induced longer first-pass reading times on regions preceding the punctuation mark, possibly suggesting an intonation-induced wrap-up process for preboundary information (i.e., a wrap-up account). However, an alternative interpretation could be that this prolonged reading time was due to more efforts on parafoveal processing of words following the punctuation mark (i.e., a preparation account). The findings that the landing position of saccades was closer to the right end of post-comma words and that the saccade length was longer when the eyes leave the precomma words can be used to support this alternative account, because more information obtained parafoveally should lead readers' eyes into a position further down the phrase (cf. Inhoff, 1989).

Although the existing eye-tracking studies provided no data concerning these two alternatives, event-related potential studies have demonstrated that both alternatives are plausible. A positive-going waveform named the closure positive shift (CPS) is consistently observed at the occurrence of a prosodic boundary for spoken sentences (Li & Yang, 2009; Pannekamp, Toepel, Alter, Hahne, & Friederici, 2005; Steinhauer, Alter, & Friederici, 1999; Steinhauer & Friederici, 2001) and for written sentences read silently (Hwang, Schafer, & Steinhauer, 2009; Steinhauer & Friederici, 2001). Steinhauer et al. (1999) postulated that the CPS may reflect two cognitive processes associated with the processing of the prosodic boundary: (a) a wrap-up process to structure the mental representation of perceived information and (b) a preparation process to prepare for the analysis of subsequent input. Using magnetoencephalography, Knösche et al. (2005) localized the sources of a CPS-like component to the posterior and anterior cingulate cortices. They argued that the posterior cingulate cortex activity may reflect memory operations related to the first of those processes and the anterior cingulate cortex activity may reflect attentional redirection related to the second.

These studies indicate that the processing of prosodic boundary information could influence not only syntactic parsing but also

other cognitive processes, such as those associated with memory or attention systems. Indeed, Cohen et al. (2001) showed that recall of words was better if the words were presented in sentences with normal prosodic boundaries or normal punctuation, compared with when the words were presented in sentences with abnormal boundaries or punctuation. Steinhauer (2003) demonstrated an enhanced P200 event-related potential component and more negative voltages in the 400- to 1,200-ms time window for words after a pause in speech than for words not preceded by a pause. He interpreted this difference as reflecting pause-induced acoustic-phonetic variations on the words. However, it is not clear from these studies what exactly the functions of prosodic boundary are and how this boundary information affects the online lexical processing of post-boundary phrases.

The present study aimed (a) to examine the prosodic "wrap-up" process for preboundary information and (b) to investigate whether a prosodic boundary indeed facilitates postboundary lexical processing. From the perspective of reading, a wrap-up process may refer to the increased processing load due to integration of the information received prior to the prosodic boundary, whereas a preparation process may refer to the more proactive processing of the upcoming reading materials at this position. We conducted three eye-tracking experiments in which participants read Chinese sentences silently and answered comprehension questions after some of them. All experimental sentences were syntactically ambiguous when no comma or other cue was provided for them, allowing for two possible interpretations depending on the prosodic structure. We chose such ambiguous sentences for two reasons: First, to comprehend these ambiguous sentences, readers are unlikely to ignore the prosodic cues but would rather use them; second, whether and how the readers use the prosodic cues can be captured by the performance in comprehension task.

Two kinds of procedures were adopted to convey prosodic boundary information. In Experiments 1 and 2, a prosodic boundary cue was provided at the disambiguating position by presenting the participants with low-pass filtered speech corresponding to the sentence before the presentation of each sentence (i.e., a melody-reading paradigm; Steinhauer & Friederici, 2001). Experiment 1 explored whether and how the prosodic boundary information provided by the aurally presented speech melody affected the pattern of eye movements on the preboundary and postboundary words. Experiment 2 investigated specifically whether the processing of a prosodic boundary provided by the speech melody could facilitate (or interfere with) the parafoveal processing of the post-boundary lexical information, using a gaze-contingent display-change technique (Rayner, 1975). According to the wrap-up process account, the prosodic boundary may interfere with parafoveal processing of the region right after the prosodic boundary and lead to increased reading times on this postboundary region. According to the preparation process account, however, the prosodic boundary may facilitate the previewing of the postboundary region and lead to decreased reading times on this region. We noted the possibility that, compared with natural reading, the melody-reading paradigm may demand more cognitive resources in order to project the prosodic boundary information from working memory onto the visually presented sentences. To further examine whether the influence of prosodic boundaries upon parafoveal processing observed in Experiment 2 was universal or paradigm-specific, we conducted a third experiment in which a comma,

rather than speech melody, was used to induce a prosodic boundary. This experiment was expected to generally replicate the results of Experiment 2. Yet given that commas are explicitly, visually presented markers of prosodic boundaries, the specification of prosodic boundary would be easier for reading sentences with commas (in Experiment 3) than for reading sentences without visual boundary cues (in Experiment 2), and this could affect the specific pattern of effects for prosodic boundaries in Experiment 3, as compared with the pattern in Experiment 2. Thus this study would provide cross-method evidence regarding how prosodic processing affects parafoveal processing of lexical information during silent reading, a question that has not been addressed by the previous studies of prosody (e.g., Cohen et al., 2001; Hirotani et al., 2006).

Experiment 1

Eye movements have been shown to be sensitive to implicit prosody during silent reading, including syllabic information (Ashby, 2006) and lexical stress (Ashby & Clifton, 2005; Breen & Clifton, 2011) at the word level as well as punctuation at the sentence level (Hirotani et al., 2006). For instance, Ashby and Clifton (2005) found that lexical stress affects eye movements such that readers had longer gaze durations and more fixations on

word durations (a)11(t)5(i)18(ons)9(a)11(n)14(d m)25(2(d)5(i)5(c(s)9(a)11(n9(hb)-13(y)27(&)12(C)7(lea)11(zs ())13(2e)-21]TJ 0 Tcb(r)7(e)11s

pated in Experiment 1. They all were native speakers of Chinese and had normal or corrected-to-normal vision.

Materials and design. Each ambiguous sentence was paired with three types of speech melody, forming three experimental conditions. For the condition with an early prosodic boundary, the speech melody provided a boundary cue at the offset of NP2. For the condition with a late prosodic boundary, the speech melody provided a cue at the offset of NP3. For the ambiguous condition, the speech melody did not provide cue at any of these positions (see below).

Forty-two Chinese sentences with the structure “NP1 + VP1 + NP2 + *hé* + NP3 + VP2 + . . .” were created, with NP1 having two to four characters and VP1, NP2, and VP2 having two to three characters. NP3 comprised a modifier with two to five characters (one or two words) and a head noun with two to three characters. The purpose of using a modifier before the noun in NP3 was to increase the distance between NP2 and the noun in NP3 so that the reader could more precisely localize the prosodic boundary cue in speech melody to the position at the offset of NP2 (in the condition with an early prosodic boundary) or at the offset of NP3 (in the condition with a late prosodic boundary). Sentences were assessed for the functional ambiguity of the conjunction *hé*. Twenty participants who did not participate in the eye-tracking experiment were asked to read each sentence and to make a speeded forced choice between the two interpretations provided. These participants were instructed to respond to their preferred interpretation of the sentence. For the selected sentences, 50.1% (ranging between 40% and 65% for each sentence) responses had the interpretation that coincided with the sentence with an early prosodic boundary, and 49.9% (ranging between 35% and 60% for each sentence) had the

interpretation that coincided with the sentence with a late prosodic boundary, demonstrating that these sentences were not strongly biased toward either reading.

A professional male speaker with broadcast training read in a soundproof chamber the sentences with prosodic boundaries (cued by commas) at the offset of either NP2 or NP3. The speech was sampled at 16 bits/41.1 kHz. To create speech without boundary information, a cross-slicing procedure was applied to the recorded speech(t)5(e)11(s)33 0 Td [(t)-17(eech-0.004 Tc1(t)5o)20(oo(s)9(t)s)9(tun)14(

words were recognized in any sentence. We also checked the durations of pauses, which are the most stable and salient phonetic markers for phrase boundaries in Chinese (Wang, Lü, & Yang, 2004). For each melody with an early prosodic boundary, a pause was detected at the offset of the original NP2, with a mean duration of 310 ms ($SD = 66$). For each melody with a late prosodic boundary, the pause was at the offset of the original NP3, with a mean duration of 307 ms ($SD = 74$). For the ambiguous melody, no obvious pause was detected at either the offset of NP2 or the offset of NP3.

Thirty-six sentences were added as fillers. They were structured similarly to those critical sentences except that they included a disambiguating adverbial after NP3. Take the sentence in 1) for an example. Adding a word, (*yiqi*, "together"), after NP3 would indicate that NP3 is the agent of VP2, that is, to indicate early closure of the first VP. This made the sentence unambiguous, although NP3 was still temporarily ambiguous as to whether it was an object of VP1 or a subject of the following VP2 before the disambiguating adverbial was read. The paired speech melody was unambiguous and correctly corresponded to its syntactic structure, as a pause was clearly detectable at the offset of the original NP2 or NP3.

Apparatus. Auditory stimuli were presented binaurally via a headphone (Sony MDR-V900HD). Eye movements were recorded with an EyeLink 2K system at a sampling rate of 2,000 Hz. Each sentence was presented in one line at the vertical position one third from the top of a 21-in. (53.34-cm) CRT screen (1024 X 768 resolution, frame rate 100 Hz). The font Song-20 was used, with one character subtending 0.5° of visual angle. Participants read each sentence with their head positioned on a chin rest 80 cm from the screen. All recordings and calibrations were based on the left eye, but viewing was binocular.

Procedure. Participants were calibrated with a 9-point grid. A Latin square design was used to assign the target sentences and the paired speech melodies into three experimental lists, such that each list had 14 melodies from each experimental condition. The filler sentences and the paired melodies were then added to each version.

Stimuli in each list were pseudorandomized such that no more than three sentences from the same condition would appear consecutively. In each trial, a high-frequency warning tone was presented before the speech melody. After the aural presentation of the melody, a fixation cross was presented at an upper-left position on the screen at which the first character of the sentences would appear. The fixation was presented for 1,000 ms, followed by

visual presentation of the whole sentence. Participants were required to listen to the melody, and to silently read the sentence and finally to press a button when finished reading. Comprehension questions irrelevant to how the participant resolved the temporary ambiguity were presented for 26 of the filler trials. Participants were instructed to press the "yes" button with their left index finger and the "no" button with their right one. To make sure that participants listened carefully, they were informed that they would have to answer questions about the melody after the eye-tracking session. But they were not explicitly told the relationship between the melody and the sentence. After the formal experiment, participants were asked whether they realized the melody was the intonation contour of the following sentence and whether they projected the melody onto what they read. Participants underwent a practice block of 15 trials before the formal experiment.

Data analysis. Four regions were selected as the regions of interest, as shown in Figure 2. Region 1 contains NP2, composed of two to three characters (e.g., the word *parents* in the example); Region 2 contains the modifier of NP3 after *hé*, which was composed of two to four characters (e.g., *newly married*); Region 3 contains the head noun of NP3, composed of two to three characters (e.g., *wife*); Region 4 contains VP2, composed of two to four characters (i.e., *go to Shanghai*). We also analyzed *hé* as a separate region, but the skipping rate on *hé* was very high ($>60\%$) in each condition. Therefore for statistical purposes we used the data from Region 2.

First-fixation duration, gaze duration, second-pass reading time, landing position, percent regressions, and skipping rate were measured for each region. First-fixation duration is the duration of the initial fixation on a region regardless of the number of fixations on that region during first-pass reading. Gaze duration is the sum of all first-pass fixations on a region before making a saccade to another region. Second-pass reading time is the sum of all fixations in a region after leaving the region and then reentering it. We also reported where the eyes initially landed in each region (i.e., landing position). First-fixation durations shorter than 60 ms or longer than 800 ms, or gaze durations shorter than 60 ms or longer than 1,000 ms, were excluded from duration and landing position analysis. We also examined observations across the four defined regions for statistical analysis.

Inferential statistics were performed based on a priori Helmert contrasts. The first contrast compared the mean of the early and late pause conditions, a test of the ambiguity effect. The second contrast compared the early pause condition to the late pause condition. Estimate

from a linear mixed model for durations and landing positions and a generalized linear mixed model for percent regressions and skipping rates, with crossed random effects for participants and items, via the lmer program of the lme4 package (Bates, Maechler, & Dai, 2008) in the R environment for statistical computing (R Development Core Team, 2008). Analyses for untransformed and log-transformed durations yielded the same pattern of significance; thus statistics are reported for log-transformed durations. Estimates larger than 2 standard errors (i.e., absolute t values greater than 2) were interpreted as significant.

Results

Participants correctly answered 91% ($SD = 7\%$) of all the questions, indicating that they read sentences carefully. All but three of the participants reported that they realized the relationship between the melody and the sentence and that they used the prosodic cues in silent reading. The participants who did not overtly sense the use of melody displayed a similar data pattern as the others, and therefore their data were included in the eye

movement analysis. Measurements for the four regions are shown in Table 2.

Region 1. When sentences followed a speech melody with an early pause, the first-fixation duration on Region 1 was 253 ms, 14 ms longer than sentences preceded by speech melody with a late pause (i.e., no pause information was provided at this region) based on 1,017 observations. The difference was significant ($b = 0.033$, $SE = 0.011$, $t = 2.9$). Similarly, gaze duration on Region 1 for sentences with an early pause (303 ms) was significantly longer by 16 ms than that for sentences with a late pause (287 ms; $b = 0.033$, $SE = 0.014$, $t = 2.3$). Durations for sentences with no pauses were numerically in the middle and yielded no significant difference from the means of durations for sentences with a pause. No significant contrasts were found for other measurements.

Region 2. In Region 2, there were no differences between the three conditions in any measure. Yet there was a consistent trend for this region to have longer reading times in sentences with an early pause (first-fixation duration: 278 ms; gaze duration: 323 ms; second-pass reading times: 465 ms) than in sentences with a late pause or with no pauses (first-fixation duration: 271 and 270 ms;

Table 2
Grand Means and Standard Errors for Sentences Preceded by Melody With the Early Pause, With the Late Pause, and Without a Pause in Experiment 1

Variable	Early pause		Late pause		Without pause	
	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>
Region 1						
FFD	253	4.69	239	4.77	247	4.91
GD	303	7.72	287	7.37	298	7.86
SEC	433	26.11	425	23.72	438	23.69
LAND	0.95	0.03	0.98	0.03	0.94	0.03
REG	0.00	0.00	0.00	0.00	0.00	0.00
SKIP	0.14	0.02	0.16	0.02	0.13	0.02
Region 2						
FFD	278	5.78	271	5.64	270	5.62
GD	323	7.95	308	7.53	310	6.99
SEC	465	28.09	423	24.67	432	21.99
LAND	0.91	0.03	0.97	0.03	0.94	0.03
REG	0.07	0.01	0.04	0.02	0.06	0.01
SKIP	0.20	0.02	0.21	0.02	0.18	0.02
Region 3						
FFD	261	4.88	270	5.75	272	5.33
GD	298	7.10	305	7.66	316	7.21
SEC	402	23.30	415	21.73	473	25.77
LAND	1.05	0.03	1.04	0.03	1.03	0.03
REG	0.07	0.01	0.08	0.01	0.07	0.01
SKIP	0.15	0.02	0.18	0.02	0.14	0.02
Region 4						
FFD	261	6.31	277	5.84	274	6.67
GD	281	7.54	296	7.07	295	7.55
SEC	309	22.32	347	24.13	432	34.11
LAND	0.61	0.03	0.60	0.03	0.60	0.03
REG	0.12	0.02	0.17	0.02	0.12	0.02
SKIP	0.05	0.01	0.04	0.01	0.03	0.01

Note. FFD = first-fixation duration (ms); GD = gaze duration (ms); SEC = second-pass reading times (ms); LAND = landing position (of character); REG = percent regressions; SKIP = skipping rate.

gaze duration: 308 and 310 ms; second-pass reading times: 423 and 432 ms, respectively). In contrast, the landing positions into this region for sentences with an early pause were numerically the shortest (0.91 character) among the three conditions.

Region 3. As shown in Table 2, sentences without pauses had longer gaze durations (316 ms) than sentences with a pause (298 ms for those with an early pause and 305 for those with a late pause; $b = 0.020$, $SE = 0.008$, $t = 2.6$). The second-pass reading times were also longer for sentences without pauses (473 ms) than for the other two types of sentences (415 ms for sentences with an early pause, 402 ms for sentences with a late pause; $b = 0.051$, $SE = 0.022$, $t = 2.3$). It is noted that although the difference of reading times between the two conditions with either an early or a late pause failed to reach significance ($t = 1.3$ for first-fixation duration and $t = 1.0$ for gaze duration), sentences with a late pause did have numerically longer reading times (first-fixation duration: 270 ms; gaze duration: 305 ms) than sentences with an early pause (first-fixation duration: 261 ms; gaze duration: 298 ms).

Region 4. Compared with sentences with an early pause (first-fixation duration: 261 ms; gaze duration: 281 ms), sentences with a late pause had longer first-fixation durations by 16 ms ($b = 0.037$, $SE = 0.015$, $t = 2.5$) and longer gaze durations by 14 ms ($b = 0.033$, $SE = 0.016$, $t = 2.1$). Sentences with no pauses had significantly longer second-pass reading times (432 ms) than sentences with a pause (309 and 347 ms for sentences with an early pause and those with a late pause, respectively; $b = 0.065$, $SE = 0.028$, $t = 2.3$).

Discussion

In line with our predictions, we found that compared with the ambiguous condition in which sentences were preceded by melody without pause, sentences preceded by melody with boundary information (for both early and late pauses) had shorter fixation durations on the disambiguating Region 3. The results of second-pass reading times further identified a more effortful rereading process in Regions 3 and 4 for sentences without prosodic boundary cues. These findings confirmed that the Chinese reader is able to project the melody just heard onto the reading material and to use prosodic boundary cues to chunk the sentence. The prosodic boundary information helps to resolve the ambiguity in syntactic parsing, and hence the disambiguated words can be easily integrated into the prior context. However, this ambiguity effect did not show at an earlier ambiguous region (i.e., Region 2). This absence of effect may be attributed to the role of the modifier in Region 2. This modifier acts as a local constraint on the head noun NP3 in Region 3, and it has no impact upon the interpretation of the ambiguous structure. Given that all the sentences had this “modifier + head noun” structure at this position, the reader may develop a reading strategy and wait for the head noun before committing to one interpretation.

More interestingly, comparing the two types of sentences preceded by speech melody with an early or a late pause, we observed longer first-fixation and gaze durations on the region immediately followed by an early prosodic boundary (Region 1). This finding is consistent with results showing that the reader tends to take longer to read sentence constituents followed by a punctuation mark (Hirotsu et al., 2006). Together, these findings suggest that when coming across a prosodic (and syntactic) boundary cued by

punctuation or speech melody, the reader starts a wrap-up process for the preceding phrases, 1(e)1(t)5(ehi)5(c)11(h 1(18(nf)20(or)7(m)12(a)11

between prosody and parsing strategy in a particular experimental condition (depending on the strategy used). For instance, if the reader used a minimal attachment strategy (Frazier, 1978; Frazier & Rayner, 1982), the postboundary Region 2 and Region 3 (modifier + NP3) would be taken as a copatient by the strategy. Then on both Region 1 and the postboundary regions the conflict between parsing strategy and prosody would engender longer reading times. It is clear from Table 2 that although this was the case for Region 1, it was not for Region 2 and Region 3. On the other hand, if the reader used an early closure strategy, then the reading times on Region 1 should be longer for the sentences with a late pause than for the sentences with an early pause because of the conflict in the former condition. Again, the data in Table 2 speak against this suggestion.

Experiment 2

Experiment 1 showed that prosodic boundary information in a speech melody can be projected onto visually presented sentences and gives rise to longer durations on preboundary regions, possibly because of a wrap-up process. Moreover, inconsistent with the preparation account, Experiment 1 showed that reading times on the postboundary regions were not shorter or were even longer than reading times on the words without a boundary preceding them. In Experiment 2, we focused more on postboundary regions and sought to examine whether the processing of prosodic boundary information would facilitate or interfere with the processing of the upcoming, postboundary lexical information. To this end, we adopted the gaze-contingent boundary paradigm (Rayner, 1975) and examined how prosodic boundaries and parafoveal preview would jointly influence the processing of the words right after and before the prosodic boundary.

In the gaze-contingent boundary paradigm, a target word is initially either visible or replaced with a preview mask (e.g., a random letter string). When a reader's eyes cross a predefined, invisible vertical boundary located between the pretarget and the target words, the initially displayed mask is replaced by the target word. The logic behind this paradigm is that if the reader obtains parafoveal information concerning the target before the eyes cross the vertical boundary, shorter fixations on the target word (preview benefits) should be found for the identical than for the masked preview.

Indeed, such a preview benefit for parafoveal word $n + 1$ (i.e., when the vertical boundary immediately precedes the target) has been reported not only for previews with identical words (see Rayner, 1998, for a review), but also for previews with words that are orthographically (Inhoff, 1990; Inhoff & Tousman, 1990; Rayner, 1975) or phonologically (e.g., Pollatsek, Lesch, Morris, & Rayner, 1992) related to the target in alphabetic scripts. This $n + 1$ preview benefit has also been observed for the logographic Chinese script (e.g., W. Liu, Inhoff, Ye, & Wu, 2002; Tsai, Kliegl, & Yan, 2012; Tsai, Lee, Tzeng, Hung, & Yen, 2004; Yan, Richter, Shu, & Kliegl, 2009; Yan, Zhou, Shu, & Kliegl, 2012; Yen, Radach, Tzeng, Hung, & Tsai, 2009). Moreover, preprocessing of word $n + 2$ has also been observed in some German and Chinese studies (Kliegl, Risse, & Laubrock, 2007; Yan, Kliegl, Shu, Pan, & Zhou, 2010; Yan, Risse, Zhou, & Kliegl, 2012; Yan, Zhou, Shu, & Kliegl, 2012).

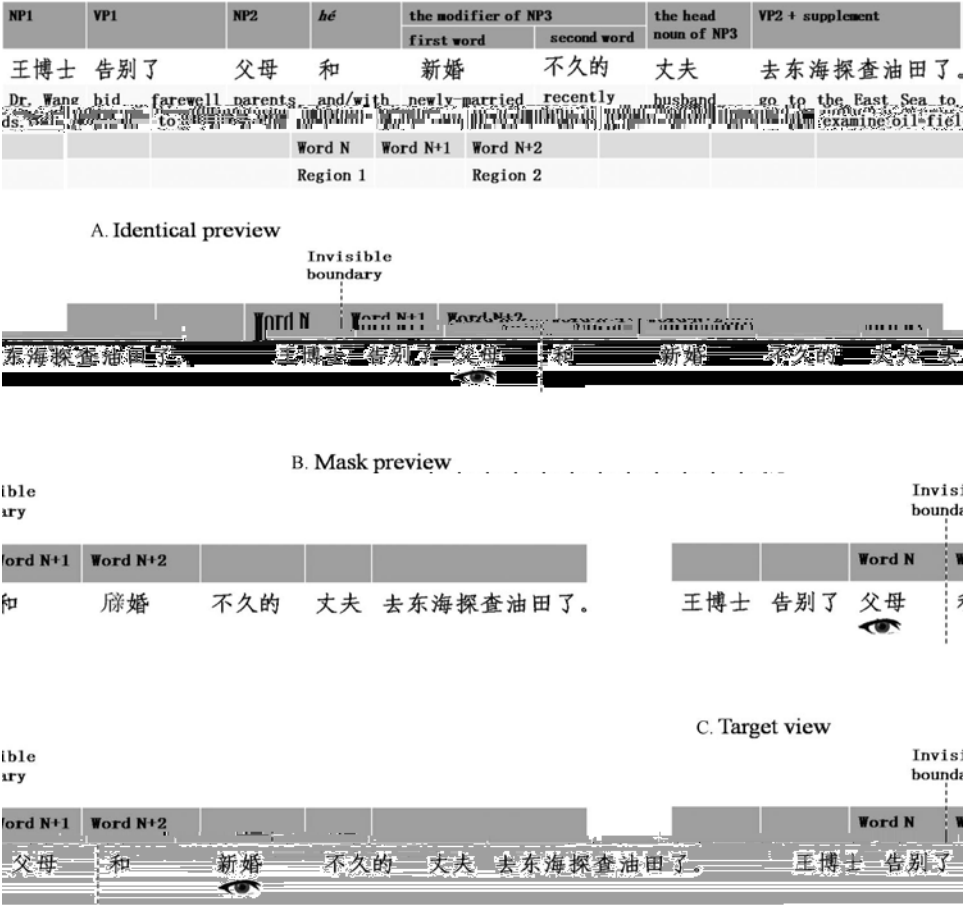


Figure 3. Exemplar sentences and interest regions in Experiment 2. (A) The sentence presented before the fixation crossed the invisible boundary between NP2 and *hé* in identical preview condition. (B) The sentence presented before the fixation crossed the invisible boundary between NP2 and *hé* in mask preview condition. (C) The sentence presented after the fixation crossed the invisible boundary. Translations: “Doctor Wang bid farewell to her parents and her newly married husband, and went to the East Sea to examine the oil fields.” / “Doctor Wang bid

participants from extracting lexical information before fixating upon the target word. An invisible vertical boundary was located between NP2 and *hé*. When a saccade crossed this invisible boundary, the previewed character was replaced by the target character (see Figure 3C). The sentence remained in this final form until the end of the trial. After the eye-tracking system had detected the crossing of the boundary, display changes were accomplished with a mean time of 7.3 ms, ranging from 2 to 13 ms. Participants read 116 sentences, including 80 experimental sentences and 36 filler sentences. For half of the sentences in each category, a comprehension question was presented after the stimulus sentence, and the participant had to decide, by pressing a response button, whether the meaning of the question sentence was congruent or incongruent with a proposition encoded in the stimulus sentence. To detect whether participants used the prosodic boundary cue to parse the sentences, two of the 58 question sentences were directly related in meaning to the interpretation of the ambiguous sentences.

After the completion of the test, participants were asked to report whether and how often they had noticed anything unusual during sentence reading. Twenty-five out of 38 participants reported seeing “flashes” on the screen, and the number of flashes noticed ranged from one to four, with a mean of 1.6. However, they could not report anything specific for the flashes. In addition, all participants except three reported that they noticed the early and the late pauses in speech melodies. Those three participants showed similar patterns of eye movements as the other participants and were included in the data analysis.

Data analysis. Two regions were selected as regions of interest, as shown in Figure 3. Region 1 contained NP2 (i.e., word *n*), composed of two to three characters. Region 2 (i.e., word *n + 2*) contained part of the modifier for the head noun in NP3, composed of two to four characters (i.e., *newly married* in the figure). Trials with either first-fixation duration less than 60 ms or greater than 800 ms or gaze duration less than 60 ms or greater than 1,000 ms (2% of all fixations) were eliminated. Trials in which the display change was inappropriately initiated during

fixations on *n + 1* or *n + 2* were also excluded. Results from six participants were further discarded because the inappropriate display change occurred in more than 40% of the trials. For the remaining 32 participants, 77% of all the fixations were entered into the analyses of duration and landing position.

Similar to Experiment 1, estimates are from a linear mixed model for durations and landing positions and a generalized linear mixed model for percent regressions and skipping rates. Participants and stimulus items were treated as crossed random factors. The fixed factors included in the model were (a) prosodic boundary cue that could be either early or late, (b) preview type that could be mask or identical, and (c) the interaction of these two factors.

Results

Participants correctly answered 85.6% ($SD = 4.3\%$) of the poststimulus sentence questions, and there was no difference in the accuracy between the four experimental conditions ($F < 1$). Measures for the two regions are shown in Table 3. The same patterns of effects were obtained for these measures when sentences that were incorrectly answered in the comprehension test were removed from the analysis. All participants correctly answered the two questions checking which interpretation was made except one, who responded incorrectly to one of the two questions. This result indicated that participants were able to use the prosodic boundary cue previously presented to help them parse the written sentences.

Region 1.

Prosodic boundary effect. For the analysis of durations based on 1,704 observations, the interaction between preview type and prosodic boundary was marginally significant for first-fixation durations ($b = 0.058$, $SE = 0.030$, $t = 1.9$). Further analyses showed that the difference between first-fixation duration in sentences with the early pause (288 ms) and those with the late pause (276 ms), that is, the prosodic boundary effect, was significant for the identical preview trials ($b = 0.048$, $SE = 0.022$, $t = 2.2$). This effect replicated Experiment 1, with longer durations on the region

Table 3
Grand Means and Standard Errors for Sentences of the Four Conditions in Experiment 2

Variable	Early pause, identical preview		Early pause, mask preview		Late pause, identical preview		Late pause, mask preview	
	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>
Region 1								
FFD	288	5.72	281	5.17	276	5.25	277	4.98
GD	340	8.20	327	7.68	323	7.11	328	7.73
LAND	1.00	0.03	1.00	0.03	1.08	0.03	1.01	0.03
REG	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SKIP	0.13	0.01	0.14	0.01	0.15	0.01	0.16	0.01
Region 2								
FFD	296	4.98	301	5.26	282	4.59	300	5.11
GD	407	9.12	406	8.49	374	8.35	407	8.42
LAND	1.19	0.03	1.12	0.03	1.18	0.03	1.11	0.03
REG	0.01	0.004	0.02	0.007	0.03	0.008	0.02	0.006
SKIP	0.07	0.01	0.06	0.009	0.08	0.01	0.08	0.01

Note. FFD = first-fixation duration (ms); GD = gaze duration (ms); LAND = landing position (of character); REG = percent regressions; SKIP = skipping rate.

immediately before the prosodic boundary. But this effect was not significant when the previewed characters were masks (281 vs. 277 ms; $t < 1$). As shown in Table 3, a similar pattern of interaction was observed for gaze durations, although the interaction failed to reach significance ($t < 1.7$).

Region 2.

Parafoveal preview benefit. For the analysis of durations based on 1,792 observations, the difference between sentences with mask preview and those with identical preview was significant for gaze durations (406 vs. 390 ms; $b = 0.038$, $SE = 0.017$, $t = 2.2$) and marginally significant for first-fixation durations (300 ms vs. 289 ms; $b = 0.027$, $SE = 0.014$, $t = 1.9$), showing increased reading times for conditions in which parafoveal information was not available as compared with conditions with normal preview (i.e., a preview benefit).

In addition, a significant interaction was found between preview type and prosodic boundary for gaze durations ($b = 0.066$, $SE = 0.033$, $t = 2.0$). Further analysis showed significantly shorter durations for the identical (374 ms) than for the mask preview condition (407 ms), that is, the preview benefit, in sentences with the late pause ($b = 0.078$, $SE = 0.025$, $t = 3.1$) but not in sentences with the early pause (407 vs. 405 ms; $t < 1$). These results indicated that less parafoveal information had been acquired about Region 2 during fixations on Region 1 when there was a prosodic boundary between the two regions than when there was no boundary.

The preview effect also manifested in landing positions, with fixation locations marginally closer to the beginning of the target words for sentences with mask preview than for sentences with identical preview (1.12 vs. 1.19 characters; $b = 0.055$, $SE = 0.029$, $t = 1.9$).

Prosodic boundary effect. Another way to interpret the significant interaction between the preview type and prosodic boundary was to examine the prosodic boundary effect. Gaze durations on Region 2 were significantly longer for sentences with the early pause than for sentences with the late pause, but only in trials with identical preview (407 vs. 374 ms; $b = 0.060$, $SE = 0.025$, $t = 2.4$), not in trials with mask preview (406 vs. 407 ms; $t < 1$).

Discussion

Experiment 2, like Experiment 1, showed that the first fixation durations on the Region 1 were longer when the region was immediately followed by a prosodic boundary. More importantly, measures at the postboundary region (Region 2) indicated that the preview benefit for word $n + 2$, which has been observed for Chinese (Yan et al., 2010; Yang et al., 2009), was obtained only when the target word was not preceded by a prosodic boundary, not when the target was preceded by a prosodic boundary. This finding, consistent with the wrap-up hypothesis, provides direct evidence that the processing of the normal and necessary prosodic boundary, despite its facilitatory role in syntactic structure building, may also hinder parafoveal processing and slow down the reading of postboundary word.

As can be seen from Table 3, the first-fixation and gaze durations in Region 2 were the shortest for the identical preview condition with the late pause, whereas they were essentially the same for the other three conditions. Thus, consistent with the wrap-up hypothesis, the existence of a prosodic boundary effectively hinders the reader from obtaining valid lexical information

from the preview, as does the existence of a mask (Rayner, 1998). It is possible that the prosodic boundary increases the processing load in integrating and packing up the perceived preboundary information when the eyes are fixating at the preboundary region, narrowing down the perceptual span. This finding also helps to rule out the possibility that the increased durations on the preboundary region (i.e., Region 1 in both experiments) are due to additional efforts devoted to parafoveal processing of postboundary information when the prosodic boundary is present.

On the basis of the above findings, one might suggest that the prosodic boundary processing, which includes a wrap-up process for the preboundary information, completely shuts down parafoveal processing. If it is the case, we should then expect to observe no parafoveal-on-foveal effect on Region 1. Although we indeed did not observe a main effect of parafoveal-on-foveal preview benefit, we did find an interaction between this effect and prosodic boundary: The prolonged readings upon the preboundary words disappeared when the information of the postboundary target word could not be accessed parafoveally due to a mask. This pattern suggests that readers did obtain information to the right of the early prosodic boundary to specify whether the postboundary character was a real one, and that the specification of prosodic boundary was more effective when the postboundary region contained meaningful or familiar characters than when it contained a pseudocharacter. Given that the orthographic information of the target word can be obtained from preview (Pynte, Kennedy, & Ducrot, 2004; Starr & Inhoff, 2004), it is possible that the parafoveal processing of the pseudocharacter in the mask conditions is harder to process and pulls the eyes toward the pseudocharacter (Kennedy, 1998). This shut down the normal wrap-up process induced by the prosodic boundary, resulting in a much reduced prosodic boundary effect at Region 1.

Experiment 3

Experiment 2 showed that a prosodic boundary may lead to impaired parafoveal processing of words after it. This finding is in accordance with the prediction of the wrap-up account, which predicts that a wrap-up process for the preboundary information would weaken the parafoveal processing of the postboundary words. There exists a possibility, however, that the pattern of results observed in Experiment 2 was paradigm-specific. Compared with natural reading, projecting prosodic information from working memory onto the visually presented sentences may require more cognitive resources, particularly at positions where the prosodic boundary cues are present. This might lead to an inefficient preview of the postboundary words. To further establish that our results can be generalized to other paradigms, we conducted Experiment 3 in which a comma, the main device of conveying prosodic structure in written Chinese sentences (Zhang, 2003), was used to provide prosodic boundary information. In Chinese, commas indicate the hierarchical prosodic boundaries (breaks) within a sentence (China State Bureau of Technical Supervision, 1995) and have a considerable influence on interpreting ambiguous sentences (C. Liu, 1998). As shown in Figure 4, the ambiguous sentence is interpreted in one way when a comma was inserted at the position of an early prosodic boundary and in another way when a comma was inserted at the position of a late prosodic boundary.

The aim of Experiment 3 was to investigate whether the presence of a prosodic boundary would elicit a prolonged reading of preboundary information and an impairment of parafoveal processing of post-

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Figure 4. Exemplar sentences in Experiment 3. (A) A sentence with an early comma. Translation: “Dr. Wang bid farewell to her parents, and went to the East Sea to explore oil fields with her newly married husband.” (B) A sentence with a late comma. Translation: “Dr. Wang bid farewell to her parents and newly married husband, and went to the East Sea to explore oil fields.”

boundary words when the prosodic boundary is cued by comma, rather than by speech melody. The same materials and gaze-contingent boundary paradigm used in Experiment 2 were employed.

Chinese text is monospace; that is, a comma in a Chinese sentence usually takes up the same amount of space as a character in the printed form. This would increase the distance between the pre- and post-comma characters, in contrast with the absence of such space

the

region. Although the interaction between preview type and prosodic boundary was not reliable ($b = 0.049$, $SE = 0.031$, $t = 1.6$), the pattern was nevertheless similar to that in Experiment 2: The difference between gaze duration in sentences with the early pause (337 ms) and those with the late pause (308 ms) in identical preview was numerically larger than the difference in mask preview (322 vs. 313 ms).

Region 2.

Parafoveal preview benefit. For the analysis of gaze durations based on 2,166 observations, the sentences with mask preview (399 ms) induced significantly longer reading times as compared with sentences with the original word (390 ms; $b = 0.040$, $SE = 0.017$, $t = 2.4$). The interaction between preview type and prosodic boundary did not reach significance ($t = 1.1$), although the preview benefit effect (3 ms) for sentences with an early comma was numerically smaller than that for sentences with a late comma (13 ms).

The preview effect was also observed on the measurement of landing position, as the eye fixations landed closer to the beginning of this region for sentences with mask preview than for sentences with identical preview (0.95 vs. 1.07 characters; $b = 0.136$, $SE = 0.026$, $t = 5.2$). We also observed a significant interaction between prosodic boundary and preview type ($b = 0.107$, $SE = 0.052$, $t = 2.0$). Detailed analysis showed that a mask preview induced significantly closer landing positions than an identical preview both in early-comma sentences (0.08 characters) and in late-comma sentences (0.18 characters; $b = 0.081$, $SE = 0.036$, $t = 2.3$, and $b = 0.181$, $SE = 0.038$, $t = 4.8$, respectively). The effect for early-comma sentences was much smaller than that for late-comma sentences as revealed by the interaction.

In addition, the preview effect was marginally significant for percent regressions (0.028 vs. 0.043; $b = 0.474$, $SE = 0.251$, $z = 1.9$, $p = .06$), reflecting slightly increased regressions back to the earlier regions for sentences with mask preview than for sentences with identical preview.

Prosodic boundary effect. The main effect of comma was significant for the analysis of gaze durations ($b = 0.040$, $SE = 0.017$, $t = 2.4$), showing that viewing times on Region 2 for sentences with the early comma were longer than those with the late comma (400 vs. 384 ms).

For the analysis of landing positions, the comma effect was marginally significant ($b = 0.051$, $SE = 0.026$, $t = 1.9$), with closer landing positions for the region in early-comma sentences relative to late-comma sentences. The difference between the condition with an early comma and that with a late comma was significant only in sentences with identical preview (1.03 vs. 1.12 characters; $b = 0.108$, $SE = 0.038$, $t = 2.8$), not for sentences with mask preview (0.95 vs. 0.95 characters; $t < 1$).

Discussion

The preview effect on Region 2 was reduced when a comma was inserted prior to Region 2 compared with when no comma was inserted at this position, although this pattern reached statistical significance only on the measure of landing position, not on the measure of reading time. Given that the measures of landing position did not differ between conditions on Region 1, the differences on Region 2 can only be explained in terms of the parafoveal processing of information of this region. The reduction of the distance of landing position by the presence of comma may

reflect the reduced parafoveal processing (cf. Beauvillain, Doré, & Baudoin, 1996; Hyönä & Pollatsek, 1998; Lavigne, Vitu, & d'Ydewalle, 2000; Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006). We may conclude that the processing of prosodic boundary that was cued by commas induced, in general, the impaired parafoveal processing of postboundary words, a pattern similar to what we observed in Experiment 2 for the processing of prosodic boundary cued by speech melody.

Results from the present experiment showed that reading times increased when the region was followed by a comma, replicating the effects of prosodic boundary in Experiments 1 and 2. However, the interaction between preview type and prosodic boundary reported for Experiment 2 did not reach statistical significance in Experiment 3. It is possible that this difference between the two experiments was partly due to how the prosodic boundary information was conveyed. We speculate that compared with the speech melody cue, the presence of a comma increases the perceptual processing load in reading the target region, leading to increased durations on the preboundary word in the mask preview condition with early comma. Alternatively, the differential patterns of interaction in the two experiments could be due to the difference in the precision of boundary specification. In Experiment 2, the prior acoustic envelope may not precisely give readers the location of the prosodic boundary; in this case, both prior knowledge (i.e., whether an early or a late prosodic boundary) and some upcoming parafoveal information may be needed for readers to jointly make a decision about whether a wrap-up process should be performed. But in Experiment 3, the prosodic boundary information conveyed by the comma could reliably indicate the end of a clause and the clause-final wrap-up process could be performed irrespective of the availability of parafoveal information. Further studies are needed to test these hypotheses.

General Discussion

This study provides evidence not only for the functional roles of prosodic boundaries in syntactic parsing, but also for the impact of prosodic boundaries upon lexical processing in silent sentence reading. Previous studies have shown an early impact of prosody upon syntactic processing in silent reading of temporarily or globally ambiguous sentences (Hwang & Schafer, 2009; Steinhauer & Friederici, 2001) by using self-paced or word-by-word presentations. The present study went further to show that prosodic boundary cues are rapidly used in natural reading to guide syntactic parsing.

More relevant to the purpose of this study, we found that the presence of a prosodic boundary, which can be interpreted as a syntactic marker for the ending of a clause (Fodor, 2002), elicits a clause-final wrap-up process that integrates preboundary information and increases processing load on the preboundary region. One consequence of this wrap-up process is that the reader's perceptual span is narrowed down by the increased demand on processing resources. This narrowed perceptual span would reduce the efficiency of parafoveal processing of postboundary sentence constituents, resulting in deficits in lexical processing and reduction of parafoveal preview benefits. It is noted that parafoveal processing is not completely disabled by the processing prosodic boundary. In Experiment 2, the wrap-up process for the preboundary region was affected by whether the first character of the postboundary target word was a mask; in

Experiment 3, the preview benefit for postcomma words was significant even when the comma was present.

Previous research on the effect of prosodic boundary in sentence reading has commonly used punctuation to convey the (implicit) prosodic structures in the sentences. However, this kind of manipulation introduces at least two confounds: (a) the unbalanced visual complexity for the target regions between the conditions with and without a comma and (b) an increased distance between the pre- and postcomma words when a comma is present. Both confounding factors have been found to influence the pattern of eye movements during sentence reading (Drieghe, Brysbaert, & Desmet, 2005; Rayner, Fischer, & Pollatsek, 1998; White, 2008). To avoid this confound, we used speech melody to convey the prosodic boundary information and observed not only the effect of wrap-up process on the preboundary region that has been reported for sentences with punctuation (e.g., Hirotsani et al., 2006), but more importantly, the impairment of parafoveal processing of postboundary words (Experiment 2). Moreover, when we did use the comma to cue the prosodic boundary but controlled the distance between the pre- and postboundary words, we obtained essentially the same pattern of impairment of lexical processing for postboundary words (Experiment 3). This cross-paradigm finding strongly supports the wrap-up account for interpreting the functions of prosodic

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