Parafoveal processing during reading is reduced across a morphological boundary

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Abstract

A boundary change manipulation was implemented within a monomorphemic word (e.g., *fountaom* as a preview for *fountain)*, where parallel processing should occur given adequate visual acuity, and within an unspaced compound (*bathroan* as a preview for *bathroom*), where some serial processing of the constituents is likely. Consistent with that hypothesis, there was no effect of the preview manipulation on fixation time on the 1st constituent of the compound, whereas there was on the corresponding letters of the monomorphemic word. There was also a larger preview disruption on gaze duration on the whole monomorphemic word than on the compound, suggesting more parallel processing within monomorphemic words.

Much has been learned about eye movements during reading (see Rayner, 1998, 2009 for reviews), but some unresolved issues remain. Arguably, the issue capturing the largest amount of attention in recent years is if readers lexically process more than one word at a time. Studies using the boundary technique (Rayner, 1975, see Figure 1) established that readers extract information from more than the fixated word. This is apparent from the fact that fixation times on a word are shorter when the letters of the word are visible when the word immediately to its left is fixated than when they were masked (Rayner, 1975). This *parafoveal preview benefit* illustrates that readers obtain information from words located in the parafovea and that more than one word can be processed on a fixation. Thus, the question of whether more than one word is processed at a time becomes whether parafoveal processing begins only after foveal processing has been concluded and attention has shifted to the next word or both words are processed in parallel. The first position has been assumed in serial models of lexical processing during reading such as the E-Z Reader model (Reichle, Rayner, & Pollatsek, 2003), whereas the parallel view is embodied in models such as SWIFT (Engbert, Nuthmann, Richter, & Kliegl, 2005).

The opera was very proud to present the young child pxvforming on Tuesday.

* * * * * * *

1 2 3 4 5 6 7

The opera was very proud to present the young child performing on Tuesday.

* * *

8 9 10

Figure 1. An example of a boundary change experiment. In this example, the target word is *performing*. When the participant begins reading the sentence, the 2nd and the 3rd letter of the target word are replaced with visually similar letters (so that *pxvforming* is initially present). When the reader's eye movement crosses an invisible boundary at the end of the word preceding the target word, *pxvforming* changes to *performing*. The asterisks represent the location of each fixation (with the numbers indicating the sequence of fixations).

This controversy has been fuelled by observations of *parafoveal-on-foveal* (PoF) effects (Kennedy, 2000; Murray, 1998) wherein characteristics of the word to the right of fixation influence the fixation duration on the currently fixated word. It is assumed that such effects are damaging to the serial assumptions of the E-Z Reader model. However, the existence of these effects is highly contested (see Rayner, White, Kambe, Miller & Liversedge, 2003 for a review) and because the E-Z Reader model incorporates occasional mislocated fixations (Nuthmann, Engbert, & Kliegl, 2005), it can account for small and/or sporadic PoF effects (Drieghe, Rayner, & Pollatsek, 2008).

However, an important point is missing from this discussion. That is, much emphasis has been placed on whether serial or parallel models of lexical processing during reading are a better account of the results of *between-word* boundary change experiments that examine the benefit of previewing a word before it is fixated on processing time when it is fixated. Although the models differ in how the effect is accounted for, both naturally predict preview benefit in such a paradigm. In the current study, we focus on the processing that takes place *within* a word.

Data from recent experiments employing the boundary paradigm to examine lexical processing within compound words (Juhasz, Pollatsek, Hyönä, Drieghe, & Rayner, 2009; White, Bertram & Hyönä, 2008) seem problematical for a parallel model. In these experiments, the 2nd constituent of an unspaced compound word was partially masked (*basketbadk* as a preview for *basketball*), and the resulting parafoveal preview benefit[1] on the 2nd constituent was considerably larger (100 ms in measures that included regressions out of the 2nd constituent) than typically observed between words (20-40 ms). However, this effect was restricted to measures on the 2nd constituent and there was no (within-word) PoF effect of the preview manipulation of the 2nd constituent on the initial viewing time on the 1st constituent. The lack of a PoF effect on the 1st constituent indicates that the initial encoding processes of longer compound words may be largely serial across the constituents. The hypothesis that the constituents of a compound word are, to some extent, independent processing units is also consistent with the fact that the frequency of the 1st and 2nd constituents each affect the fixation time on a compound word (Hyönä, Bertram, & Pollatsek, 2004; Pollatsek, & Hyönä, 2005). However, other experiments have shown that the frequency of the whole compound word also influences gaze duration on the word (Juhasz, 2008; Pollatsek, Hyönä, & Bertram, 2000) and that the whole-word representation also plays a part in identifying these words. Pollatsek et al. (2000)

proposed a race model in which a morphemic decomposition process and a whole-word direct-access occur in parallel, but with a preference for whole-word look-up when the compound is short, as research has shown constituent frequency effects to be more elusive for short Finnish compounds (Bertram & Hyönä, 2003)[2].

More generally, researchers agree that processing is parallel when it takes place *within* a morpheme (Rayner & Johnson, 2005) as long as the morpheme falls within the word identification span, extending 7-8 letter positions to the right of fixation (Rayner, 1998). However, the data just discussed indicate that constituents within morphemically complex words may not be processed in parallel. Thus, we wanted to determine whether the limit to what is processed in parallel during a fixation is determined by "deeper" properties of the input such as morphemic complexity rather than surface features such as length. To test this hypothesis, we implemented a boundary change manipulation *within* a monomorphemic word and compared it to a boundary change within an unspaced compound word.

The current experiment is the first to implement a boundary change manipulation in a situation in which lexical processing is uncontroversially parallel (i.e. within the currently fixated morpheme given adequate visual acuity). The "depth" hypothesis above makes the following predictions about the differences between processing of a monomorphemic and compound word of equal length.

1. The disruption of having an incorrect preview of the 2nd part of the word should be greater for the monomorphemic word than for the compound word. That is, we hypothesize that all letters of monomorphemic words are processed in parallel, whereas the 2nd constituent of the compound words would be processed in a shallower manner due to there being a priority of processing the first constituent first.
2. Thus (as with Juhasz et al., 2009), there should be little or no PoF effect of the preview manipulation on the 1st constituent of a compound, whereas there should be a substantial PoF effect on the corresponding letters of a monomorphemic word.

Method

Participants. Twenty-eight native speakers of English with normal or corrected-to-normal vision from the University of Massachusetts participated for $7 or course credit.

Apparatus. Eye movements were sampled every millisecond via an SR Research Eyelink1000 system. Viewing was binocular but eye movements were recorded from the right eye only. Calibration was checked on each trial and spatial resolution was better than 0.5°. Participants were seated 61 cm from a 19-inch Vision Master Pro 545 monitor; 3.15 characters equalled 1 degree of visual angle.

Materials. 32 unspaced compounds were selected: 21 8-letter-words, 9 9-letter-words and 2 10-letter-words (*M*=8.4, *SD*=.61). Each unspaced compound was matched with a monomorphemic word of identical length. The frequencies and number of morphemes were obtained from the HAL corpus of the English Lexicon project (Balota et al., 2007). The average natural log of the whole-word frequency was 7.75 for both compounds and monomorphemic words. There were no differences between the initial bigram log frequencies of the compounds (4.99) and the monomorphemic words (4.94), $t(31)<1$, nor between the initial trigram log frequencies (4.03 vs. 3.90), $t(31)<1$. The first lexemes of the compound words ranged from 3-5 characters (*M*=4.1, *SD*=.42); their average log frequency was 10.77.

Identical sentence frames (except the target word) were created for each compound-monomorphemic pair. Two parafoveal previews were prepared (see Table 1 and Appendix). For the compound word, the partial preview was created by preserving the identity of the first two letters of the 2nd lexeme, but changing all other letters. The corresponding letters in the monomorphemic word were changed to create the partial preview for those words. The invisible boundary was set immediately after the last letter of the 1st constituent of the compound and after the corresponding character in the monomorphemic word.

Table 1. An example sentence from the experiment illustrating each of the four conditions.

1. Unspaced compound – correct preview

Charles announced that he was going to the *bathroom* to wash his hands.

2. Unspaced compound – incorrect preview

Charles announced that he was going to the *bathroan* to wash his hands.

3. Monomorphemic word – correct preview

Charles announced that he was going to the *fountain* to wash his hands.

4. Monomorphemic word – incorrect preview

Charles announced that he was going to the *fountaom* to wash his hands.

Note: The stimuli shown in italics indicate the preview for each condition prior to the eyes' crossing of the display change boundary. All sentences were displayed on one or two lines on the screen with a maximum of 85 characters per line. All letters were lowercase and in mono-spaced Courier font. The preview was always approximately in the middle of the screen and replaced by the correct word after the boundary had been crossed.

Procedure. Participants read the sentences and pressed a button when they finished reading. Comprehension questions were asked after 25% of the trials; accuracy was 97%. In total, participants read 148 sentences: 32 experimental sentences randomly intermingled with 106 fillers preceded by 10 practice sentences. The initial calibration of the eye-tracking system required about 5 minutes and the experiment lasted about 35 minutes.

Results

Trials were removed if there was a blink or track loss or if the display change did not occur at the correct time, resulting in the loss of approximately 16% of the data, distributed evenly across conditions. In addition, fixations on adjacent characters were combined if one was shorter than 80 ms. Other fixations shorter than 100 ms or longer than 1000 ms were eliminated by the data analysis software. Various eye movement measures are presented in Table 2. The main measures that we discuss are *first fixation duration* (the duration of the first fixation on a word or otherwise specified region) and *gaze duration* (the sum of all fixations on a region prior to that region being left). Both measures are conditional on the region not being skipped initially.

Analyses employed a linear mixed-effects (lme) model specifying participants and items as crossed random effects. The significance values and standard errors reported reflect both participant and item variability. The *p*-values were estimated using posterior distributions for model parameters obtained by Markov-Chain Monte Carlo sampling. The regression weights of both the fixation probabilities and the regression probabilities cannot be directly interpreted as effect sizes because they originate from a logistic lme model. However, to increase transparency, an inverse logistic transformation was carried out on the means for the measures reported in Table 2[3].

A multitude of factors, such as word length, word length of the 1st constituent, whole word frequency, and orthographic uniqueness point were examined, but only the factors directly manipulated (word type and preview) contributed significantly and are reported. A main effect of word type was observed in some measures, consistently pointing in the direction of the compound word being processed faster than the matched monomorphemic word. Main effects of word type will not be discussed further[4], since they replicate previous findings using lexical decision (Fiorentino & Poeppel, 2007).

Table 2. Eye movement measures on the target word (fixation durations in ms).

	Compound			Monomorphemic		
	Full Preview	Partial Preview	Difference (PB)	Full Preview	Partial Preview	Difference (PB)
Initial Landing Position (in character positions)	2.06	2.03	-.03	1.87	1.83	-.04
Probability of fixating Part 1	.69	.68	-.01	.72	.63	-.09°
First Fixation on Part 1 #	224	236	12	230	255	25*
Gaze Duration on Part 1#	240	244	4	239	285	46**
Go-Past for Part 1 #	289	318	29	306	366	60*
First Fixation on Part 2 #	183	288	105***	202	309	107***
Gaze Duration on Part 2 #	184	330	146***	212	363	151***
Subgaze 2 #	194	365	171***	223	420	197***
Probability of Fixating Part 2 #	.22	.66	.44***	.27	.72	.45***
Probability of a Regression from Part 2 #	.01	.13	.12***	.01	.10	.09**
Gaze duration on total word #	288	411	123***	292	517	225***
Gaze duration on total word	271	384	113***	285	448	163***

# Conditional upon the 1st part (lexeme1 of the compound or the corresponding part of the monomorphemic word) being fixated during first-pass. This selection ensures the preview falling within the word identification span prior to crossing the boundary. The other measures consist of all the data without this restriction.
PB = Preview Benefit (= Partial Preview – Full Preview).
° $p < .10$, * $p < .05$, ** $p < .01$, *** $p < .001$

Initial landing position in the target word. To examine whether the preview manipulation affected the saccade into the target word, the initial landing positions were examined. There was no effect of preview (b=-.03, SE=.13, p>.20). The eyes landed slightly further into the compound word but this effect was not significant (*b*=.19, *SE*=.13, p>.10), and there was no interaction (*b*=.01, *SE*=.25, p>.20). Taking into account the word lengths of the target words, the average landing position data indicate that the entire target word almost always fell within the word identification span on the first fixation.

Fixation measures on the 1st part of the target word (lexeme1 for the compound). There was no effect of preview on the probability of fixating the 1st part of the target word (*b*=.22, *SE* =.16, p>.10) nor was the interaction with word type significant (*b*=.35, SE=.32, p>.20). However, there was a marginally significant difference for monomorphemic words (*b*=.40, *SE*=.23, p>.05) but not for compounds (*b*=.05, *SE*=.23, p>.20). First fixation duration showed a significant effect of preview (*b*=-18.39, *SE*=6.90, p<.01). Although the interaction was not significant (*b*=-12.66, *SE*=13.83, p>.20), there was a significant effect of preview (*b*=-23.11, *SE*=9.86, p<.05) for the monomorphemic words but not for the compounds (*b*=-13.20, *SE*=9.66, p>.10). For gaze duration on the first part of the target word, both the effect of preview (*b*=-24.47, *SE*= 10.07, p<.05) and the interaction between preview and word type were significant (*b*=-42.27, *SE*=20.09, p<.05). Contrasts showed that this was again due to the preview manipulation being significant for monomorphemic words (*b*=-43.29, *SE*=14.34, p<.01) but not for compounds (*b*=-5.40, *SE* =14.05, p>.20). Finally, we also examined the go-past time (the sum of all fixations until the region is exited to the right). There was a 44ms effect of preview (*SE*=17.27, p<.05), but no interaction with word type (*b*=-31.47, *SE* = 34.58, p>.20). Contrasts showed a significant effect of preview for the monomorphemic words (*b*=-55.59, *SE*=24.66, p<.05), but not for the compounds (*b*=-31.40, *SE* = 24.20, p=.20).

Fixation measures on the 2nd part of the target word (lexeme2 for the compound). Because our main focus is on how the preview manipulation affected eye movement measures within the target word, we restricted the analysis of the second part of the target word to those instances when the readers made a fixation on the first part of the word. This restriction ensures that the preview was located in the word identification span prior to the eyes landing on the 2nd part of the word. There was an effect of preview (*b*=-1.92, *SE*=.21, p<.001) on the fixation probability on the 2nd part of the word and no interaction between preview and word type (*b*=0, *SE*=.42, p>.20)[5]. For first fixation duration, readers fixated 106 ms longer with the partial preview

(*SE*=13.68, p<.001). The interaction of preview and word type (*b*=-2.43, *SE*=26.65, p>.20) was far from significant. Similarly, the 148 ms effect of preview on gaze duration was significant (*SE*=17.18, p<.001), and there was virtually no interaction (*b*=-4.80, *SE*=33.43, p>.20). We also examined a measure referred to as *subgaze2* (Pollatsek & Hyönä, 2005): the time spent fixating on the second lexeme (or corresponding part in the monomorphemic word), including any regressions back to the 1st part before moving off of the target word to the right. As with gaze duration on the second part, there was an effect of preview (*b*=-185.17, *SE*=20.88, p<.001), but no interaction (*b*=-26.09, *SE*=40.82, p>.20). Finally, there was an effect of preview on the probability of regressing from the 2nd part of the word (*b*=-2.43, *SE*=.53, p<.001) but no interaction (*b*=.64, *SE*=1.07, p>.20).

Gaze duration on the entire word. It is important to stress here that the measures for the whole word are more meaningful when analyzing later measures for the monomorphemic words as they do not have a true 2nd part. Restricting the analyses to instances when the 1st part of the word was fixated, gaze durations were 173 ms longer in the partial preview condition (*SE*=18.92, p<.001). This effect was 102 ms larger in the monomorphemic condition than in the compound-word condition (SE=37.63, p<.01). We also carried out an analysis of the gaze duration on the entire word independent of a fixation on the 1st part of the target. Gaze durations were 138 ms longer in the partial preview condition (*SE*=14.43, p<.001) Here, the 50 ms interaction was only marginally significant (*SE*=28.77, p<.10).

Discussion

The results confirmed the two hypotheses made in the Introduction. The preview effect observed for gaze duration for monomorphemic words was 225 ms compared to 123 ms for the compounds. The different sizes of these effects support the view that the 2nd constituent of the compound did not initially receive as much processing resources as the corresponding letters of the monomorphemic word because, in the former case, the processing of the 1st constituent is prioritized. The second hypothesis was also confirmed: there was virtually no PoF effect of the preview manipulation on the 1st constituent of an unspaced compound (see also White et al., 2008), whereas there was a sizeable effect (46 ms in gaze duration) for the monomorphemic words. This indicates that earlier findings of no PoF effect within compounds were not due to the length of the words or lack of statistical power but instead to their morphological structure.

Our data indicate that there was little initial parallel processing of the constituents for compound words even though suggestions have been made that for compounds as short as these, a whole-word direct-access would be the default (Bertram & Hyönä, 2003). However, the finding that there was a 123 ms preview effect even for compound words on total gaze duration indicates that the processing of the letters in these words is less serial[6] than the processing of letters from adjacent words, where preview manipulations at distances comparable to those in the current experiment yield effects of only 20–40 ms (Hyönä, et al., 2004). While the preview effects observed here were slightly larger than observed in previous within-word boundary change experiments (Juhasz et al., 2009), this is probably because our words were somewhat shorter. Also, it may be more appropriate to talk about 'preview disruption' rather than 'preview benefit' as the incorrect preview – especially in the monomorphemic condition – obviously slowed down our participants.

The pattern of results can be explained by the following account. First, it would be magic for readers to instantly know that a word is a compound when landing on it. Thus, there must be an initial period in which this determination is made in which all the letters are processed to some extent, but once it is determined that the word has two constituents[7], the cognitive system focuses attention on the initial constituent and the decision to move the eyes off this constituent is based solely on whether that constituent has been encoded. When the reader shifts attention to encode the second constituent, however, the fact that incorrect letters were processed during the initial period of fixating the word produces interference. This contrasts, in a serial processing model, with the processing of parafoveal information from the next word, where no significant letter processing occurs until processing of the fixated word is completed. Moreover, as processing of the compound involves more than identification of the constituents, one would also expect greater interference from early arrival of incorrect letters. This pattern, of course, also differs from that of monomorphemic words, where all the letters are likely to be processed in parallel as soon as the word is fixated, and thus the disruptive effect of the incorrect letters in the partial preview condition is much greater. Thus, the results are consistent with the E-Z

Reader model (Reichle et al., 2003) in which attention and lexical processing shift in a serial fashion from one word/constituent to the next.

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Footnotes

1. Consistent with the literature, the term ‘parafoveal preview’ is used although due to the proximity of the 2nd constituent, it often will fall in foveal vision.
2. Juhasz (2008) and Juhasz et al. (2009) examined compound processing in English, whereas the other studies in this paragraph examined Finnish compounds. Juhasz (2008) found that short English words are decomposed into their constituents during processing.
3. The reported means are calculated from the beta estimates of the lmer analysis; minor differences can occur between these effect sizes and those obtained from the contrast analyses.
4. The main effect was, at best, marginally significant in measures on the 1st constituent (or corresponding letters in the monomorphemic words), but significant in later measures (gaze duration on the 2nd part of the word and on the entire word).
5. All contrasts for measures on the 2nd part of the word and gaze duration on the entire word were significant for compounds and monomorphemic words (all $ps<.001$).
6. This could also be considered compatible with the numeric trend for a PoF effect observed in go-past time for the first constituent of the compound words, although this effect was far from being statistically significant.
7. A plausible mechanism for detecting that the word is a compound is identifying the first 40-60% of the word as a lexeme that is the first part of at least one compound word.

Appendix

Stimuli used in the experiment. The unspaced compound is always listed before the monomorphemic word. Incorrect previews were created by replacing the characters of the 2nd lexeme, creating an orthographic illegal preview, but preserving the identity of the first two letters (e.g. *baseball* becomes *basebakh* and *conflict* becomes *conflimh*). Ascenders and descenders were respected creating a visual similar preview. The characters that were changed in the compound were also changed in the corresponding letters of the monomorphemic word to create the partial preview for those words.

1. A lot of people write about baseball/conflict using lots of statistics and charts.
2. On the computer screen was a picture of a watermelon/chimpanzee to brighten up his workspace.
3. Charles announced that he was going to the bathroom/fountain to wash his hands.
4. Barbara was convinced the moonlight/champagne added to the romantic character of the evening.
5. The documentary was about the preservation of the remaining wildlife/elephant in the national park.
6. There were no further details specified in the handbook/brochure even though it should have had them.
7. To pass the time, he had brought a paperback/catalogue to read in the waiting room.
8. Bob succeeded in becoming the preferred bodyguard/architect for the president of the company.
9. Because of his peculiar habits, the shy roommate/bachelor was opposed to a new person in the house.
10. She had heard a lot of bad stuff about the new cookbook/sergeant but she didn't believe the rumors.
11. The first thing Bill visited was the famous riverside/cathedral where he took a lot of pictures.
12. After consulting the checklist/colleague the commission decided that no error was made.
13. On the table was the notebook/cassette which contained his diary.
14. Everybody agreed the mechanic was missing the backbone/cylinder to finish the job.
15. During his time ashore he was accompanied by his girlfriend/lieutenant and they did some sightseeing.
16. They walked until they came to the beginning of the railroad/savannah where they made camp.
17. On the bottom of the ocean was the precious pipeline/treasure well out of everybody's reach.
18. Bert was complaining that he had too much homework/caffeine and that he couldn't go to bed.
19. The wall was a lot prettier with the sunlight/graffiti on it so they decided to keep it.
20. After the battle, he received orders to return to the mainland/fortress and await further instructions there.

21. In the harbor there was a sailboat/carousel which had been there for over a century.
22. The neighbors were always complaining about the sound of the doorbell/mandolin and they were thinking of taking legal action.
23. The police investigation established that the campfire/cannibal was responsible for the forest fire.
24. There was an urgent need for the restoration of the woodwork/pavilion but there was not enough money.
25. Tim was hit on the head by a snowball/cucumber thrown by his own wife.
26. Because Jane had forgotten her swimsuit/trombone she could not attend the practice.
27. No further information on the incident was given in the workshop/bulletin even though a lot of people were curious about it.
28. Adrian was not certain how to assemble the workbench/apparatus so he had to call the helpline for instructions.
29. Because of the awful sandstorm/avalanche everybody was being evacuated from the nearby towns.
30. There was an illustrated guide on the bookshelf/labyrinth which he wanted to show to George.
31. It was Raymond's first visit to the courtroom/synagogue and he was impressed by the grandeur of the architecture.
32. Even though she tried to hide it, it was obvious Lucy was suffering more from her headache/handicap than she was letting on.