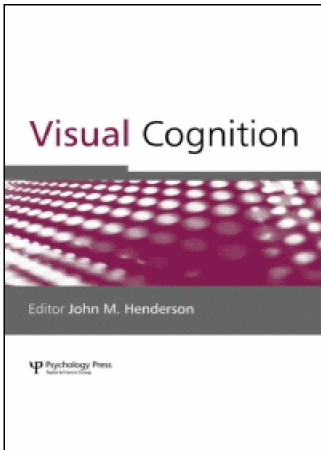

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Parafoveal processing in reading: Manipulating **n**+1 and **n**+2 previews simultaneously

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Parafoveal processing in reading: Manipulating $n+1$ and $n+2$ previews simultaneously

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The boundary paradigm (Rayner, 1975) with a novel preview manipulation was used to examine the extent of parafoveal processing of words to the right of fixation. Words $n+1$ and $n+2$ had either correct or incorrect previews prior to fixation (prior to crossing the boundary location). In addition, the manipulation utilized either a high or low frequency word in word $n+1$ location on the assumption that it would be more likely that $n+2$ preview effects could be obtained when word $n+1$ was high frequency. The primary findings were that there was no evidence for a preview benefit for word $n+2$ and no evidence for parafoveal-on-foveal effects when word $n+1$ is at least four letters long. We discuss implications for models of eye-movement control in reading.

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An important debate with far-reaching theoretical implications for eye-movement control and lexical processing in reading has recently emerged regarding the spatial extent of the influence of parafoveal words on the processing of the (1) currently fixated word and (2) lexical processing of upcoming (i.e., parafoveal) words in reading. The theoretical issue at stake is whether words are assumed to be processed serially or in parallel in the perceptual span. There are two types of parafoveal-on-foveal effects: Orthographic and lexical. While it is generally agreed that orthographic effects are reliable, there is some controversy over the reliability of lexical parafoveal-on-foveal effects (mostly indicated by the counted frequency of words). Moreover, the validity of lexical parafoveal-on-foveal effects is under considerable dispute (see Kennedy, Pynte, & Ducrot, 2002; Kliegl, 2007; Kliegl, Nuthmann, & Engbert, 2006; Rayner & Juhasz, 2004; Rayner, Pollatsek, Drieghe, Slattery, & Reichle, 2007b).

Aside from parafoveal-on-foveal effects there is a second type of effect related to parafoveal preprocessing during reading: Preview benefit effects (which are well-established and not at all controversial, see Rayner, 1998, for a review). Preview benefit effects are measured via a gaze-contingent display change technique referred to as the boundary paradigm (Rayner, 1975). In boundary paradigm experiments, prior to fixating on a target word the reader is provided with either a valid or invalid preview of the target word. When the reader's eye movement crosses an invisible boundary location, the preview changes to the target word. The amount of preview benefit is determined by subtracting the fixation time on the target word when there was a valid preview from when there was an invalid preview. Generally, it is assumed that preview benefit effects are due to sublexical processing as orthographic and phonological codes primarily serve as the basis for such effects (Rayner, 1998).

A difference between serial and parallel processing is implemented in the two major computational models of eye movement control in reading: The E-Z Reader model (Pollatsek, Reichle, & Rayner, 2006; Reichle, Pollatsek, Fisher, & Rayner, 1998) and the SWIFT model (Engbert, Nuthmann, Richter, & Kliegl, 2005). On the one hand, according to serial attention shift (SAS) models like E-Z Reader, lexical processing of words in reading occurs in a strictly serial manner. Thus, words n, $n+1$, and $n+2$ are processed in that order, and while E-Z Reader predicts preprocessing for word $n+1$ (while the reader is fixated on word n), the preprocessing of word $n+2$ would occur only in very specific cases such as when word $n+1$ is intended to be skipped (McDonald, 2006; Rayner, Juhasz, & Brown, 2007a). In general, E-Z Reader does not predict a preview benefit for word $n+2$.

On the other hand, guidance by attentional gradient (GAG) models like SWIFT propose that all words in parafoveal vision are processed simultaneously, though at different speeds depending on their distance from fixation. Thus, such models allow for parafoveal preprocessing to extend beyond word $n+1$. In principle, SWIFT does allow for such influences due to its target selection mechanism (i.e., preprocessing to the right of fixation affects refixation probabilities and distributions of fixation durations, see Engbert et al., 2005; Risse, Engbert, & Kliegl, in press). Moreover, in general, but not under all circumstances, SWIFT predicts preview benefits for word $n+1$ and word $n+2$, if they fall into the perceptual span (McConkie & Rayner, 1975). Indeed, the dynamics of the model (e.g., the rise and fall of lexical activity representing word processing) may cancel such effects (Kliegl, Risse, & Laubrock, 2007; Risse et al., in press).

A number of studies have recently examined parafoveal-on-foveal effects and the extent to which there is a preview benefit for word $n+2$. First, Rayner et al. (2007a) found standard preview benefits for word $n+1$, but no evidence of preview benefit for word $n+2$ and no evidence of parafoveal-on-foveal effects. Second, Kliegl et al. (2007) likewise found no preview benefit for word $n+2$, but they did obtain parafoveal-on-foveal effects of the lexical status of word $n+1$ and of preview of word $n+2$ on word n. Furthermore, they reported an effect of $n+2$ preview on fixation times on word $n+1$. This could be considered a preview benefit, even if it occurred on an earlier fixation. Third, Risse et al. (in press) reported similar effects of $n+2$ frequency on fixation times on word n in a corpus analysis. These effects were only significant when word $n+1$ was two to three letters long and word $n+2$ was not longer than four letters. Finally, Yang, Wang, and Rayner (2007) found parafoveal-on-foveal effects when they manipulated the preview of Chinese single-character and two-character words in the $n+2$ position. None of these results, however, rule out that the effects are caused by mislocated fixations (in this case failed attempts at skipping word $n+1$), which would make the observed parafovea-on-foveal effects compatible with E-Z Reader model predictions as well.

In the experiment reported here, we utilized the boundary paradigm (Rayner, 1975) and manipulated the preview information available from words $n+1$ and $n+2$ such that:

(1) accurate previews were available for both words,
(2) an accurate preview was available for word $n+2$ (but not $n+1$),
(3) an accurate preview was available for word $n+1$ (but not $n+2$), or
(4) inaccurate previews were presented for words $n+1$ and $n+2$.

Comparisons between the second condition and the fourth condition provided a test of the mislocated fixations account mentioned above. Complete preprocessing of word $n+1$ is impossible before the boundary is crossed in both of these conditions. However, in the second condition it is theoretically possible for word $n+2$ to be preprocessed. Critically, only parallel models would predict this preprocessing of word $n+2$. Serial models move attention away from a word only after it has been completely processed and are therefore unable to make such a prediction. In addition, the frequency of word $n+1$ was manipulated. When word $n+1$ was high frequency, readers might be more likely to obtain useful information from $n+2$ in comparison to when word $n+1$ was low frequency.

METHOD

Participants

Thirty-two undergraduate students at the University of Massachusetts at Amherst participated in the study. They either received extra course credit or \$10.00 for their participation. They all had either normal or corrected to normal vision, and they were all naïve concerning the purposes of the experiment.

Apparatus

Eye movements were recorded via an SR Eyelink1000 eyetracker, which sampled the eye position every millisecond. Viewing was binocular, but only the right eye was recorded. Participants read sentences on an NEC Multisync FP1370 video monitor. The display change was implemented in 5–7 ms from when the reader's eye movement crossed the boundary location; thus the display change typically occurred during the saccade (when vision is suppressed). The participants' eyes were 61 cm from the video monitor and 3.8 letters equalled one degree of visual angle.

Materials and procedure

Participants read 10 practice sentences and 152 experimental sentences. In each sentence there were three critical words: word n, $n+1$, and $n+2$. Table 1

TABLE 1
Length and frequency information for the three critical words

Critical word	*Min–max length*	*Mean length*	*Mean freq. per mio. (CELEX)*
N	3–13	7	177
$N+1$	4–10	6	high freq.: 178, low freq.: 5.8
$N+2$	3–13	7	185

		N	N+1	N+2	
Both identical:	The book was a	fairly	common	example	of postmodernist thought.
(N+1)-nonword:	The book was a	fairly	asunsw	example	of postmodernist thought.
(N+2)-nonword:	The book was a	fairly	common	snzxqfz	of postmodernist thought.
(N+1/N+2)-nonword:	The book was a	fairly	asunsw	snzxqfz	of postmodernist thought.

Figure 1. Examples of the four conditions in the experiment prior to the display change. When the reader's eye movement crossed over the invisible boundary (located after the last letter in word *n*), the incorrect previews changed to the correct target word. Thus, following the display change "common example" was present in locations $n+1$ and $n+2$, respectively.

shows the properties of these critical words. Whereas words *n* and $n+2$ were identical across conditions, word $n+1$ was either a high or low frequency word (and the two words never differed in length by more than one character); frequency was determined from the CELEX count.

The gaze contingent boundary paradigm (Rayner, 1975) was used to present either identical or nonword previews of word $n+1$ and $n+2$. The previews were replaced by the target words once the participant moved his/her eyes across an invisible boundary which was located after the last letter of word *n*. The nonword previews were generated by randomly replacing letters of the target words with alternative letters, keeping word shape intact. As described above, there were four preview conditions (see Figure 1):

(1) The preview was correct for words $n+1$ and $n+2$ (both identical condition),
(2) the preview was correct for word $n+2$, but incorrect for word $n+1$ (($n+1$)-nonword condition),
(3) the preview was correct for word $n+1$, but incorrect for word $n+2$ (($n+2$)-nonword condition), and
(4) the preview was incorrect for words $n+1$ and $n+2$ (($n+1/n+2$)-nonword condition).

In addition to that, there were two $n+1$ frequency conditions:

(1) Word $n+1$ was a high frequency word,
(2) word $n+1$ was a low frequency word.

Participants pressed a button box to indicate that they had finished reading. After 58 of the sentences, they were asked a comprehension question, which appeared on the video monitor; three alternative answers were provided for each question and participants responded by pressing the appropriate button.

RESULTS

First pass fixation times on the three critical words were analysed, as were other relevant measures (probability of first pass fixation, number of fixations, landing position, and launch site). Trials in which there were tracking errors or invalid display changes were eliminated (7% of the data), as were all fixations shorter than 80 ms (0.29% of the data) or longer than 800 ms (1.65% of the data). Participants answered the comprehension questions correctly 90% of the time. We will first report the fixation time measures and then other eye movement measures.

Fixation time measures

For each of the three critical words, a 2 ($n+1$ word frequency: high, low) $\times$ 4 (preview condition: Both identical, ($n+1$)-nonword, ($n+2$)-nonword, ($n+1$/$n+2$)-nonword) analysis of variance (ANOVA) was computed based on participant (*F1*) and item (*F2*) variability. First fixation duration (the duration of the first fixation on a word; FFD), single fixation duration (cases when only one fixation is made on a word; SFD), and gaze duration (the sum of all fixations on a word prior to moving to another word; GD) were computed.

Word n. For FFD, SFD, and GD (see Table 2), neither of the main effects nor the interaction approached significance (with *F*s generally < 1 and *p*s $> .09$). Thus, the correctness of the preview, the frequency of word $n+1$, and correctness of the preview of word $n+2$ did not influence fixation

TABLE 2
Fixation time measures for word *n* (standard deviations are in parentheses)

	Both identical	*(N+1)-nonword*	*(N+2)-nonword*	*(N+1/N+2)-nonword*
First fixation duration (*N*+1 frequency)				
High	232 (34)	226 (31)	225 (33)	230 (30)
Low	226 (29)	229 (32)	227 (27)	229 (36)
Mean	229 (32)	228 (32)	226 (30)	230 (33)
Single fixation duration (*N*+1 frequency)				
High	237 (40)	233 (34)	232 (40)	237 (34)
Low	230 (35)	235 (35)	231 (32)	234 (41)
Mean	234 (38)	234 (35)	231 (37)	235 (38)
Gaze duration (*N*+1 frequency)				
High	288 (67)	278 (58)	279 (59)	288 (61)
Low	284 (61)	288 (59)	278 (64)	297 (69)
Mean	286 (65)	283 (59)	278 (62)	292 (66)

TABLE 3
Fixation time measures for word $n+1$ (standard deviations are in parentheses)

	Both identical	*(N+1)-nonword*	*(N+2)-nonword*	*(N+1/N+2)-nonword*
First fixation duration ($N+1$ frequency)				
High	244 (41)	265 (43)	241 (36)	267 (55)
Low	261 (39)	285 (45)	266 (48)	284 (52)
Mean	252 (41)	275 (45)	254 (45)	275 (55)
Single fixation duration ($N+1$ frequency)				
High	248 (47)	280 (44)	247 (36)	283 (46)
Low	269 (41)	313 (49)	281 (62)	319 (72)
Mean	259 (46)	296 (50)	249 (46)	301 (64)
Gaze duration ($N+1$ frequency)				
High	274 (55)	316 (76)	273 (47)	320 (91)
Low	306 (60)	361 (94)	323 (63)	358 (84)
Mean	290 (60)	338 (89)	298 (62)	339 (91)

time on word *n*. We also examined the duration of the fixation prior to crossing the boundary location, and there were no differences between conditions (with means ranging between 219 ms and 224 ms). Thus, there was no evidence of any parafoveal-on-foveal effects.

Word $n+1$. There were significant main effects of preview and $n+1$ frequency in all three measures (see Table 3) with no interaction between the two variables (with *F*s generally < 1 and *p*s $> .22$). Specifically, low frequency words received 20 ms longer FFDs, $F1(1, 31) = 50.79$, $p < .001$, $F2(1, 151) = 43.19$, $p < .001$, 33 ms longer SFDs, $F1(1, 31) = 55.94$, $p < .001$, $F2(1, 114) = 104.15$, $p < .001$, and 42 ms longer GDs, $F1(1, 31) = 87.79$, $p < .001$, $F2(1, 151) = 79.41$, $p < .001$, than high frequency words. The main effect of preview was highly significant in all three measures: 23 ms FFD, $F1(3, 93) = 11.54$, $p < .001$, $F2(3, 453) = 15.55$, $p < .001$, 43 ms SFD, $F1(3, 93) = 25.28$, $p < .001$, $F2(3, 342) = 15.56$, $p < .001$, and 49 ms GD, $F1(3, 93) = 16.18$, $p < .001$, $F2(3, 453) = 27.29$, $p < .001$. Paired sample *t*-tests revealed highly consistent effects; specifically, there were significant differences between the identical preview condition versus the both different nonword preview condition and the $n+1$ nonword preview condition (all *p*s $< .01$). There was no significant difference between these two latter conditions. Likewise, there were no differences between the identical preview condition and the $n+2$ nonword preview condition.

Word $n+2$. The only consistently reliable effect was that of the frequency of word $n+1$ (see Table 4): 14 ms FFD, $F1(1, 31) = 19.02$, $p < .001$, $F2(1, 146) = 24.4$, $p < .001$, 20 ms SFD, $F1(1, 31) = 25.71$, $p < .001$,

TABLE 4
Fixation time measures for word $n+2$ (standard deviations are in parentheses)

	Both identical	*(N+1)-nonword*	*(N+2)-nonword*	*(N+1/N+2)-nonword*
First fixation duration ($N+1$ frequency)				
High	233 (31)	241 (38)	238 (35)	239 (34)
Low	245 (39)	258 (51)	248 (46)	253 (41)
Mean	239 (36)	249 (46)	243 (41)	246 (38)
Single fixation duration ($N+1$ frequency)				
High	237 (33)	242 (38)	242 (37)	241 (34)
Low	253 (43)	266 (55)	257 (52)	265 (48)
Mean	245 (39)	254 (49)	249 (46)	253 (44)
Gaze duration ($N+1$ frequency)				
High	275 (53)	280 (50)	278 (50)	273 (46)
Low	292 (54)	301 (53)	293 (56)	298 (58)
Mean	284 (54)	290 (53)	285 (54)	286 (54)

$F2(2, 119) = 26.07$, $p < .001$, and 20 ms GD, $F1(1, 31) = 25.32$, $p < .001$, $F2(1, 146) = 25.19$, $p < .001$. This apparently reflects a spillover effect (Rayner, 1998) from word $n+1$ to word $n+2$. None of the paired sample *t*-tests indicated any significant difference between preview conditions.

Other eye movement measures

In addition to the fixation time measures, we also examined:

(1) The probability of a first pass fixation on each of the critical words,
(2) the number of fixations on the critical words, and
(3) the landing position and launch site of saccades with respect to the critical words.

For words *n* and $n+2$, there were no differences among the conditions in terms of the probability of a first pass fixation on the word (with means ranging between .92 and .94). For word $n+1$, there were reliable effects of frequency, $F1(1, 31) = 8.08$, $p < .001$, $F2(1, 151) = 6.0$, $p < .05$, and preview, $F1(3, 93) = 9.72$, $p < .01$, $F2(3, 453) = 9.82$, $p < .001$. Consistent with prior research (Rayner, Sereno, & Raney, 1996), readers were more likely (ps $< .01$) to fixate a low frequency word (.95) than a high frequency word (.92). And, paired *t*-tests (ps $< .01$) revealed that readers were more likely to fixate word $n+1$ when it had an incorrect preview (.96) than when it had a correct preview (.91).

The number of fixations on the word did not differ across conditions for word *n* (with all conditions averaging 1.1 to 1.2 fixations) or word $n+2$ (with all conditions averaging close to 1.1 fixations). However, the number of fixations on word $n+1$ differed as a function of frequency and preview (all ps $< .001$); high frequency $n+1$ words received 1.13 fixations while low frequency words received 1.26 fixations. The number of fixations on the identical (1.11) and $(n+2)$-nonword (1.14) preview conditions differed from those on the $(n+1/n+2)$-nonword preview condition (1.27) and the $(n+1)$-nonword preview (1.27) condition (ps $< .01$).

Finally, the landing position in word $n+1$ was influenced by the type of preview, $F1(3, 93) = 13.37$, $p < .001$, $F2(3, 453) = 7.48$, $p < .001$, but not by frequency (ps $> .11$). As with the other measures discussed in this section, the $n+1$ landing position in the identical condition (3.35 letters into the word) did not differ from the $(n+2)$-nonword condition (3.37), and both identical and $(n+2)$-nonword conditions differed (ps $< .01$) from the $(n+1/n+2)$-nonword preview (3.1) and the $(n+1)$-nonword preview (3.06) conditions, which did not differ from each other.

Power statistics

We computed post hoc power statistics for the frequency effect and three contrasts on all three target words from simulations based on linear mixed-effects estimates of between-participant, between-item, and residual variances and taking also into account the proportion of lost data (Gelman & Hill, 2007). We simulated log-transformed data with effect sizes of 7 ms for FFD and 14 ms for GD. With one exception, power estimates based on 5000 simulations each were all larger than .72 for FFDs and .95 for GDs (i.e., effect of frequency and contrasts for $(n+1/n+2)$-nonword preview vs. $(n+1)$-nonword preview and both identical vs. $(n+2)$-nonword preview); estimates for the contrast for $(n+1/n+2)$-nonword preview and $(n+1)$-nonword preview vs. both identical and $(n+2)$-nonword preview ranged only between .45 and .82. Using log-transformed data and linear mixed-effects models yielded the same effects as using traditional ANOVA methods; thus, we only reported the results of the latter in this paper.

DISCUSSION

In the present study, we found clear evidence of an $n+1$ preview benefit effect as well as an effect of $n+1$ frequency on $n+1$ fixation times. This replication of the standard preview benefit and frequency effects (see Rayner, 1998, for review) clearly demonstrates the validity of the novel paradigm used in the present study. However, we failed to find evidence for either an $n+2$ preview benefit effect or any parafoveal-on-foveal effects. As with the results of McDonald (2006) and Rayner et al. (2007a), at a general level, these results appear to be more consistent with SAS model predictions than with those of GAG models.

It is important to note, however, that parafoveal-on-foveal and preview effects associated with word $n+2$ could be related to the length of word $n+1$. In the present study and in Rayner et al. (2007a) word $n+1$ was always at least four letters long, reducing the skipping probability for word $n+1$ but at the same time possibly moving $n+2$ out of the perceptual span. Kliegl et al. (2007) may have found parafoveal-on-foveal effects of word $n+2$ preview only because word $n+1$ was always three letters long in their experiment. In a corpus analysis, Risse et al. (in press) found an $n+2$ frequency effect on single fixation durations only when word $n+1$ was two or three letters long and at the same time word $n+2$ was not longer than four letters. Finally, Radach, Glover, and Vorstius (2007) recently reported an experiment quite similar to ours, but with three-letter words $n+1$. They obtained preview benefits for word $n+2$ in the $n+2$-mask and $n+1/n+2$-mask conditions for all duration measures as well as small parafoveal-on-foveal effects in the $n+1/n+2$-mask condition for gaze duration and total viewing time. Therefore, it appears that $n+2$ preview effects can be observed, but only when word $n+1$ is not longer than three letters. Another possible issue with the design might be the availability of $n+2$ preview while $n+1$ is fixated. This arguably constitutes a qualitative difference in the preview manipulations, since $n+2$ can always be preprocessed before it is fixated, whereas $n+1$ cannot.

What are the implications of these results for computational models? Serial models handle the present set of results, but the case is still open for short words $n+1$. The fact that there are $n+2$ effects (even if only for very short words $n+1$) can be considered consistent with parallel distributed processing. In this case, from the perspective of parallel processing, the acuity limits of the perceptual span (McConkie & Rayner, 1975) appear to force a seriality of lexical processing for medium and long words. Of course, distributed processing may be even less extensive than parallel distributed processing within acuity limits would suggest. These questions can be profitably addressed in future research and will help to constrain computational models. The present study, even with its null effects for the theoretically motivated questions, suggests clear limits for parafoveal processing once word $n+1$ is of medium length.

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