Parafoveal processing of word n+2 during reading:

Do the preceding words matter?

Bernhard Angele and Keith Rayner

Department of Psychology

University of California, San Diego

Correspondence to:

Bernhard Angele

Department of Psychology

University of California, San Diego

9500 Gilman Drive #0109

La Jolla, CA 92093-0109

Email: bangele@ucsd.edu

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Abstract

The boundary paradigm (Rayner, 1975) was used to test two hypotheses that might explain why there is no conclusive evidence for the existence of n+2 preprocessing effects. In Experiment 1, we tested whether parafoveal processing of the second word to the right of fixation (n+2) only takes place when the preceding word (n+1) is very short (Angele, Slattery, Yang, Kliegl & Rayner, 2008); word n+1 was always a three-letter word. Prior to crossing the boundary, preview for both words n+1 and n+2 was either incorrect or correct. In a third condition only the preview for word n+1 was incorrect. In Experiment 2, we tested whether word frequency of the preboundary word (n) had an influence on the presence of preview benefit and parafoveal-on-foveal effects. Additionally, Experiment 2 contained a condition in which only preview of n+2 was incorrect. Our findings suggest that effects of parafoveal n+2 preprocessing are not modulated by either n+1 word length or n frequency. Furthermore, we did not observe any evidence of parafoveal lexical preprocessing of word n+2 in either experiment.

Keywords: Parafoveal processing, reading, eye-movement control, preview benefit, parafoveal-on-foveal effects

A major debate in the study of eye movements in reading concerns the question of how attention is allocated during word identification and, consequently, how many words can be identified at the same time. This debate is reflected in the recent development of several competing computational models of eye movements in reading. A serial account of word identification (e.g. Reichle, Liversedge, Pollatsek & Rayner, 2008) assumes that readers obtain and process information about printed words in essentially the same way they process spoken words: they focus their attention (a "spotlight" as proposed by Posner, 1980) on one word at a time, process it, and then shift their attention to the subsequent word. This view is implemented in serial attention-shift (SAS) models such as E-Z Reader (Reichle, Fisher, Pollatsek, & Rayner, 1998; Reichle, Rayner & Pollatsek, 2006). While there are parallel components of E-Z Reader, lexical processing of words occurs in a serial fashion.

Conversely, proponents of parallel accounts of word identification (e.g. Kennedy & Pynte, 2008) posit that readers are able to distribute their visual attention (an "attentional gradient") over more than one word, and, consequently, process multiple words at the same time. Guidance by attentional gradient (GAG) models such as SWIFT (Engbert, Longtin & Kliegl, 2002; Engbert, Nuthmann, Richter & Kliegl, 2005) have been developed to implement parallel processing. In SWIFT, the current processing status of all words in the visual field is represented by a field of activation which is constantly updated over the course of processing. As in E-Z Reader, processing of each word takes place in two stages: During preprocessing, activation on a word increases until it reaches a threshold determined by its processing difficulty. This is followed by lexical completion, during which the activation on the word decreases until it reaches zero. The amount of activation on a word directly determines the probability that it will be the target of the upcoming saccade, which is triggered by a random timer (although the processing difficulty of the currently foveated word can cause a delay in triggering the next saccade). Processing speeds for each word are determined by eccentricity as well as processing difficulty. Since the activation of every word in the visual field is updated simultaneously, lexical processing of words in parafoveal vision in SWIFT is generally assumed to be the norm instead of the exception (which it is in E-Z Reader). How the meanings of multiple words can be processed and integrated simultaneously in GAG models is not fully clear. An alternative interpretation of parallel processing is that some processing which is independent of lexical processing (rather than lexical identification itself) occurs in parallel. This is perhaps a critical distinction that has not been fully addressed by proponents of GAG models. Our sense is that the latter is the case.

Both E-Z Reader and SWIFT do a good job of accounting fora variety of established phenomena in reading such as word frequency and predictability effects or costs of word skipping. Because of this, attempts to provide evidence for one or the other model have mostly focused on a small number of effects for which E-Z Reader and SWIFT make divergent predictions. One such class of effects, parafoveal-on-foveal effects, involves the properties of a word in the parafovea influencing the processing of the currently fixated word (as evidenced by the fixation times measured on that word). There is a considerable body of evidence for orthographic parafoveal-on-foveal effects, i.e. the effect of an unusual letter string in the parafovea on fixation times on the current word (e.g. Drieghe, Brysbaert, & Desmet, 2005; Pynte, Kennedy & Ducrot, 2004). Since such effects are at a sublexical level, however, they cannot be considered a valid test for models of lexical processing such as E-Z Reader and SWIFT. The reliability of lexical parafoveal-on-foveal effects (i.e. an effect of the word frequency of a parafoveal word on fixation measures on the current word), on the other hand, which would be a valid test for the models, is still being debated (see Rayner, 2009).

With respect to lexical parafoveal-on-foveal effects, the predictions of the two models are not clear-cut. In general, lexical parafoveal-on-foveal effects are not predicted by E-Z Reader. In contrast, SWIFT might be able to predict parafoveal-on-foveal effects, but only for certain fixation time measures such as gaze duration. In the following, we will discuss these predictions in detail. In SWIFT, only properties of the currently fixated word can influence fixation times directly through foveal inhibition. Therefore, SWIFT does not have a mechanism that would directly predict parafoveal-on-foveal effects. Since parafoveal processing of an upcoming word affects the relative activation level of the current word, SWIFT might, however, predict effects of lexical variables on refixation probability (and, consequently, gaze duration, Risse, Engbert & Kliegl, 2008). Also, it is worth noting that in its current version, SWIFT does not incorporate effects of orthographical regularity, although they would be easy to add to the model.

In contrast, E-Z Reader currently has no specific implemented mechanism (apart from mislocated fixations, see below) to account for parafoveal-on-foveal effects of any kind, be they orthographical or lexical. Despite this, the SAS account of lexical processing does not preclude the possibility that certain visual or even orthographical properties of the upcoming words might be processed early on in a parallel fashion. As a consequence, it would certainly be possible to include such early visual processing in the E-Z Reader model without violating its general premises. Indeed, E-Z reader includes a low-level attentional scan stage which could be influenced by unusual patterns in the parafovea. Lexical parafoveal-on-foveal effects, however, cannot, in principle, be accounted for in an SAS model – again, with the exception of mislocated fixation cases. Evaluating the presence or absence of such lexical effects is therefore critical in order to distinguish between serial and parallel accounts of word identification.

Given the inconclusiveness of parafoveal-on-foveal effects, a second test ground to distinguish between the models has revolved around preview effects. The parafoveal preview of a word during a prior fixation influences fixation times on that word itself once it is fixated. This influence, which yields a reduction in fixation times on the preprocessed word, is known as the parafoveal preview benefit effect. It is usually measured via the boundary paradigm (Rayner, 1975) in which a reader is presented with either a valid or an invalid preview of the target word while fixating to the left of the target word. Once the reader's eyes cross an invisible boundary between the pretarget and the target word, the preview is replaced by the target word. Since these gaze-contingent display changes occur during the saccade from the pretarget to the target, readers usually do not notice the changes due to saccadic suppression. Parafoveal preview benefit effects for the word to the right of fixation (word n+1) have been found in a large number of studies (see Rayner, 1998, 2009 for overviews). There is, however, also the possibility that readers can obtain a preview benefit from word n+2. While n+1 preview benefit effects are predicted both by E-Z Reader and SWIFT, preview benefit effects on the second word to the right of fixation (n+2) are only predicted by SWIFT (except for one scenario in E-Z Reader described next). In E-Z Reader, parafoveal preprocessing of word n+1 occurs whenever the lexical completion stage for the currently fixated word n finishes before the saccade programming stages initiate a saccade to n+1. In this situation, the attentional spotlight shifts to n+1 while the eyes remain on n. Preprocessing of word n+2 is much rarer in E-Z Reader. It is only possible when lexical processing for both word n and word n+1 can be completed before the saccade programming terminates. In this case word n+1 does not need to be fixated at all and a new eye movement to n+2 is programmed, skipping n+1. In SWIFT, parafoveal preprocessing takes place constantly for all words in the perceptual span including word n+1 and word n+2, although SWIFT predicts a smaller preview benefit on word n+2 due to its eccentricity.

Recently, a number of studies have attempted to examine the effects described above. Rayner, Juhasz and Brown (2007) used the boundary paradigm to manipulate the preview of a target word. They found a standard n+1 preview benefit effect but were unable to find either an n+2 preview benefit effect or parafoveal-on foveal effects. While Kliegl, Risse and Laubrock (2007) also did not find an n+2 preview benefit, they reported finding both a significant parafoveal-on-foveal effect of n+1 lexical status (content or function word) on first fixation and gaze durations on word n and an effect of n+2 preview availability on gaze durations on word n+1. Kliegl et al.'s findings might, however, be explained by mislocated fixations (Nuthmann, Engbert & Kliegl, 2005). Due to the saccadic range error long saccades often tend to fall short of their targets – they undershoot (McConkie, Kerr, Reddix, & Zola, 1988). It is therefore possible that the effects observed on word n+1 by Kliegl et al. were due to readers intending to skip word n+1 (and fixate on n+2), but undershooting their target and landing on n+1 instead. In this case, fixation times on n+1 actually reflect processing of word n+2. Such an explanation is compatible with E-Z Reader. A similar explanation could be applied to the apparent parafoveal-on-foveal effects found on word n, which might be caused by readers trying to fixate on word n+1 but undershooting and refixating word n instead (Drieghe, Rayner & Pollatsek, 2008).

In order to further examine n+2 preview effects and to eliminate the possibility of mislocated fixations leading to parafoveal-on-foveal effects, Angele, Slattery, Yang, Kliegl and Rayner (2008) used a variation of the boundary paradigm in which, prior to crossing the boundary to the right of word n, readers received either (1) correct previews for n+1 and n+2 (both correct), (2) an incorrect preview of n+1 and a correct preview of n+2 (n+1 incorrect), (3) a correct preview of n+1 and an incorrect preview of n+2 (n+2 incorrect) or (4) incorrect previews for both n+1 and n+2 (both incorrect). The comparison between the n+1 incorrect and the both incorrect conditions provided a critical test for n+2 parafoveal preview, since E-Z

Reader does not allow for skipping of an illegal letter string (lexical processing will not be able to terminate normally for a random letter string), making preprocessing of word n+2 in the n+1 incorrect condition impossible. Parallel models, on the other hand, do allow for the possibility of n+2 preprocessing even if n+1 processing has not terminated yet. Angele et al. (2008) found a standard n+1 preview benefit effect but were unable to find parafoveal-on-foveal or n+2 preview benefit effects.

Radach and Glover (2007) employed a similar paradigm and reported finding both n+2 preview benefit and lexical parafoveal-on-foveal effects. Furthermore, Risse and Kliegl (2010) found n+2 preview benefit effects and an effect of n+2 preview on word n+1 both in college-age and older readers. Why did Kliegl et al. (2007), Radach and Glover (2007), and Risse and Kliegl (2010) find effects when Angele et al. (2008) did not? One possible explanation might be the length of the n+1 words used in the studies. While Kliegl et al. (2007) and Radach et al. (2007) exclusively used three-letter words. Angele et al. (2008) used n+1 words that were on average six characters long. Because of this, n+2 might have been too far in the parafovea for any meaningful preprocessing to take place. While the Angele et al. (2008) study therefore establishes upper limits for the spatial extent of parafoveal preprocessing, it is still unclear how acuity constraints impact preprocessing at lower eccentricities. We tested this hypothesis in Experiment 1 by manipulating word type and frequency of word n+1 while using the same preview manipulation for word n+1 and n+2 as Angele et al (2008).

A second explanation for the diverging results described above concerns the properties of the pre-target word n. Specifically, the extent of parafoveal processing might not only be influenced by the properties of word n+1 but also by the properties of word n. The effect of foveal load caused by word n on preprocessing of word n+1 has been documented by Henderson and Ferreira (1990) as well as White, Rayner and Liversedge (2005), who manipulated word frequency (and, correspondingly, ease of processing) of word n. Both studies found reduced preview benefit on word n+1 when word n was a low frequency word (spillover effect). Foveal load might also limit the amount of preview that can be obtained from word n+2. Alternatively, a parallel processing model such as SWIFT might predict that by prompting longer fixations immediately to the left of the boundary, low frequency pre-target words could actually result in a higher amount of preprocessing than high frequency pre-target words. If either of these hypotheses is true, the choice of pre-target words in a given study might determine whether effects of n+2 preprocessing can be observed or not. In Experiment 2, we tested whether pre-target frequency can account for the divergence in results by directly manipulating the frequency of word n in addition to the preview manipulation utilized in Experiment 1.

Experiment 1

In Experiment 1, we used the same experimental procedure as in the Angele et al. (2008) study to manipulate preview information for very short (three-letter) n+1 words as well as word n+2. If parafoveal preprocessing of n+2 is indeed influenced by n+1 word length, we would expect to find a much stronger degree of preprocessing in this case. Importantly, while parallel models predict an influence of eccentricity on n+2 preview benefit and parafoveal-on-foveal effects, serial models predict no such effects even for extremely short n+1 words.

Radach's (1996) word grouping hypothesis represents a different approach to parafoveal processing. He proposed that an article and the subsequent noun might be processed as a perceptual unit. Because of this, parafoveal preprocessing of word n+2 might be restricted to cases where n+1 was an article. Drieghe, Pollatsek, Staub and Rayner (2008) attempted to replicate Radach's (1996) findings in an experimental design. However, their findings suggested that readers targeted the articles and the subsequent nouns separately. In this case, we would not expect increased parafoveal processing of words following articles. In the present experiment, we tested both of these possibilities.

Method

Subjects. Thirty-two undergraduate students at the University of California, San Diego participated in the experiment for course credit. All were native speakers of English, had either normal or corrected to normal vision, and were naïve concerning the purpose of the experiment. Data were collected from 14 additional subjects, but subsequently excluded from the analysis due to reasons described below.

Apparatus. An SR Research Eyelink 2000 eyetracker was used to record subjects' eye movements with a sampling rate of 2000 Hz (i.e. the eye position was sampled twice every millisecond). The experimental sentences were displayed on an Iiyama Vision Master Pro 454 video monitor with a refresh rate of 150 Hz. Subjects read binocularly, but only their right eyes were recorded. Viewing distance was approximately 60 cm, with 3.8 letters equaling one degree of visual angle. Custom designed software ensured that the display change occurred within 9 ms of a reader's gaze crossing the boundary.

Materials. 120 sentence frames featuring a succession of a verb (word n), the article the or a three letter word (word n+1), and a noun (word n+2) were used to create the experimental conditions. Sixty of the sentence frames were taken from Drieghe, et al. (2008) and sixty more were newly created. In the three-letter word condition, word n+1 was a high frequency three-letter word (either two, one, old, his, her, new or all) instead of the article the. Fifty University of California, San Diego undergraduates who participated for course credit provided norming data in order to ensure that articles and non-article three-letter words fit the sentence frames equally well. Table 1 shows length and frequency (determined from the CELEX count using the N-Watch software, Davis 2005) of the critical words n, n+1 and n+2.

INSERT TABLE 1 ABOUT HERE

Using the gaze contingent boundary paradigm (Rayner, 1975) readers were presented with either identical or nonword previews of word n+1 and n+2 prior to fixating the target word. Once readers crossed the invisible boundary located immediately to the right of word n, the previews were replaced by the target words. The nonword previews were generated using the same algorithm employed in Angele et al. (2008) and Kliegl et al. (2007), replacing n+1 and n+2 with randomly chosen letters while keeping the word shape intact. In total, there were three preview conditions (see Table 2): (1) Preview was either available for both n+1 and n+2, (2) preview was denied for word n+1, but available for word n+2, or (3) preview was denied both for word n+1 and n+2.

INSERT TABLE 2 ABOUT HERE

Procedure. After receiving the experimental instructions participants read 10 practice sentences without display changes. They were then presented with the 120 experimental sentences embedded in 48 filler sentences in random order. Approximately 33% of the sentences were followed by a two-alternative forced choice comprehension question which participants answered by pressing the button corresponding to the correct answer on a button box. After the experiment, participants were asked whether they had noticed anything unusual during the experiment. If participants confirmed this and reported seeing a display change, they were asked to give an estimate of the number of changes they had seen. The 14 excluded subjects reported seeing more than three changes. Because of this, their data were discarded from the subsequent analysis (leaving 32 subjects as noted above). This high exclusion rate is likely due to the size of the display change region (two words). The Angele et al. (2008) study, which featured even larger display change regions, reported similar exclusion rates.

Results and Discussion

As in Kliegl et al. (2007), inferential statistics are reported based on a linear mixed-effects (lme) model with subjects and items as crossed random effects. This is necessary as high skipping rates in the the condition lead to unequal group sizes, reducing the statistical power of traditional ANOVA methods (Baayen, Davidson & Bates, 2008). In order to fit the lme models, the lmer function from the lme4 package (Bates, Maechler & Dai, 2008) was used within the R Environment for Statistical Computing (R Development Core Team, 2009); as in Kliegl et al. (2007), regression coefficients (b), standard errors and p values based on confidence intervals generated from the posterior distribution of parameter estimates using Markov Chain Monte Carlo methods (obtained from the mcmcsamp function contained in the lme4 package with default parameters) will be reported. For each measure, the initial models fitted included both the main effects of word n frequency and preview and their interaction. If the interaction term was not significant in a model, we fitted a restricted model without the interaction. In this case, the coefficients and p-values reported are from the restricted model rather than the full one.

For each of the critical words, we examined first pass fixation times as well as first-pass fixation probability and initial landing position. Trials with track losses or display changes that were not effectively implemented during the saccade were eliminated (6.6% of the data), as well as fixations shorter than 80 ms or longer than 800 ms (0.7% of the data). Subjects answered 94.5% of the comprehension questions correctly. The fixation time measures (see Rayner, 1998, 2009) computed included first fixation duration (the mean duration of the first fixation on a word, FFD); gaze duration (the mean sum of first fixations and subsequent refixations on a word, GD); single fixation duration (mean fixation time for all cases in which a word was fixated exactly once, SFD); and go-past time (also known as regression path duration: the mean time from the point when a word was first fixated to when a reader first moves his or her eyes past it).

Since there were three preview conditions, two orthogonal contrasts were used in the analysis. The first contrast compared the both correct condition to the mean of the n+1 denied and the both denied conditions and therefore represents the effect of word n+1 preview availability, while the second contrast compared the n+1 denied to the both denied condition and represents the effect of denying preview for word n+2 when word n+1 preview was denied as well. In order to make sure that the effects found in the models are not due to violations of normality, we fitted the models both for raw and log-transformed data. Since the pattern of effects was virtually identical for raw and log-transformed values (with one exception detailed below) we will report coefficients based on the raw data which are directly interpretable as differences between group means (adjusted for the other effects included in the model). The mean fixation times, fixation probabilities, and initial landing positions for the target words n, n+1 and n+2 are shown in Table 3.

INSERT TABLE 3 ABOUT HERE

Word n. There was a significant difference between the both identical and the masked preview conditions, i.e. an effect of n+1 preview availability, for gaze durations ($b = 6.196$, $SE = 2.701$, $p = 0.024$) as well as go-past times ($b = 12.575$, $SE = 4.055$, $p < .01$) with durations being longer in the masked conditions. A similar effect was observed on landing position, with fixations landing slightly further to the right when preview for word n+1 was denied ($b = 0.116$, $SE = 0.057$, $p = 0.046$). Since the preview manipulation introduced orthographically illegal letter strings into the parafovea, this effect is clearly driven by orthography and thus can be interpreted as an orthographical parafoveal-on-foveal effect. None of the other effects or interactions on fixation time measures reached significance, nor were there any significant main effects or interactions in a logistic lme analysis of fixation probability for word n (all $ps > .05$). In particular, there was no evidence of a parafoveal-on-foveal effect of n+1 word type on fixations on word n.

Word n+1. There was a highly significant effect of n+1 word type on all fixation time measures, with three-letter words being fixated longer than the (FFD: b = 20.53, SE = 2.79, p < .01; SFD: b = 22.98, SE = 2.88, p < .01; GD: b = 20.07, SE = 3.35, p < .01; Go-past: b = 36.84, SE = 6.075, p < .01). Mostly, this reflects the difference in word frequency and predictability between the definite article and other three-letter words, but it might also in part be a direct effect of word type. There also was a significant effect of n+1 preview availability (FFD: b = 7.558, SE = 2.148, p < .01; SFD: b = 9.145, SE = 2.209, p < .01 GD: b = 8.451, SE = 2.591, p < .01; Go-past: b = 18.308, SE = 4.695, p < .01), which can be considered a replication of the standard preview benefit effect (Rayner, 1975).

In gaze duration, there was also a significant interaction between n+1 preview availability and n+1 word type (b = 13.492, SE = 5.179, p = .01), to the point where the n+1 preview benefit effect was not present at all when n+1 was the and the main effect described above was driven exclusively by the strong preview effect on three-letter words. The same numerical pattern was present in first-fixation duration and single fixation duration on n+1, even though the corresponding interaction terms did not reach significance. The absence of any preview effect in the article condition might be a result of the high skipping rate in that condition. Alternatively, the processing of articles might be so easy that the availability of preview does not make a significant difference in fixation times on an article.

On fixation probability, the logistic lme analysis showed that three-letter words were fixated significantly more often than the article the (b = .63, SE = .079, p < .01). Additionally, word n+1 had a higher fixation probability when preview for it had been denied (b = .85, SE = .056, p < .01). In addition to this, the interaction between n+1 preview and word type was significant ($b = .86$, $SE = .11$, $p < .01$). This interaction is driven by the extremely low fixation probability for the definite articles (31%) when their preview had been available. Receiving a correct preview of the seems to almost automatically trigger skipping, while receiving a preview of another three-letter word or a mask is much more likely to prompt readers to fixate on that word. Whether the skipping of the definite article is truly automatic (as suggested by Gautier, O'Regan, & Le Gargasson, 2000) or just the result of extremely fast lexical access remains to be determined.

In contrast, when preview for n+2 had been unavailable (in addition to the n+1 mask), n+1 was less likely to be fixated than when preview for n+2 had been available and only n+1 had been masked ($b = -.28$, $SE = .097$, $p < .01$). It might be plausible to assume that the highly irregular n+2 letter string in the parafovea attracted fixations away from n+1. This could be seen as evidence of orthographic parafoveal preprocessing. Interestingly, a similar effect reached significance on landing position, with fixations landing slightly further to the right when n+2 preview had been denied along with n+1 preview ($b = .025$, $SE = .012$, $p = .044$). This effect might reflect readers' attention being attracted by the irregular orthographic information in the parafovea. However, it did not reach significance when log-transformed landing position was used as a dependent variable, thus it might be a spurious effect due to violations of normality assumptions.

Word n+2. There was a significant effect of n+1 preview on all fixation time measures, with fixation times being shorter when n+1 preview was denied (FFD: $b = -7.74$, $SE = 1.684$, $p < .01$; SFD: $b = -9.94$, $SE = 1.85$, $p < .01$, GD: $b = -10.212$, $SE = 2.441$, $p < .01$). A similar effect was observed on landing position, with fixations landing further to the right on n+2 when n+1 preview had been denied ($b = 0.161$, $SE = 0.064$, $p = 0.012$). Like the effect observed on word n+1, this effect may reflect a difference in saccade targeting when the parafovea contained an irregular letter string. For go-past time, the n+1 preview effect was only significant in the log-transformed analysis (b = -0.024, SE = 0.011, p = 0.037). This appears to be an issue of outliers in the raw data affecting the statistical power of the analysis. The fact that this effect is reduced or even reversed for three-letter words n+1 as evidenced by a significant interaction between n+1 preview and word type (FFD: b = 13.59, SE = 3.38, p < .01; SFD: b = 14.28, SE = 3.72, p < .01; GD: b = 15.54, SE = 4.91, p < .01, Go-past: b = 29.28, SE = 8.71, p < .01) points to it being caused by the high skipping probability in the both correct condition when n+1 was the article the. This would also explain the landing position effect: saccades from word n+1 are shorter than saccades from word n and thus should have a higher probability of ending up further inside word n+2. Finally, there was a significant effect of n+1 word type on n+2 fixation probability (b = -.46, SE = 0.12, p < .01), which is most likely due to the enhanced skipping probability when n+1 was the article the. Since readers very rarely skip two words in a row, the probability of skipping word n+2 is clearly much higher in trials where n+1 was fixated compared to trials where n+1 was skipped.

In summary, while we found the expected effects of word type and n+1 preview, we found no effects that would point to parafoveal lexical processing of more than one word to the right of the currently fixated word. The only measure that was affected at all by the availability of n+2 preview was the probability of making a fixation on word n+1, suggesting that an unusual letter string in the parafovea might attract fixations. This is, however, not a lexical effect.

Experiment 2

In Experiment 2, we tested whether properties of the pre-target word n influenced the extent of preprocessing of word n+2 (i.e. whether spillover from processing of word n extended to preprocessing of n+2). In order to do this we manipulated the frequency (and with it, processing difficulty) of word n. We used the same preview conditions as in Experiment 1, with the addition of a condition in which preview for word n+1 was available, but preview of word n+2 was denied. This condition corresponds to the designs used in Kliegl et al. (2007) and Radach and Glover (2007). Including this condition also allowed us to test directly whether the effects related to preprocessing of word n+2 found in those studies when preview for word n+1 was available can be explained by failed skipping of word n (i.e., mislocated fixations).

Method

Subjects. Thirty-two undergraduate students at the University of California, San Diego participated in the experiment for course credit or pay. All were native speakers of English, had either normal or corrected to normal vision, and were naïve concerning the purpose of the experiment. None of the subjects had participated in Experiment 1. Data were collected from 14 additional subjects, but subsequently excluded from the analysis due to reasons described below.

Apparatus. The apparatus was the same as in Experiment 1.

Materials. The materials consisted of 120 new sentence frames not used in Experiment 1, which featured a succession of a verb (word n), the article the (word n+1) and a noun (word n+2). In each sentence frame, word n could either be a low or a high frequency word.

We used the same preview manipulation as in Experiment 1, adding a preview condition in which the preview was correct for word n+1, but incorrect for word n+2 for a total of four preview conditions and two word n frequency conditions (see Table 4 for examples).

INSERT TABLE 4 ABOUT HERE

One hundred and twenty-nine University of California, San Diego undergraduates who participated for course credit provided norming data in order to ensure that high and low frequency words n fit the sentence frames equally well. Twenty-seven additional undergraduates recruited from the same population performed a cloze task for the sentence frames up to n. From the results, we calculated predictability norms for the high and low frequency versions of word n. Table 5 shows length and frequency (determined from the CELEX count using the N-Watch software, Davis 2005) of the critical words n, n+1 and n+2 as well as the predictability measure obtained from the cloze task.

INSERT TABLE 5 ABOUT HERE

Procedure. The procedure was identical to Experiment 1. Thirty-nine of the sentences were followed by a comprehension question. As in Experiment 1, subjects were asked whether they were aware of the display changes after the experiment. Thirteen of the 14 excluded subjects reported seeing more than three changes and their data were discarded from the subsequent analysis. In addition, the data for an additional subject who showed an exceptionally high proportion of late display changes (43%) were removed from the analysis, resulting in a total of 32 subjects included in the analysis as reported above.

Results and Discussion

As in Experiment 1, we examined first pass fixation times as well as first-pass fixation probability and landing positions for words n, n+1 and n+2. Trials with track losses or display changes that were not effectively implemented during the saccade were eliminated (14.1% of trials), as well as individual first-pass and go-past times shorter than 80 ms or longer than 800 ms (less than 0.5 % of the data). On average, subjects answered 93.2% (minimum: 84.6 %) of the comprehension questions correctly.

The data were analyzed in a fashion similar to Experiment 1: For each dependent variable (FFD, SFD, GD, go-past time, fixation probability and initial landing position), a linear mixed-effects (lme) model with subjects and items as crossed random effects and word n frequency (high vs. low) and n+1/n+2 preview conditions as fixed effects was fitted using the lmer function from the lme4 package. In order to determine how the dependent variables were influenced by the four preview conditions, we specified three contrasts. The first contrast compared the two preview conditions in which preview for n+1 was available with the two preview conditions in which it was unavailable. This contrast therefore reflects the standard n+1 preview benefit effect. The second contrast compared the two preview conditions in which preview for n+1 was available, i.e. it reflects the effect of n+2 preview availability when n+1 preview was unavailable. This contrast is theoretically important since it indicates whether processing on n+2 took place before n+1 processing had finished (processing of the random letter n+1 mask should not be able to complete normally). Finally, the third contrast compared the two preview conditions in which preview for n+1 was available, i.e. it reflects the effect of n+2 preview availability when n+1 preview was available as well. The inclusion of this comparison, which was absent from Experiment 1, enabled us to examine whether the presence of an n+1 mask in the parafovea had an effect on the processing of n+2. However, the comparison specified by the third contrast might be influenced by mislocated fixations stemming from attempted but failed skipping of the easily identifiable word n+1 which was always the definite article the.

As in Experiment 1, the initial models fitted included both the main effects of word n frequency and preview and their interaction, followed by a restricted model without the interaction if the interaction term was not significant in the full model. In this case, the coefficients and p-values reported are from the restricted model. Again, in order to make sure that the effects found in the models are not due to violations of normality, we fitted the models both for raw and log-transformed data. The pattern of effects was identical for raw and log-transformed values; therefore, we will report coefficients based on the raw data which are more easily interpretable. Table 6 shows the raw fixation time measures, fixation probabilities and landing positions for the three target words.

INSERT TABLE 6 AROUND HERE

Word n. As expected, all fixation time measures showed a strong frequency effect (FFD: b = 16.629, SE = 2.943, p < .01; GD: b = 27.541, SE = 3.869, p < .01; SFD: b = 19.683, SE = 3.134, p < .01; Go-past: b = 33.281, SE = 6.883, p < .01). Additionally, there was an orthographical parafoveal-on-foveal effect of n+1 preview availability on gaze durations (b = 28.409, SE = 7.766, p < .01), single fixation durations (b = 15.123, SE = 6.275, p = 0.018), and go-past times (b = 37.087, SE = 13.816, p < .01). This indicates that the presence of an orthographically unusual mask in place of the upcoming word caused readers to stay longer on the current word, and, consequently, that word n+1 was preprocessed at least at a sublexical level while readers were fixating word n. Finally, in a logistic lme model, there was a significant effect of word n frequency on fixation probability on word n (b = .35, SE = .12, p < .01). None of the other contrasts or interactions reached significance.

Word n+1. As expected, all fixation time measures showed the standard preview benefit effect, i.e. fixation times on word n+1 were longer when preview for n+1 had not been available (FFD: b = 28.989, SE = 6.717, p < .01, p < .01; SFD: b = 34.885, SE = 6.728, p < .01; GD: b = 39.605, SE = 7.435, p < .01; Go-past: b = 48.419, SE = 15.837, p < .01). Additionally, there was a significant spillover effect of word n on go-past times on word n+1 (b = 14.781, SE = 7.303, p = 0.043). Finally, go-past times on n+1 showed a significant effect of n+2 preview in those conditions where n+1 preview was available (b = 29.65, SE = 12.904, p = 0.02). This replicates Kliegl et al.'s (2007) findings of a delayed parafoveal-on-foveal effect on word n+1, albeit in a later fixation time measure. However, in the conditions where n+1 preview was unavailable, there was no effect of n+2 preview ($p > .05$), replicating the findings of Angele et al. (2008). This suggests that whether readers can preprocess word n+2 depends on whether they have the opportunity of preprocessing word n+1 as well.

As mentioned above, one possible explanation for this phenomenon may be that, if n+1 preview is available, readers frequently finish processing it while they are still fixating word n. As a consequence, they plan an eye movement directly to word n+2, skipping word n+1. Furthermore, these skipping saccades undershoot occasionally, resulting in a mislocated fixation on word n+1 which nevertheless is influenced by the properties of word n+2. In the case of the present study, it is entirely possible that making a saccade to the wrong word triggers a breakdown in processing, which then leads to readers making a regressive saccade, thus increasing go-past time on word n+1. Indeed, a logistic lme analysis showed that fixation probability on word n+1 was significantly affected by availability of preview for n+1 ($b= 2.92$, $SE = .16$, $p < .01$), with a higher probability of fixations on n+1 when it had been masked. The higher probability of skipping n+1 when preview for it had been available should also lead to a higher probability of failed skipping attempts, which fits in well with the hypothesis described above. Finally, on landing positions, there was a significant interaction between n+2 preview availability when n+1 preview was denied and word n frequency ($b = 0.313$, $SE = 0.13$, $p = 0.018$). Specifically, separate analyses showed that when word n was a high-frequency word, fixations landed further to the left of a previously masked word n+1 when word n+2 had been masked as well in the preview ($b = -.191$, $SE = .092$, $p = .045$). When n was a low-frequency word, this effect did not reach significance, and there was a nonsignificant trend in the opposite direction ($p > .05$). This effect is potentially interesting since it is the only effect of availability when n+1 preview was denied in Experiment 2 and the only effect on which word n frequency modulated a preview effect. This parafoveal-on-foveal effect seems to suggest that parafoveal orthographical information can influence the decision of where to fixate on a word to some degree; however, its small effect size makes it difficult to interpret.

Word n+2. As on word n+1, there was a significant spillover effect of word n frequency in all measures (FFD: $b = 9.72$, $SE = 2.826$, $p < .01$; SFD: $b = 8.73$, $SE = 3.173$, $p < .01$; GD: $b = 13.335$, $SE = 3.784$, $p < .01$; Go-past: $b = 30.937$, $SE = 7.169$, $p < .01$), indicating that the frequency of word n has an impact on processing even two words down the line. This effect was also present in landing position, with a low frequency word n resulting in fixations landing further to the left ($b = -.159$, $SE = .058$, $p < .01$). Furthermore, there was a significant effect of n+1 preview availability on word n+2 in all the measures (FFD: $b = -40.873$, $SE = 5.67$, $p < .01$; SFD : $b = -33.966$, $SE = 8.954$, $p < .01$; b GD: $b = -56.314$, $SE = 7.581$, $p < .01$; Go-past $b = -39.175$, $SE = 14.388$, $p < .01$). Notably, this effect is in the opposite direction compared to the effect of n+1 preview on fixation times on word n+1 itself: while fixation times on word n+1 were longer when its preview had been unavailable, the subsequent fixations on word n+2 were shorter. One explanation for this effect might be that the longer fixation times on word n+1 enabled readers to perform more preprocessing of word n+2 (the preview of which was always available at this point). Again, there was a corresponding effect on landing position, with fixations landing further to the right when preview for word n+1 had been denied. Importantly, we found a significant effect of n+2 preview when n+1 preview had been available on GD ($b = 12.338$, $SE = 5.442$, $p = 0.026$). This difference was not significant when n+1 preview had been denied ($p > .05$). This can be considered an n+2 preview benefit effect. However, fitting separate models for cases in which n+1 was skipped and for cases in which it was not shows that the n+2 preview benefit effect on GD was only significant if the fixation on n+2 had been preceded by skipping (n+1 skipped: $b = 15.42$, $SE = 6.438$, $p = 0.015$; n+1 fixated: $p > .05$) . This is consistent with the predictions of the E-Z Reader model.

Furthermore, there was a significant interaction between n+1 preview availability and word n frequency in SFD (b = -29.74, SE = 12.665, p = 0.019): If word n had been a low frequency word, single fixations on word n+2 were even shorter in those conditions where n+1 preview had not been available compared to those where it had been available. This effect is surprising and unexpected and it is not clear whether it is interpretable, since there was no interaction between word n frequency and n+1 preview availability on word n+1 itself. As with n+1, landing positions on n+2 showed an effect of word n+2 preview when n+1 had been masked, with first fixations landing further to the right when n+2 preview had been denied (b = 0.177, SE = 0.081, p = 0.031). This might be a consequence of the corresponding effect on word n+1. In any case, it can be considered a type of preview benefit effect, albeit on an orthographical level. Finally, there were no significant effects on n+2 fixation probability (all ps > .05).

Post-hoc analysis: Effects of n+2 frequency

In addition to the analyses described above, we also attempted to test whether the frequency of word n+2 had an influence on the degree to which it was parafoveally processed. In order to do this, we fitted an additional model for each measure described above containing the preview contrasts, log n+2 frequency as a continuous predictor, and the interactions between those factors. None of the interaction terms reached significance (all ps > .05), indicating that the frequency of word n+2 had no impact at all on the size of parafoveal preview benefit and parafoveal-on-foveal effects on the target words. An exception was the landing position analysis, which showed an interaction between log n+2 frequency and preview availability of n+2 when preview for n+1 had been available as well (b = -.112, SE = .053, p = .029). This potential lexical parafoveal-on foveal effect of n+2 may be caused by subsequent skipping of word n+1.

Indeed, when cases in which n+1 was skipped were removed from the analysis, the effect no longer reached significance.

General Discussion

In the present study, we were able to test two factors that might explain why some studies found evidence of parafoveal preprocessing of the second word to the right of fixation (i.e., n+2), while other studies found no such evidence. In Experiment 1, we investigated whether the properties, specifically word length and word type (the definite article the vs. high-frequency three-letter word), of the first word to the right of fixation (word n+1) influenced whether word n+2 could be processed parafoveally or not. Even when word n+1 was an the article the – arguably the word that can be identified with the least processing effort – we found no evidence of parafoveal lexical preprocessing of n+2, neither when n+1 was the definite article nor when it was a non-article 3-letter word.

In Experiment 2, we tested whether the amount of preprocessing of word n+2 was influenced by the frequency of word n. Again, we did not find any solid evidence of parafoveal n+2 processing, except in those conditions where parafoveal information about n+1 was available, so that it could be easily identified and subsequently skipped or attempted to be skipped. The only variable that showed some effects of n+2 preview even when n+1 preview was denied was landing position, although these effects might reflect low-level properties of the masks used rather than effects of lexical processing.

It is, of course, possible, that the extent of parafoveal processing of word n+2 is determined by a variable not systematically manipulated in this or any previous study. This study, therefore, does not demonstrate that readers never use parafoveal information from beyond an unidentified word n+1, or that they never process word n+1 and word n+2 at the same time. It does however show that readers, at least when reading English, do not seem to make use of parafoveally available information about word n+2 on a regular basis. This implies that parallel lexical processing is a fairly rare phenomenon in reading, with serial lexical processing being the default.

An alternative explanation might be that fixation times simply are not very reliable indicators of parafoveal preprocessing in reading beyond word n+1. In the face of a wealth of studies that demonstrate a clear link between word identification and fixation times (Rayner, 1998, 2009), that would be quite surprising. Experiment 2 did show some effects of word n+2 preview on landing positions on n+1 and n+2. It is not clear however what type of process would only affect landing positions while having no effect at all on fixation durations. One possibility is that saccade target selection is determined more by low-level characteristics such as orthographic regularity, while the decision when to move the eyes is influenced more by lexical processing. Nevertheless, it might be profitable for future studies attempting to distinguish between parallel and serial processing models to focus on different measures such as landing position. Additionally, the effects of different masks on fixation location should be studied.

In conclusion, despite providing near-optimal conditions for preprocessing, the present study did not find clear evidence for parallel modes of processing. On the contrary, the results of this study suggest that if parallel processing does exist, it is limited to very specific effects in very specific circumstances, with all other processing occurring serially by default.

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Acknowledgments

This research was supported by Grant HD26765 from the National Institute of Health. Portions of the data were presented at the 15th European Conference on Eye Movements (Southampton, UK, 2009). We thank Albrecht Inhoff and two anonymous reviewers for helpful comments on an earlier version of the paper. Correspondence should be addressed to Bernhard Angele, bangele@ucsd.edu.

Table 1

Experiment 1: Length and Frequency Information for the Three Target Words (Standard Deviations in Parentheses).

Target word	Min – max length	Mean length	Mean Word Frequency per million (CELEX)
n	3 – 10	7 (1.4)	56 (119)
n+1	3	3 (0)	Article (“the”): 62,281 (0) High frequency three-letter word: 2793 (1556)
n+2	3 – 11	7 (1.8)	57 (97)

Table 2

Experiment 1: Examples of the Three Preview Conditions Prior to the Display Change. After a participant's gaze position crossed the boundary located to the right of word n (dashed line), all incorrect previews changed to the correct words (i.e. the sentence appeared as it did in the "both available" condition).

Preview condition	n+1 word type condition	Sentence prior to display change Word n	n+1	n+2
Both available	Article ("the")	The impertinent youth insulted	the	ladies on the street.
Both denied	Article ("the")	The impertinent youth insulted	ldc	toktaz on the street.
n+1 denied	Article ("the")	The impertinent youth insulted	ldc	ladies on the street.
Both available	3-letter Word	The impertinent youth insulted	two	ladies on the street.
Both denied	3-letter Word	The impertinent youth insulted	lmc	toktaz on the street
n+1 denied	3-letter Word	The impertinent youth insulted	lmc	ladies on the street.

Table 3

Experiment 1: Fixation Time Measures (in ms) and Fixation Probabilities for the Three Target Words n, n+1, and n+2. Standard Deviations are in Parentheses.

	n+1 word type	Preview condition	Word n	Word n+1	Word n+2
First fixation duration	Article (“the”)	Both available	244 (96)	214 (75)	232 (73)
	Article (“the”)	Both denied	249 (101)	214 (66)	212 (72)
	Article (“the”)	n+1 denied	245 (92)	215 (60)	209 (70)
	3-letter Word	Both available	239 (89)	224 (83)	215 (70)
	3-letter Word	Both denied	244 (91)	236 (72)	217 (75)
	3-letter Word	n+1 denied	247 (95)	238 (75)	213 (74)
Single fixation duration	Article	Both available	252 (97)	214 (77)	233 (69)
	Article	Both denied	256 (105)	216 (67)	212 (73)
	Article	n+1	252	216	205

		denied	(96)	(58)	(68)
	3-letter Word	Both available	247 (92)	226 (85)	214 (71)
	3-letter Word	Both denied	250 (92)	242 (71)	214 (75)
	3-letter Word	n+1 denied	256 (96)	242 (70)	211 (70)
Gaze duration	Article ("the")	Both available	280 (121)	228 (90)	264 (99)
	Article ("the")	Both denied	292 (131)	225 (76)	241 (105)
	Article ("the")	n+1 denied	288 (121)	227 (78)	237 (106)
	3-letter Word	Both available	282 (117)	233 (91)	248 (112)
	3-letter Word	Both denied	284 (118)	252 (85)	247 (112)
	3-letter Word	n+1 denied	297 (131)	254 (84)	241 (106)
Go-past time	Article ("the")	Both available	320 (183)	250 (127)	323 (184)
	Article ("the")	Both denied	339 (197)	260 (143)	304 (207)

	Article ("the")	n+1 denied	332 (181)	267 (137)	304 (201)
	3-letter Word	Both available	311 (163)	276 (164)	281 (152)
	3-letter Word	Both denied	332 (196)	306 (162)	301 (186)
	3-letter Word	n+1 denied	337 (188)	303 (161)	298 (181)
Fixation probability	Article ("the")	Both available	0.96 (0.19)	0.31 (0.46)	0.91 (0.29)
	Article ("the")	Both denied	0.95 (0.21)	0.71 (0.45)	0.91 (0.29)
	Article ("the")	n+1 denied	0.94 (0.23)	0.66 (0.47)	0.92 (0.28)
	3-letter Word	Both available	0.96 (0.21)	0.61 (0.49)	0.87 (0.34)
	3-letter Word	Both denied	0.95 (0.22)	0.75 (0.44)	0.86 (0.35)
	3-letter Word	n+1 denied	0.94 (0.24)	0.70 (0.46)	0.88 (0.32)
Initial landing position	Article ("the")	Both available	2.59 (1.70)	1.70 (1.21)	2.40 (1.78)
	Article	Both	2.46	1.45	2.25

	("the")	denied	(1.70)	(1.08)	(1.77)
	Article	n+1	2.59	1.65	2.49
	("the")	denied	(1.68)	(1.09)	(1.71)
	3-letter	Both	2.32	1.62	2.14
	Word	available	(1.74)	(1.20)	(1.61)
	3-letter	Both	2.43	1.70	2.07
	Word	denied	(1.65)	(1.16)	(1.67)
	3-letter	n+1	2.38	1.63	2.16
	Word	denied	(1.62)	(1.10)	(1.62)

Table 4

Experiment 2: Examples of the Four Preview Conditions Prior to the Display Change.

After a participant's gaze position crossed the boundary located to the right of word n (dashed line), all incorrect previews changed to the correct words (i.e. the sentence appeared as it did in the "both available" condition).

Word n frequency	Preview condition	Sentence prior to display change: Word n	n+1	n+2
High	Both available	The generous aunt gives	the	present to her niece.
High	Both denied	The generous aunt gives	dlc	gmocak to her niece.
High	n+1 denied	The generous aunt gives	dlc	present to her niece.
High	n+2 denied	The generous aunt gives	the	gmocak to her niece.
Low	Both available	The generous aunt sends	the	present to her niece.
Low	Both denied	The generous aunt sends	dlc	gmocak to her niece.
Low	n+1 denied	The generous aunt sends	dlc	present to her niece.
Low	n+2 denied	The generous aunt sends	the	gmocak to her niece.

Table 5

Experiment 2: CELEX Mean Word Frequency (Occurrences per Million) for the Critical Words as well as Cloze Predictability Estimates for Word n+1.

Critical word	Min - max length	Mean length	CELEX frequency	Cloze predictability
n	3 – 9	5.25 (1.15)	high frequency condition: 129 (122)	high frequency: .023 (.091)
			low frequency condition: 5.69 (7.79)	low frequency: .0019 (.039)
n+1	3	3 (0)	64,368 (0)	--
n+2	3 – 14	5.75 (1.99)	50.76 (101)	--

Table 6

Experiment 2: Fixation Time Measures (in ms) and Fixation Probability for the Three Target Words n, n+1, and n+2. Standard Deviations are in Parentheses.

	Word n frequency	Preview condition	Word n	Word n+1	Word n+2
First fixation duration	high	Both available	234 (81)	204 (59)	233 (77)
	high	Both denied	233 (77)	223 (66)	220 (74)
	high	n+1 denied	232 (81)	223 (68)	220 (78)
	high	n+2 denied	231 (86)	208 (51)	238 (82)
	low	Both available	245 (90)	211 (65)	250 (94)
	low	Both denied	255 (96)	226 (62)	223 (85)
	low	n+1 denied	250 (96)	229 (68)	225 (80)
	low	n+2 denied	246 (91)	216 (82)	251 (85)
Single fixation duration	high	Both available	236 (75)	204 (58)	238 (80)
	high	Both denied	236 (74)	226 (63)	221 (73)
	high	n+1 denied	236 (81)	227 (64)	221 (80)
	high	n+2 denied	234 (85)	209 (50)	240 (83)
	low	Both available	247 (91)	211 (66)	252 (99)
	low	Both denied	262 (92)	228 (60)	222 (83)
	low	n+1 denied	259 (97)	233 (64)	224 (78)
	low	n+2 denied	253 (87)	217 (84)	255 (84)
Gaze duration	high	Both available	256 (105)	207 (65)	261 (102)
	high	Both denied	263 (106)	234 (70)	241 (98)

	high	n+1 denied	263 (114)	234 (72)	242 (104)
	high	n+2 denied	258 (111)	216 (68)	275 (116)
	low	Both available	266 (108)	218 (73)	277 (114)
	low	Both denied	298 (126)	235 (69)	256 (121)
	low	n+1 denied	297 (126)	240 (75)	248 (109)
	low	n+2 denied	289 (120)	224 (88)	288 (114)
Go-past time	high	Both available	311 (211)	238 (126)	312 (171)
	high	Both denied	322 (219)	282 (147)	313 (186)
	high	n+1 denied	316 (213)	276 (138)	309 (205)
	high	n+2 denied	294 (176)	275 (159)	331 (183)
	low	Both available	323 (198)	254 (138)	360 (226)
	low	Both denied	359 (202)	297 (175)	336 (219)
	low	n+1 denied	351 (211)	292 (154)	331 (204)
	low	n+2 denied	345 (209)	279 (168)	361 (225)
Fixation probability	high	Both available	0.88 (0.33)	0.35 (0.48)	0.87 (0.34)
	high	Both denied	0.88 (0.33)	0.63 (0.48)	0.87 (0.34)
	high	n+1 denied	0.90 (0.30)	0.68 (0.47)	0.84 (0.36)
	high	n+2 denied	0.88 (0.33)	0.34 (0.47)	0.88 (0.32)
	low	Both available	0.91	0.31	0.89

			(0.28)	(0.46)	(0.32)
	low	Both denied	0.91 (0.29)	0.65 (0.48)	0.88 (0.32)
	low	n+1 denied	0.91 (0.29)	0.66 (0.47)	0.89 (0.32)
	low	n+2 denied	0.91 (0.28)	0.34 (0.47)	0.88 (0.32)
Initial landing position	high	Both available	2.59 (1.70)	1.70 (1.21)	2.40 (1.78)
	high	Both denied	2.46 (1.70)	1.45 (1.08)	2.25 (1.77)
	high	n+1 denied	2.59 (1.68)	1.65 (1.09)	2.49 (1.71)
	high	n+2 denied	2.32 (1.74)	1.62 (1.20)	2.14 (1.61)
	low	Both available	2.43 (1.65)	1.70 (1.16)	2.07 (1.67)
	low	Both denied	2.38 (1.62)	1.63 (1.10)	2.16 (1.62)
	low	n+1 denied	2.41 (1.73)	1.52 (1.07)	2.28 (1.51)
	low	n+2 denied	2.40 (1.61)	1.71 (1.21)	2.18 (1.64)