Dissociating Preview Validity and Preview Difficulty in Parafoveal Processing of Word *n*+1 during Reading

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Abstract

Many studies have shown that previewing the next word *n*+1 during reading leads to substantial processing benefit (e.g., shorter word viewing times) when this word is eventually fixated. However, evidence of such preprocessing in fixations on the preceding word *n* when in fact the information about the preview is acquired is far less consistent. A recent study suggested that such effects may be delayed into fixations on the next word *n*+1 (Risse & Kliegl, 2012). In order to investigate the time course of parafoveal information-acquisition on the control of eye movements during reading, we conducted two gaze-contingent display-change experiments and orthogonally manipulated the processing difficulty (i.e., word frequency) of an *n*+1 preview word and its validity relative to the target word. Preview difficulty did not affect fixation durations on the pretarget word *n* but on the target word *n*+1. In fact, the delayed preview-difficulty effect was almost of the same size as the preview benefit associated with the *n*+1 preview validity. Based on additional results from quantile-regression analyses on the time course of the two preview effects, we discuss consequences as to the integration of foveal and parafoveal information and potential implications for computational models of eye guidance in reading.

Keywords: perceptual span, parafoveal preview benefit, parafoveal-on-foveal effect, eye movements, display-change awareness

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Word recognition during reading is the result of a very efficient coordination of attention allocation and eye-movement control. There is no doubt anymore that during reading it is not only the currently fixated word that matters (i.e., word *n*) but that preview of at least the next word (i.e., word *n*+1) must be taken into consideration as well. Subject of much controversy, however, is the question as to how not-yet-fixated words in parafoveal vision influence the oculomotor decisions and when this can be seen in the eye-movement record (e.g., in word viewing times). Studying the time course of preview effects relative to the moment of information acquisition in parafoveal vision may contribute substantially to the understanding of foveal and parafoveal information-integration during reading. It may also provide constraining evidence for competing theoretical proposals about the processes coordinating attention allocation, word processing, and oculomotor control.

Parafoveal processing and the boundary paradigm

The region of text from which information is used to read a sentence at normal speed is called the *perceptual span* and is substantially larger than the fixated word in foveal vision. In total, it corresponds to about 20 character spaces, extending from 3 to 4 letters to the left to 15 letters to the right of a given fixation position (McConkie & Rayner, 1975; Rayner, Well, & Pollatsek, 1980). This allows processing also of not-yet-fixated words in the parafovea, mainly to the right of fixation. The strong asymmetry of the perceptual span indicates that reading is not simply limited by decreasing visual acuity beyond foveal vision, but also by attentional demands. In fact, reading models view the perceptual span as the maximal region across which attention is gradually distributed (Engbert, Nuthmann, Richter, & Kliegl, 2005; Inhoff, Radach, Starr, & Greenberg, 2000; McDonald, Carpenter, & Shillcock, 2005; Reilly & Radach, 2006; Vitu, Brysbaert, & Lancelin, 2004) or sequentially shifted (Engbert & Kliegl, 2001; Morrison, 1984; Reichle, Pollatsek, Fisher, & Rayner, 1998) during the duration of a fixation.

Given the size of the perceptual span, the question arises how parafoveal word information is integrated into ongoing processing and when it affects eye-movement control. The majority of empirical findings on the role of processing parafoveal words during reading come from studies utilizing gaze-contingent display-changes in the boundary paradigm (Rayner, 1975). In these experiments, participants read sentences in which an invisible boundary is located prior to a target word. While the eyes are still fixating to the left of the boundary, the word to the right of the boundary (i.e., the preview of word *n*+1) is masked, for example by presenting a random string of letters in parafoveal vision. As soon as the eyes cross the boundary, the preview is replaced by the target word. In order to measure the effect of parafoveal processing on reading, the condition with invalid preview is then compared to the condition with valid preview in which word *n*+1 is the same word both before and after the display change.

The most prominent finding in the boundary paradigm is that fixation durations on the target word are shorter when valid rather than invalid preview of word *n*+1 was provided during fixations before the boundary. This result is interpreted as a parafoveal *preview benefit* and suggests facilitation from a head-start of processing that speeds up target-word recognition due to the successful integration of valid preview information (Inhoff, 1990; Rayner, McConkie, & Ehrlich, 1978). Preview benefit counts among the most reliable findings in reading research with a substantial effect size of 20-50 ms (see Hyönä, 2011; Schotter, Angele, & Rayner, 2012, for reviews). It has been demonstrated for integrating orthographic information such as letter identities (Balota, Pollatsek, & Rayner, 1985; Drieghe, Rayner, & Pollatsek, 2008; Inhoff, 1990), phonological codes as in the case of homophones (Chace, Rayner, & Well, 2005; Henderson, Dixon, Peterson, Twilley, & Ferreira, 1995;

Miellet & Sparrow, 2004, Pollatsek, Lesch, Morris, & Rayner, 1992), and in German and Chinese language also for semantic information when presenting parafoveal previews with a related meaning (Hohenstein & Kliegl, in press; Yan, Zhou, Shu, & Kliegl, 2012; for different results in English see Inhoff & Rayner, 1980; Rayner, Balota, & Pollatsek, 1986).

Thus, although stemming from parafoveal processing, preview benefit is an effect of the target word's immediate processing demand that is reduced by integrating useful preview information into foveal word recognition. Given the time when the preview information was acquired, namely during the previous fixation on word *n* before the boundary, it must be considered a rather late effect of parafoveal processing. Conversely, immediate effects must be expected on word *n* when the neighboring word *n*+1 is just now preprocessed and a difficult preview (e.g., a nonword of random letters) may be encountered in parafoveal vision. Alas, such so-called *parafoveal-on-foveal* effects are not consistently observed across boundary experiments (see Drieghe, 2011, for a review). They have been reliably documented for orthographic difficulties of a parafoveal preview such as irregular letter sequences in case of nonwords with longer foveal fixation durations in the presence of parafoveal processing difficulties (Drieghe et al., 2008; Inhoff et al., 2000; Inhoff, Starr, & Shindler, 2000; White, 2008). In contrast, lexical or postlexical difficulty such as the printed word frequency (Henderson & Ferreira, 1993; White, 2008), syntactic class (Henderson & Ferreira, 1993), or semantic relatedness (Hohenstein & Kliegl; in press) and plausibility (Rayner, Warren, Juhasz, & Liversedge, 2004) showed no such effects. Word frequency when it was investigated together with word length sometimes even showed an inverse parafoveal-on-foveal effect suggesting an early saccade towards the location of the parafoveal difficulty (Hyönä & Bertram, 2004; Kennedy, 2000; Kennedy, Pynte, & Ducrot, 2002).

Delayed effects of parafoveal processing

Moreover, it is not uncommon that lexical or postlexical effects of processing difficulty are not observed immediately, but with some delay. A prominent example is the sentence wrap-up effect indicating semantic integration that is postponed until the final word of the sentence (e.g., Just & Carpenter, 1980; Kuperman, Dambacher, Nuthmann, & Kliegl, 2010; Stine-Morrow et al., 2010). Moreover, many studies reported spillover effects of a word's difficulty (e.g., lexical frequency) into eye movements on the next word during reading (Rayner & Duffy, 1986; Schroyens, Brysbaert, Vitu, & d'Ydewalle, 1999), but also for reaction times in lexical decision tasks in terms of processing spillover across trials (Masson & Kliegl, 2013).

During reading such delays can imply that modulations of fixation durations based on parafoveal processing difficulties are not obtained immediately (e.g., as parafoveal-on-foveal effects on word *n*), but on word *n*+1, that is only after the eyes moved to the next word. This has been found to be the case in boundary experiments varying the preview of word *n*+2 (i.e., the word two words to the right of the boundary) rather than word *n*+1 (Kliegl, Risse, & Laubrock, 2007; Risse & Kliegl, 2011, 2012). Processing a valid or invalid preview of word *n*+2 in parafoveal vision did not affect the fixation duration immediately on word *n* before the boundary but instead the next fixation duration on word *n*+1 after the boundary. Therefore, we called it a *delayed* rather than an *immediate* parafoveal-on-foveal effect. Together with a small but reliable benefit in case of valid *n*+2 preview when the target word was finally fixated, these results suggested that parafoveal processing during reading influences saccadic control at different time points across a spatial region of several words. When the target word is eventually fixated and processed in foveal vision, the availability of valid preview information seems to facilitate foveal word recognition and elicits an earlier saccade program than in the case of invalid preview information (i.e., preview benefit). More importantly, the same preview information can also affect saccadic decisions prior to the target word, although not always immediately when it is acquired in parafoveal vision (i.e., during fixating word *n*).

The present study aims at investigating the time course of preview effects across a smaller region of interest containing only two instead of three words. Manipulating the preview of word *n*+1 that is located closer to the fovea where visual acuity is not yet so strongly reduced, we expected to find larger preview effects than in the previous studies on parafoveal processing of word *n*+2. Moreover, if effects of parafoveal processing-difficulty are delayed also in the *n*+1 boundary paradigm, we should observe evidence for them on the target word *n*+1 that is on the same word where we also expect evidence of preview benefit. Therefore, we propose a preview manipulation that allows us to test the two effects of preview in the same fixation duration on the same word *n*+1. In two experiments, we investigated the time course of parafoveal processing of the neighboring word *n*+1 on the timing of saccades immediately during fixating word *n* (i.e., parafoveal-on-foveal effects) but more importantly, also delayed on word *n*+1 simultaneously with and independently of the classic preview benefit.

Experiment 1: Crossing preview validity and preview difficulty

Adopting an experimental paradigm introduced by Risse and Kliegl (2012), we crossed two factors, preview validity and preview difficulty, in a 2 x 2 design as illustrated in Figure 1. Word processing difficulty was assessed as the lexical frequency of the preview. As a first test, we were interested in manipulating the overall processing difficulty, not a dissociation of lexical and sublexical features. Therefore, words were not controlled for sublexical variables such as initial letter frequencies. Participants read sentences in which a target word was embedded that was either a high-frequency (i.e., easy) or a low-frequency (i.e., difficult) word of the same length. An invisible boundary was located at the beginning of the empty space before that word. While the eyes were to the left of the boundary, preview of the target word was either the same word as the target or the other word with the opposite frequency. In other words, as long as the eyes fixated word *n*, the preview of word *n*+1 was either valid or invalid relative to the later target word. Therefore, the manipulation of preview validity tested the classical preview benefit in fixation durations on the target word *n*+1.

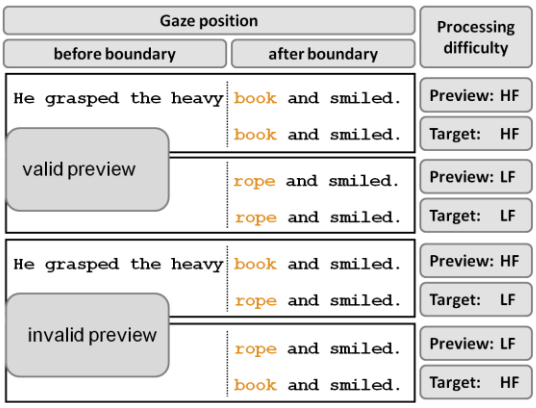

Figure 1. Orthogonal preview-word and target-word difficulty conditions in the present *n*+1-boundary experiments. While the eyes were before the boundary (to the left of it) preview of word *n*+1 after the boundary was a high-frequency (HF; easy) or low-frequency (LF; difficult) word. As soon as the eyes crossed the boundary the preview was replaced by a HF or LF target word *n*+1. Valid preview was obtained when the processing difficulty remained constant across the boundary. Invalid preview of the target word was provided when the processing difficulty of word *n*+1 changed before and after the boundary.

The manipulation of preview difficulty yielded a different and independent estimate of parafoveal processing. As long as the eyes were to the left of the boundary on word *n*, the preview was either easy (a high-frequency word) or difficult (a low-frequency word). Therefore, the preview difficulty tested the classical immediate parafoveal-on-foveal effect in fixation durations on the pretarget word *n*. As to the novel feature of the experiment, the preview difficulty in the invalid preview condition was of the opposite processing difficulty than the later target word and independent of the validity of the preview. This allowed us to test preview-difficulty effects also in fixation durations on word *n*+1 after the boundary. Therefore, for fixation durations on word *n*+1, the preview difficulty tested delayed effects of preview on the same word (and for the same fixation duration) as the preview benefit.

In addition, the interaction tested additivity of preview validity x preview difficulty. In our experimental design, this interaction corresponds to the main effect of the target difficulty of word *n*+1. As shown in Figure 1, in the two valid preview conditions (1) and (2) target difficulty is equal to preview difficulty (nothing changed), but in the two invalid preview conditions, (3) the easy preview was replaced by a difficult target and (4) the difficult preview was replaced by an easy target. Therefore, when the eyes are on word *n+1*, conditions (1) and (2) are easy targets and conditions (3) and (4) are difficult targets. Thus, the preview validity x preview difficult interaction is mathematically identical to the main effect of target difficulty, independent of whether the preview was valid or invalid and independent of whether the preview was easy or difficult (see Kliegl, Mayr, Junker, & Fanselow, 1999; Shaffer, 1977, for a reconceptualization of interactions as main effects). In a 2 x 2 design, the two main effects and the interaction have the same statistical power because all of them involve contrasts of two conditions against the remaining two conditions.

In summary, our two-factorial design returned three orthogonal main effects for fixation durations on the target word *n*+1: (a) preview validity (corresponding to preview benefit), (b) preview difficulty (corresponding to a delayed preview effect), and (c) target difficulty (corresponding to the interaction between preview validity x preview difficulty). In addition, we also tested (d) the immediate parafoveal-on-foveal effect of preview difficulty for fixation durations on the pretarget word *n*.

Method

Participants

In the present experiment, we tested 29 students from a Potsdam high-school or from the University of Potsdam (22 female vs. 7 male) between 16 and 26 years old (M = 19.7 years; SD = 2.8). They were part of larger study comprising three experimental units of which one unit contained the two experiments reported here. Participants were reimbursed with a total of 30 Euros for their participation in the full study. Every second participant was assigned to the present boundary experiment; every other was assigned to Experiment 2. The experiment lasted about 40-50 minutes and participants were provided sufficient breaks between experimental units. The other two experimental units were unrelated to the present question and are not reported here. All participants had normal or corrected-to-normal vision.

Materials and Design

A total of 120 sentences were selected from 144 sentence units used in Dambacher, Rolfs, Göllner, Kliegl, & Jacobs (2009). The original study investigated frequency and predictability effects in eye movements during reading. Therefore, neutral target sentences were preceded by a contextualizing sentence which rendered a high- or low-frequency target word in the target sentence either high or low predictable. For the present study, we selected only the neutral target sentences that contained the factorial frequency-manipulation of the target word. The target word could either be a high-frequency (e.g., *book*) or a low-frequency (e.g., *rope*) open-class word. Predictability of the target words in the neutral sentences should be low. Moreover, we selected only those sentences in which a pair of target words had the same word length such that a gaze-contingent replacement by the other word would not alter the spatial positions of the words following the target word.

Target-word pairs were mostly nouns and therefore presented with a capitalized initial letter (92 out of 120 sentences). The remaining target words were verbs (19 sentences) and adverbs (9 sentences) and not capitalized. Detailed summary statistics on the printed word frequency and word length of the target and pretarget words are provided in Table 1. Frequency norms were collected from the DWDS data base (Geyken, 2007; Heister et al., 2011; http://www.dlexDB.de). Target words differed also on many other linguistic variables such as their initial letter-bigram and letter-trigram frequency, neighborhood size and neighborhood frequency. All variables indicated easier processing for the high-frequency target word. Thus, preview and target word difficulty did not differ exclusively on lexical variables (e.g., word frequency) but also on sublexical variables (e.g., orthographic letter frequency). Sentences comprised between 9 and 12 words (M = 10, SD = 0.81) with the target word occupying the sixth, seventh, or eighth position in the sentence (M = 7, SD = 0.76).

Table 1. *Summary statistics for pretarget word n and target word n+1.*

		Word *n*				Word *n*+1			
		M	*SD*	*min.*	*max.*	*M*	*SD*	*min.*	*max.*
Frequency (word form)	HF	5,698	8,579	0.02	26,530	151.1	127.8	18.5	939.4
	LF					4.0	2.1	1.0	9.8
Frequency (lemma)	HF	19,539	30,873	0.07	80,100	279.2	278.5	100.5	1,759.5
	LF					4.9	2.6	0.2	10.0
Word length		5.1	2.8	2	14	5.3	1.1	3	8

Note. Frequencies are normalized (number of occurrence per million words). Provided are the mean (*M*), standard deviation (*SD*), minimum (*min.*) and maximum (*max.*) for high-frequency (HF) and low-frequency (LF) words.

Apparatus and Procedure

Eye movements were tracked through individual head-mounted video cameras and recorded with an EyeLink II system (SR Research, Osgoode, Ontario, Canada). Eye monitoring was binocular with a sample frequency of 500 Hz, 0.5° average accuracy and a spatial resolution of 0.01°. End-to-end sample delays that is the time to access new eye position data is claimed to be less than 3 ms on average with EyeLink II and the given sampling rate. The experiment software was programmed in Matlab (R2007b, The MathWorks, Natick, Massachusetts, USA) using the Psychophysics (Brainard, 1997; Pelli, 1997) and Eyelink (Cornelissen, Peters, & Palmer, 2002) toolbox extensions, and the experiment was running on a remote computer working on a Mac OS 9 operating system. Sentences were displayed on an Iiyama Vision Master 514 Pro monitor (22 inch) with a screen resolution of 1024 x 768 pixels and a monitor refresh rate of 150 Hz. Participants were seated at a distance of 60 cm in front of the monitor with their heads positioned in a chin rest to reduce head movements during reading. Sentences were presented in black letters on a white background using 14 pt Courier regular as a monospace font. Each letter extended 8 pixels in horizontal width resulting in 3.4 letters per degree of visual angle. Given the eyetracker accuracy, the true fixation position was within an area of 1.7 letters radius from the measured fixation position. This is comparable to other boundary studies.

On arrival, participants were familiarized with the apparatus and procedure and signed informed consent. After reading the written instruction, participants were seated in front of the presentation computer and the head band containing the eye-tracking cameras was attached. Both eyes were calibrated fixating random dots on a nine-point grid and recalibrated every 15 trials (additional drift corrections were assigned every 5 trials). After successful calibration, participants were instructed to fixate a point that was displayed on the horizontal midline of the computer screen and that indicated the word centre of the subsequently appearing sentence-initial word. As sentences were presented with a fixed left-border offset of 40 pixels, the designated fixation position prior to the display of the sentence varied between trials according to the initial word's length. The sentence was displayed when binocular gaze was detected within a 16 x 16 pixels area around the fixation point within two seconds. After two successive failures, a drift correction was deployed in the center of the screen. After another failure, a recalibration was advised. In case of successful fixation control, the sentence was displayed at the horizontal midline of the screen with a fixed left-border offset of 40 pixels. Participants read the sentence for comprehension and gazed into the lower right corner to terminate the trial. In one third of trials, a three-alternative multiple-choice question followed sentence presentation and participants had to answer using the mouse. At the end of the experiment, participants were administered a short questionnaire in which they were asked about having noticed something unusual (e.g., display changes) and if so, were requested to estimate the percentage of display changes during the experiment.

The experiment consisted of six practice sentences without manipulation and 120 experimental sentences in which an invisible boundary was located at the end of the last letter of a pretarget word *n* preceding the target word *n*+1. The processing difficulty of word *n*+1 varied relative to the online gaze position being left or right of the boundary. While the eyes were to the left of the boundary, preview of word *n*+1 was either an easy high-frequency word (e.g., *book*) or a difficult low-frequency word (e.g., *rope*). When the eyes crossed the boundary, word *n*+1 was replaced either by the easy (i.e., *book*) or the difficult (i.e., *rope*) target word. Thus, each sentence was presented in four conditions which were counterbalanced across participants: (1) easy – easy, (2) difficult – difficult, (3) easy – difficult, and (4) difficult – easy (see Figure 1 for an illustration). Conditions (1) and (2) were valid previews of word *n*+1 and conditions (3) and (4) were invalid previews of word *n*+1. Order of sentence presentation was randomized for each participant preserving the counterbalancing of the experimental conditions.

Data Selection and Analysis

Fixation sequences for both eyes were generated post-hoc using the saccade-detection algorithm introduced by Engbert and Kliegl (2003; Mergenthaler & Engbert, 2006). Data of the right eye were further screened and filtered prior to statistical analysis. First, only those trials were selected in which display changes were completed during a forward saccade crossing the boundary and before the eyes landed to the right of it. This excluded all cases in which a drift movement on the pretarget word *n* triggered the preview replacement while word *n* remained fixated and cases in which the display change occurred within fixations on the target word *n*+1. Thereby, a total of 28% of the sentences were removed including 1.6% due to signal loss of the eye tracker (e.g., in case of blinks) leaving 2,521 experimental sentences for data analysis. Display changes were on average completed 8.3 ms after the first eye crossed the invisible boundary (ranging from 5 to 11.7 ms).

From the remaining data, early and late processing measures were derived as dependent variables. As an index of early word processing, we computed the duration of first fixations irrespective of the total number of fixations on that word (referred to as first fixation duration or FFD) and single fixation duration (SFD) considering only those cases in which a word was fixated exactly once in the first reading pass. We also computed gaze duration (GD) as the sum of all fixation durations on a word from its first encounter until the eyes left off to another word (including all the word's immediate refixations). As an index of later processing, the total viewing time (TVT) of words was defined as the sum of all fixation durations on a word also including revisits after regressions back to the word from other regions in the text. In addition, probabilities of skipping (not fixating a word) and refixation (fixating a word more than once) were computed for the first pass of reading.

Fixation duration outliers were removed from all reported analyses. The upper and lower duration cutoffs were chosen from boxplot-analyses of the distributions of each individual fixation duration measure. For SFD and FFD, fixation durations shorter than 50 ms or longer than 800 ms were defined as outliers. For GD and TVT, fixation durations shorter than 50 ms and longer than 2000 ms were excluded. Thus, less than 1 % of data points in the target region (i.e., word *n* and word *n*+1) were eliminated for each fixation duration measure.

Linear-mixed models (LMMs; for fixation durations as dependent variables) and generalized linear-mixed models (GLMMs; for fixation probabilities as dependent variables) were estimated using the lmer-function (*lme4* package; Bates & Maechler, 2010) in R, a free software for statistical computing (version 2.11.1; R Development Core Team, 2010). Participants (subjects) and sentences (items) were specified as random intercepts[1]. We included preview validity (valid vs. invalid preview of word *n*+1), preview difficulty (easy vs. difficulty preview of word *n*+1), and their interaction in the models. All fixed effects were coded with -0.5 and 0.5 around zero such that the estimated regression coefficient (*b*) reflects the difference in the dependent variable between the two factor levels and thus the effect size. We further report the standard error (*SE*) and the *t*-statistic (ratio of *b* and *SE*) for the coefficients. In GLMMs, this ratio reflects a standard normal distribution and is reported accordingly as a *z*-value. Effects larger than two times their standard errors are interpreted as significant at the 5 % level. In fact, absolute values larger than 1.96 fall within the 95 % confidence interval. LMMs were fitted to untransformed and log-transformed fixation durations for cross-check. The latter are in agreement with the model assumption of normal distribution of residuals and are therefore reported in the results.

Results and Discussion

We report findings in early and late processing measures and in two fixation probabilities. Whereas fixation durations give rise to the word-processing success through differences in the decision of when to move the eyes to the next fixation location, fixation probabilities indicate processing differences through the decision of where to move the eyes next. We analyzed the probability of skipping a word as an indicator of efficient parafoveal processing of that word prior to the saccade. We also investigated the probability of refixations on a word, which may reflect processing difficulties associated with that word. Fixation data were analyzed separately for the pretarget word *n* before the eyes crossed the boundary and for the target word *n*+1 after the eyes crossed the boundary. Individual

(G)LMMs were fitted to each dependent variable estimating the same random and fixed effect structure for each model (see *Data Selection and Analysis*). We report the results from the target word *n*+1 first because this is where the preview-difficulty manipulation should reveal its impact if such preview effects are delayed.

Target word n+1

Table 2a shows the condition means for six untransformed fixation measures on the target word *n*+1. Table 2b summarizes the results of the (G)LMM analyses for log-transformed fixation durations. Hence, we omit the *b*-, *SE*-, and *t*-statistics in the text. Fixation durations were significantly shorter for valid preview of word *n*+1 during the previous fixation compared to invalid preview (FFD: 16 ms, SFD: 14 ms, GD: 24 ms, TVT: 59 ms). This result replicates the standard preview-benefit effect in the *n*+1-boundary paradigm. Moreover, there was a significant effect of the preview difficulty of word *n*+1. Fixation durations on the target word were about 20 ms longer when its parafoveal preview was difficult before the boundary (i.e., low frequent) and shorter in case of an easy (i.e., high frequent) preview of word *n*+1 (FFD: 18 ms, SFD: 19 ms, GD: 17 ms, TVT: 8 ms). Note that in 50 % of the time word *n*+1 had changed prior to its fixation and the target-word difficulty was now the inverse preview difficulty. The interaction between preview validity and preview difficulty, however, was not significant. In other words, there was no reliable evidence for an additional immediate effect of the foveal difficulty of the target word, but the trends were in the expected direction (FFD: 5 ms, SFD: 4 ms, GD: 6 ms, TVT: 15 ms).

Table 2a
Experiment 1: Condition means on the target word *n*+1.

	Preview difficulty	easy (HF)		difficult (LF)	
Measure	Preview validity	valid	invalid	valid	invalid
First fixation duration		208 (5.7)	228 (8.0)	230 (7.0)	241 (7.0)
Single fixation duration		209 (5.9)	227 (8.1)	232 (7.2)	242 (7.3)
Gaze duration		218 (7.0)	247 (11.0)	240 (7.7)	258 (9.7)
Total viewing time		241 (11.4)	315 (17.3)	264 (10.6)	308 (13.2)
Skipping probability		.26 (.04)	.23 (.03)	.15 (.03)	.14 (.03)
Refixation probability		.04 (.02)	.06 (.02)	.05 (.02)	.05 (.02)

Note. Standard deviations listed in parentheses. HF: high-frequent *n*+1 preview. LF: low-frequent *n*+1 preview.

Table 2b
(G)LMM coefficients for analyses of fixation durations on the target word *n*+1.

	First fixation duration			Single fixation duration			Gaze duration			Total viewing time		
REs	*var*	*SD*		*var*	*SD*		*var*	*SD*		*var*	*SD*	
Subjects (I)	0.01	0.09		0.01	0.10		0.01	0.10		0.02	0.13	
Items (I)	0.02	0.13		0.02	0.13		0.02	0.15		0.03	0.18	
Residuals	0.09	0.29		0.08	0.28		0.10	0.32		0.15	0.38	
FEs	*b*	*SE*	*t*	*b*	*SE*	*t*	*b*	*SE*	*t*	*b*	*SE*	*t*
(I)	**5.36**	**0.03**	**210.8**	**5.37**	**0.03**	**197.4**	**5.41**	**0.03**	**180.5**	**5.53**	**0.04**	**149.9**
pvD	**0.08**	**0.01**	**6.4**	**0.09**	**0.01**	**7.1**	**0.08**	**0.01**	**5.9**	**0.07**	**0.02**	**4.0**
pvV	**0.06**	**0.01**	**4.7**	**0.06**	**0.01**	**4.2**	**0.08**	**0.01**	**5.3**	**0.18**	**0.02**	**10.7**
pvD:pvV	-0.02	0.04	-0.4	-0.01	0.04	-0.3	-0.03	0.05	-0.6	-0.10	0.06	-1.7

Note. Variance (*var*) and standard deviation (*SD*) of random effects (*REs*); regression coefficient (*b*), standard error (*SE*), and *t*-value (*t*) of fixed effects (*FEs*) for log-transformed fixation durations on word *n*+1. Significant coefficients ($|t| > 1.96$) are set in bold. pvD: preview difficulty of word *n*+1. pvV: preview validity of word *n*+1. (I): Intercept.

We also analyzed skipping and refixation probabilities of word *n*+1. The only significant effect was more skipping of easy compared to difficult previews (b = -.71, SE = .12, z = -5.91; absolute *z*-values for all other effects and interactions were smaller than 1.17). Thus, in a proportion of trials an easy preview was sufficient to trigger a saccade program to skip the next word.

A further interesting result relates to comparisons of fixed effects for the different dependent variables in Table 2b. For first fixations on word *n*+1, and even more so for single fixations, the effect of preview difficulty was larger than the effect of preview validity. The benefit from a valid preview increased substantially in reading times that are typically associated with later processing difficulties, necessitating the refixation of a word and sometimes even its later rereading. In GD the two preview effects were similar, in TVT the preview-validity effect increased to more than twice the size of the preview-difficulty effect that is when rereading of the target word was included. The differences in the size of the two effects for early and late processing measures may be a first indicator for different time courses of these two preview effects. In summary, preview difficulty was stronger in early fixation measures on the target word *n*+1 (i.e., FFD and SFD) and preview validity was stronger in later measures (i.e., GD and TVT).

Effects of display-change sensitivity on parafoveal preview. There is an ongoing debate about whether awareness of display changes in the boundary paradigm alters the findings of preview effects (e.g., Slattery, Angele, & Rayner, 2011). We carried out an additional set of analyses to statistically control the influence of change sensitivity of each participant on the present results. Note that trials in which the display change happened after the eyes landed on word *n*+1 (i.e., all cases in which the target-word replacement occurred within a fixation) were carefully excluded prior to any data analysis. Still, this does not preclude the possibility that participants become aware of such changes. The results from the questionnaire that each participant completed at the end of the experiment confirmed that participants widely differed on the detection of display changes. There were seven participants that were unaware of any display changes, an additional six participants reported 5% or fewer changes, and 15 participants reported 10% or more changes. Only one participant overestimated the true number of display changes.

We computed (G)LMMs for each fixation measure adding the percentage of self-reported display changes for each participant as a covariate to the fixed-effect structure of the models reported above. Participants were split into two groups with Group 1 consisting of all participants who reported 5 % or less display changes (i.e., low DC detection) and Group 2 with participants reporting 10 % or more changes (i.e., high DC detection). A significant interaction with preview difficulty and preview validity would indicate a moderating effect of display-change awareness on preview effects. The individual change-detection rate did not contribute much to explaining the variance in the data. None of the interactions containing the detection rate were significant (all t values < 1.79); the expanded models did not yield significantly better goodness of fit in a likelihood-ratio test (all χ^2 (4) < 5.4, p > .25).

Pretarget word n

Table 3 summarizes the results of the (G)LMM analyses for fixation durations on the pretarget word *n* and shows the condition means for fixation durations and two fixation-probability measures. There were no significant effects in fixation-duration analyses except in TVT that showed a main effect of preview validity. The total time spent on the pretarget word was longer after invalid preview of word *n*+1 suggesting that wrong parafoveal preview increased the later rereading of words even to the left of the target. There was no evidence for an immediate parafoveal-on-foveal effect of the preview difficulty in fixation durations on word *n* before the boundary, and the results were not modulated by the display-change sensitivity of the participants (all critical interactions with absolute t values < 1.79). Model comparisons provided no evidence for preferring the more complex over the simpler main models (all χ^2 (4) < 6.1, p > .20).

Table 3a
Experiment 1: Condition means on the pretarget word *n*.

	Preview difficulty	easy (HF)		difficult (LF)	
Measure	Preview validity	valid	invalid	valid	invalid
First fixation duration		228 (7.3)	221 (6.6)	231 (7.8)	226 (7.2)
Single fixation duration		227 (7.6)	222 (7.0)	233 (8.6)	227 (7.0)
Gaze duration		243 (9.8)	249 (9.8)	256 (10.2)	245 (9.5)
Total viewing time		268 (12.9)	309 (18.7)	262 (14.7)	285 (13.7)
Skipping probability		.29 (.04)	.28 (.04)	.28 (.04)	.27 (.04)
Refixation probability		.06 (.02)	.12 (.03)	.11 (.03)	.07 (.02)

Note. Standard deviations listed in parentheses. HF: high-frequent *n*+1preview. LF: low-frequent *n*+1 preview.

Table 3b
(G)LMM coefficients for analyses of fixation durations on the pretarget word *n*.

	First fixation duration			Single fixation duration			Gaze duration			Total viewing time		
REs	*var*	*SD*		*var*	*SD*		*var*	*SD*		*var*	*SD*	
Subjects (I)	0.01	0.07		0.01	0.08		0.01	0.11		0.02	0.13	
Items (I)	0.01	0.09		0.01	0.09		0.01	0.12		0.03	0.17	
Residuals	0.08	0.29		0.08	0.29		0.10	0.32		0.16	0.40	
FEs	*b*	*SE*	*t*	*b*	*SE*	*t*	*b*	*SE*	*t*	*b*	*SE*	*t*
(I)	**5.37**	**0.02**	**270.3**	**5.38**	**0.02**	**273.1**	**5.43**	**0.03**	**214.1**	**5.53**	**0.04**	**159.2**
pvD	0.01	0.01	1.0	0.02	0.01	1.1	0.02	0.02	1.1	0.02	0.02	0.8
pvV	-0.02	0.01	-1.5	-0.02	0.01	-1.4	-.004	0.02	-0.2	**0.04**	**0.02**	**2.2**
pvD:pvV	-.003	0.04	-0.1	-.007	0.04	-0.2	-0.06	0.05	-1.1	-0.11	0.06	-1.8

Note. Variance (*var*) and standard deviation (*SD*) of random effects (*REs*); regression coefficient (*b*), standard error (*SE*), and *t*-value (*t*) of fixed effects for log-transformed fixation durations on word *n*+1. Significant coefficients ($|t| > 1.96$) are set in bold. pvD: preview difficulty of word *n*+1. pvV: preview validity of word *n*+1. (I): Intercept.

There were also no effects in the skipping probability of the pretarget word *n* (all absolute *z* values < .63). However, refixation probability revealed a significant interaction of preview difficulty and preview validity, that is a significant main effect of target difficulty ($b = -1.84$, $SE = .80$, $z = -2.30$). This interaction was not expected due to the fact that the validity of the preview should become apparent only after the eyes left word *n* and triggered the display change. Since this finding did not replicate in Experiment 2, we consider the effect as spurious.

In summary, the results of Experiment 1 suggested that a reliable portion of the variance in fixation durations on word *n*+1 in standard boundary experiments is due to the difficulty of the preview as perceived before the eyes crossed the boundary and only partly due to the validity of the preview. Moreover, preview-difficulty effects are observed in fixations on word *n*+1 even though they were not significant in fixations on word *n*. There was no evidence that results depended on participants' self-reported awareness of display changes that occurred during the experiment.

Experiment 2: Reading without capitalization of initial letters

In Experiment 1, the majority of readers were aware of at least some display changes; only seven out of 29 participants did not notice any word replacements. There is evidence that participants' awareness of display changes modulates the amount of preview that can be gained from the parafoveal word *n*+1 in readers of English (Slattery et al., 2011; White, Rayner, & Liversedge, 2005). Statistical control of the degree of self-reported awareness of display change did not significantly modulate the results in Experiment 1, but absence of evidence is not evidence of absence for such an effect. Therefore, in a second experiment we aimed at reducing the frequency with which participants would detect the critical changes.

In Experiment 1, sentences were presented normally with the initial letter of words capitalized according to German spelling rules. This is the case for the first word in each sentence, but also for all nouns (including proper names), irrespective of their position in the sentence. Display changes involving words with an initial uppercase and remaining lowercase letters may be more salient than changes involving only lowercase letters. Thus, in Experiment 2 all words in the sentences were presented without capitalization. Punctuation was preserved and participants were informed that they would read sentences consisting of words written only in lowercase letters.

Violation of capitalization rules of German was reported to lead to a lower overall reading rate, indicative of enhanced processing difficulty (Bock, 1989). Importantly, however, although lowercase writing is illegal according to German spelling rules, nowadays it is quite familiar and frequently used in SMS and emails. In fact, none of the participants in Experiment 2 reported any difficulties in reading the sentences. Nevertheless, there may still be an effect on reading rate and if so, then Experiment 2 also represents a replication of Experiment 1 in a slightly more challenging reading situation.

Method

Participants

Thirty-one students (26 female vs. 5 male) participated in the present experiment. They were between 17 and 33 years old (M = 21.3 years, SD = 3.7). All participants had normal or corrected-to-normal vision.

Materials and Design

Experiment 2 replicated Experiment 1 in material and design using the same sentences with the same preview and target-word difficulty manipulation. The only difference was that all words (i.e., sentence-initial words and all nouns, also when presented as previews) were written in lower case without capitalization of the beginning letter.

Apparatus and Procedure

The same eye-tracker setup and experimental procedure was used as in Experiment 1.

Data Selection and Analysis

Data selection was performed according to the criteria described for Experiment 1. A total of 24% of the sentences were removed due to invalid display changes and 3.4% due to signal loss of the eye tracker, leaving 2,742 experimental sentences for statistical analysis. Less than 1% of word-based fixation durations in the target region were additionally excluded due to being identified as outliers.

Results and Discussion

Target word n+1

Table 4 summarizes the findings of Experiment 2. Fixation durations on word n+1 were generally longer and fixed effects were mostly smaller than in Experiment 1. Yet, the main effect of preview validity was significant across all fixation-duration measures showing substantial benefit in target-word viewing times when valid preview of word n+1 was available (FFD: 13 ms, SFD: 13 ms, GD: 21 ms, TVT: 51 ms). In addition, there was again a main effect of preview difficulty. Fixation durations were shorter after easy compared to difficult previews of word n+1 irrespective of the current target-word difficulty replicating the novel finding of Experiment 1 (FFD: 8 ms, SFD: 8 ms, GD: 8 ms, TVT: 2 ms). Moreover, as in Experiment 1, the effect size of preview difficulty was slightly larger than that of preview validity for FFD and SFD. It reversed for GD and was more than three times the size of the preview-difficulty effect for TVT. The results strongly suggest differences in the time course of the two preview effects. In Experiment 2, there was a significant interaction between preview validity and preview difficulty (main effect of target difficulty) in GD and TVT. Conditions with a low-frequent target word (valid low-frequency preview and invalid high-frequency preview) showed significantly longer fixation durations than conditions with a high-frequent target word (valid high-frequency preview and invalid low-frequency preview). In GD, the target-word frequency effect amounted to 10 ms and increased to 33 ms in TVT (FFD: 3 ms, SFD: 4 ms). In Experiment 1, the numerical trend for these effects was in the same direction.

Table 4a
Experiment 2: Condition means on the target word *n*+1.

	Preview difficulty	easy (HF)		difficult (LF)	
Measure	Preview validity	valid	invalid	valid	invalid
First fixation duration		231 (6.8)	246 (8.2)	241 (6.9)	251 (8.0)
Single fixation duration		231 (7.0)	248 (8.6)	243 (7.1)	252 (8.2)
Gaze duration		237 (7.3)	267 (10.3)	254 (7.8)	265 (9.5)
Total viewing time		257 (9.5)	340 (15.2)	291 (11.4)	309 (12.9)
Skipping probability		.18 (.03)	.16 (.03)	.14 (.03)	.15 (.03)
Refixation probability		.03 (.02)	.07 (.02)	.05 (.02)	.04 (.02)

Note. Standard deviations listed in parentheses. HF: high-frequent *n*+1 preview. LF: low-frequent *n*+1 preview.

Table 4b
(G)LMM coefficients for analyses of fixation durations on the target word *n*+1.

	First fixation duration			Single fixation duration			Gaze duration			Total viewing time		
REs	*var*	*SD*		*var*	*SD*		*var*	*SD*		*var*	*SD*	
Subjects (I)	0.01	0.09		0.01	0.10		0.01	0.11		0.02	0.13	
Items (I)	0.03	0.18		0.04	0.19		0.04	0.20		0.05	0.22	
Residuals	0.09	0.30		0.09	0.30		0.10	0.32		0.15	0.38	
FEs	*b*	*SE*	*t*	*b*	*SE*	*t*	*b*	*SE*	*t*	*b*	*SE*	*t*
(I)	**5.41**	**0.03**	**157.4**	**5.42**	**0.04**	**152.9**	**5.45**	**0.04**	**145.2**	**5.57**	**0.04**	**130.2**
pvD	**0.05**	**0.01**	**3.7**	**0.05**	**0.01**	**4.2**	**0.05**	**0.01**	**4.1**	**0.04**	**0.02**	**2.2**
pvV	**0.04**	**0.01**	**3.1**	**0.04**	**0.01**	**3.3**	**0.06**	**0.01**	**4.4**	**0.15**	**0.02**	**9.7**
pvD:pvV	-0.04	0.04	-1.1	-0.05	0.04	-1.3	**-0.09**	**0.04**	**-2.2**	**-0.20**	**0.05**	**-3.9**

Note. Variance (*var*) and standard deviation (*SD*) of random effects (*REs*); regression coefficient (*b*), standard error (*SE*), and *t*-value (*t*) of fixed effects for log-transformed fixation durations on word *n*+1. Significant coefficients ($|t| > 1.96$) are set in bold. pvD: preview difficulty of word *n*+1. pvV: preview validity of word *n*+1. (I): Intercept.

Skipping probability showed an effect of the preview difficulty of word *n*+1 ($b = -.27$, $SE = .13$, $t = -2.28$) indicating that word *n*+1 was skipped more often when presented as an easy preview in parafoveal vision. With respect to refixation probabilities, only the interaction between preview validity and preview difficulty (the main effect of target difficulty) reached significance (*b* = -1.25, *SE* = .52, *t* = -2.39). Thus, the main effect of target difficulty on GD was also obtained for refixation probability.

Effects of display-change sensitivity on parafoveal preview. Participants were assigned to two different groups of display-change sensitivity with respect to their self-reported detection rates. Group 1 (i.e., low DC detection) consisted of 12 participants who did not notice any display changes and an additional nine participants who reported that 5 % or less sentences during the experiment contained display changes. Group 2 (i.e., high DC detection) comprised the remaining 10 participants who reported to have noticed 10 % or more display changes, one of who overestimated the true number of display changes in the experiment. Comparing the group sizes between experiments confirmed that display changes were less often detected in Experiment 2 without capitalization in which all words were written in lower case. Group 1 contained 13 participants in Experiment 1 but 21 participants in Experiment 2, whereas Group 2 consisted of 16 participants in Experiment 1 and only 10 participants in Experiment 2.

Adding the group factor of the participant's display-change sensitivity as covariate, the (G)LMMs did not differ significantly from the results reported above. Particularly, the sensitivity towards detecting display changes did not interact with any preview variable (all critical interactions showed absolute *t* value < 1.4). Irrespective of whether participants were aware or unaware of occasional word replacements during sentence reading, they were sensitive to both preview validity and preview difficulty. Specifically, the effect of preview difficulty was obtained delayed on fixation durations after the boundary. None of the more complex models provided a significantly better fit of the data (all χ^2 (4) < 1.9, *p* > .74).

Pretarget word n

The results from word *n* before the eyes crossed the boundary are summarized in Table 5. Again, there was no evidence for significant parafoveal-on-foveal effects of the preview difficulty in fixation durations on the pretarget word *n*. There were also no effects of preview validity before crossing the boundary and no interactions. Only in TVT, preview validity showed a significant influence, replicating a result from Experiment 1. Therefore, processing an invalid preview before the boundary seems to trigger regressions back from the postboundary into the preboundary region; participants not only reread the critical target word but also the pretarget word *n*. No effects were significant in the analysis of skipping and refixation probabilities (all absolute *z* values < 1.40), suggesting that the interaction between preview validity and preview difficulty in refixation probability in Experiment 1 was spurious.

Table 5a
Experiment 2: Condition means on the pretarget word *n*.

	Preview difficulty	easy (HF)		difficult (LF)	
Measure	Preview validity	valid	invalid	valid	invalid
First fixation duration		235 (7.4)	229 (6.8)	223 (6.8)	229 (7.5)
Single fixation duration		235 (7.8)	232 (7.1)	224 (7.0)	231 (8.1)
Gaze duration		261 (10.2)	248 (8.6)	245 (9.6)	258 (11.0)
Total viewing time		296 (14.9)	305 (14.7)	272 (11.6)	303 (14.7)
Skipping probability		.27 (.04)	.25 (.03)	.27 (.04)	.27 (.04)
Refixation probability		.12 (.03)	.08 (.03)	.10 (.03)	.09 (.03)

Note. Standard deviations listed in parentheses. HF: high-frequent *n*+1preview. LF: low-frequent *n*+1 preview.

Table 5b
(G)LMM coefficients for analyses of fixation durations on the pretarget word *n*.

	First fixation duration			Single fixation duration			Gaze duration			Total viewing time		
REs	*var*	*SD*		*var*	*SD*		*var*	*SD*		*var*	*SD*	
Subjects (I)	0.01	0.08		0.01	0.09		0.02	0.14		0.03	0.16	
Items (I)	0.02	0.14		0.02	0.14		0.02	0.15		0.03	0.19	
Residuals	0.08	0.28		0.08	0.27		0.10	0.32		0.16	0.41	
FEs	*b*	*SE*	*t*	*b*	*SE*	*t*	*b*	*SE*	*t*	*b*	*SE*	*t*
(I)	**5.38**	**0.03**	**193.8**	**5.39**	**0.03**	**192.3**	**5.44**	**0.03**	**173.1**	**5.53**	**0.04**	**147.1**
pvD	-0.02	0.01	-1.7	-0.02	0.01	-1.3	-0.01	0.01	-1.0	-0.02	0.02	-1.1
pvV	-0.01	0.01	-0.5	-.0002	0.01	-.01	-.004	0.01	-0.3	**0.05**	**0.02**	**2.9**
pvD:pvV	0.05	0.04	1.3	0.05	0.04	1.3	0.06	0.05	1.2	0.03	0.06	0.5

Note. Variance (*var*) and standard deviation (*SD*) of random effects (*REs*); regression coefficient (*b*), standard error (*SE*), and *t*-value (*t*) of fixed effects for log-transformed fixation durations on word *n*+1. Significant coefficients ($|t| > 1.96$) are set in bold. pvD: preview difficulty of word *n*+1. pvV: preview validity of word *n*+1. (I): Intercept.

Including the display-change detection sensitivity for each participant as covariate into the statistical models revealed some hint for preview-difficulty effects on the pretarget word *n* at least for participants who reported a higher percentage of display changes. As Figure 2 illustrates, the effect of preview difficulty was stronger in Group 2 (i.e., high DC detection) than in Group 1 (i.e., low DC detection), and this interaction was marginally significant both in FFD ($b = .05$, $SE = .03$, $t = 1.95$) and GD ($b = .06$, $SE = .03$, $t = 1.91$).

In summary, the results of Experiment 2 confirmed that the individual display-change sensitivity of participants did not interact with parafoveal processing in the boundary paradigm, except in case of immediate parafoveal-on-foveal effects on the pretarget word *n*. Moreover, the results support the conclusion from Experiment 1 that fixation durations on the target word *n*+1 are not only shortened by preview validity, but that there is an independent delayed effect of preview difficulty. Both effects are due to the preprocessing of word *n*+1 in parafoveal vision. However, preview validity is an immediacy effect of foveal processing in that it reflects the processing demand of the later target word mediated by the parafoveal information perceived during the previous fixation (i.e., parafoveal preview benefit). The effect of preview difficulty, in contrast, stems solely from the processing situation that was perceived on word *n* before the boundary. In other words, it reflects a delayed effect of the parafoveal preview that modulates fixation durations after the eyes already left the pretarget word *n*. As these two preview effects yet occur on the same word *n*+1, we conducted a supplementary analysis to further investigate their differential time courses in fixation durations, suggested by differences in relative effect sizes between FFD and SFD as opposed to GD and TVT in both experiments.

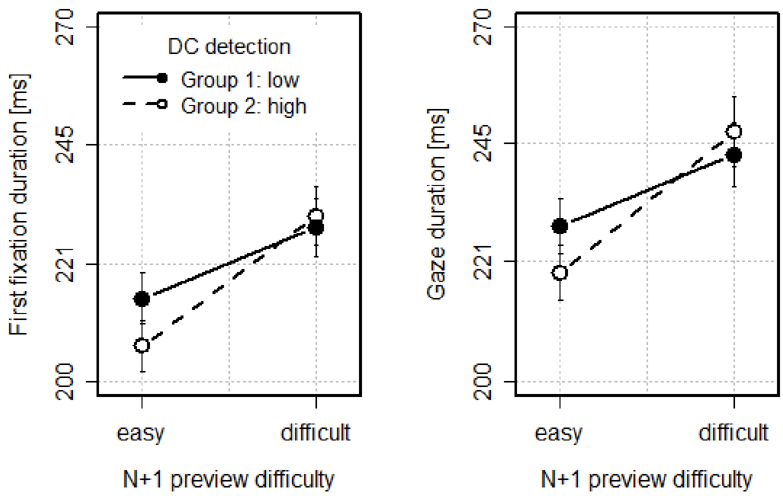

Figure 2. First fixation duration (left panel) and gaze duration (right panel) on the pretarget word *n* as a function of preview difficulty in Experiment 2. Fixation durations are re-transformed from logarithmic fixation durations. Group 1 and Group 2 reflect participants with different display change (DC) detection sensitivities. Steeper slopes of the lines reflect stronger parafoveal-on-foveal effects.

Supplementary Analysis

Quantile regression (Koenker, 2005) can be used to investigate the time course of experimental effects on the when-decision of the oculomotor system. Estimating the conditional quantiles of the fixation-duration distribution in linear models, we tracked the impact of the two preview effects on fixations of different durations. On the one hand, given that the integration of parafoveal preview information into foveal processing could only start after the eyes landed on the target word, preview-validity effects should be more likely for longer fixation durations on word *n*+1. Therefore, preview benefit should be significant in the high quantiles of the fixation-duration distribution rather than in the low quantiles. On the other hand, we argued that the preview-difficulty effect is primarily a consequence of the processing situation at word *n* and only too late to affect the associated fixation on the word before the boundary. Having started on word *n*, delayed preview-difficulty effects should thus influence oculomotor decisions on word *n*+1 already quite early and appear in the low quantiles of the fixation-duration distribution on the target word.

Figure 3 shows the results from a repeated-measures quantile-regression analysis for log-transformed FFDs on the target word *n*+1 (i.e., the first fixation after the eyes crossed the boundary) pooled across experiments[2]. Depicted are the mean effects for preview validity (pvV) and preview difficulty (pvD) as a function of 10 fixation-duration quantiles based on separate quantile regressions for each participant. In the box at the bottom of Figure 3, the significance of the t-values for each slope in each quantile is summarized with respect to conventional significance levels based on a simple quantile-regression model including intercept, pvV and pvD slope estimates and their interaction across all 60 participants. From the latter analysis, we can re-transform the upper and lower quantile values (i.e., log-transformed FFDs) into meaningful fixation durations in milliseconds. However, it should be born in mind that these time points show substantial individual variation between participants.

Time course of preview effects

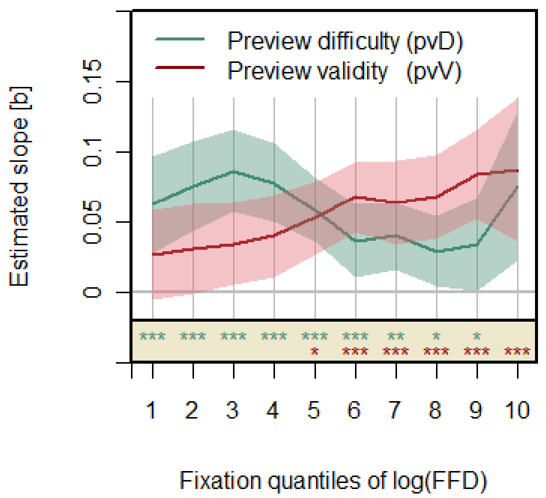

Figure 3. Quantile regression (QR) for target-word *n*+1 fixation durations. Mean slope estimates for preview difficulty and preview validity as a function of log-transformed first-fixation duration quantiles derived from repeated-measures QR. Shaded areas show the 95 % confidence intervals of these estimates among participants. Asterisks below the curves indicate the significance level of the slopes in the respective quantile of the model across all participants: *** p < .001, ** p < .01, * p < .05. See text for more details.

As expected, the preview-validity effect (pvV slope) increased continuously from short to long target-word viewing times. In the first quantiles up to around 217 ms the benefit of preview validity was not significant. In contrast, the effect of preview difficulty was significant already in the earliest quantiles (<= 180 ms). Starting from fixation durations greater than 180 ms, the pvD-slope then decreased but failed to reach significance only in the last quantile of fixation durations greater 340 ms. Thus, the strength of the preview-difficulty effect was already at maximum immediately after fixation onset on the target word and slowly decreased with increasing target-word viewing times.

In summary, the results of the supplementary analysis corroborated the hypothesis of a different time course for the two parafoveal preview effects. The present time-course analysis of fixation durations on word *n*+1 indicated that preview difficulty affected the fixation duration distribution on the target word much earlier than preview validity. Therefore, the effect of preview difficulty presumably started already on the preboundary fixation, in agreement with its interpretation as a delayed preview effect from the pretarget word *n*.

General Discussion

Two experiments tested the time course of parafoveal processing of word *n*+1 in the boundary paradigm. We distinguished two types of preview effects that are indicative for a differential temporal impact on the decision of when to move the eyes ahead during reading: The classic effect of preview benefit resulting from information overlap between parafoveal preview and foveal target word (i.e., situation after the display change) and another effect of parafoveal preview difficulty exclusively due to its processing demand before the target word was fixated (i.e., situation before the display change). We tested the preview benefit as an effect of preview validity and the other preview effect as an effect of preview difficulty. Crossing both preview factors, we went beyond findings from previous boundary experiments and assessed the contribution of both types of preview effects on the same word *n*+1.

The time course of parafoveal processing

In the boundary paradigm, preview effects have been typically investigated on different words in the target region (e.g., Hyönä & Bertram, 2004; Kennedy et al., 2002; Rayner et al., 2004). Preview benefit is measured on the target word *n*+1 after the display change and typically shows reduced foveal word-recognition times if the parafoveal preview contained valid information about the target word (i.e., preview validity). This preview information is acquired on word *n* before the boundary. Therefore, preview benefit is a rather late effect of parafoveal processing. Immediate preview effects, on the contrary, are measured on word *n*. These parafoveal-on-foveal effects are not consistently observed across studies (see Drieghe, 2011, for a review), but this may be because the effects did not have enough time to materialize during the fixation on the preboundary word *n*. We manipulated the preview difficulty of word *n*+1 as one option to test such immediate effects of parafoveal processing. The most intriguing finding of the present experiments was that the effect of the preview difficulty was observed not immediately on word *n* (except in Experiment 2 for participants with a higher sensitivity for display changes) but delayed on word *n*+1. As the preview validity was manipulated independently of the preview difficulty, the latter effect could be detected in addition to a reliable preview benefit on word *n*+1. In previous studies, any such effects were confounded with the assessment of preview benefit.

The results of the present study integrate several findings related to the boundary paradigm, some of which are controversial. They allow a unified view on the temporal influence of parafoveal processing on immediate and subsequent eye-movement decisions. The results replicated evidence for preview benefit on the target word *n*+1 (e.g., Inhoff, 1990; Rayner et al., 1978) and are consistent with research using the boundary paradigm that did not find significant evidence for immediate parafoveal-on-foveal effects of the preview difficulty on the pretarget word *n* (e.g., White, 2008). In order to control the overall processing difficulty of the previews we varied their lexical frequency in the first place, but the previews also differed in low-level orthographic measures such as their initial bigram- or trigram-frequency. Orthographic familiarity of the initial letters or random letter-strings in parafoveal vision, however, exerted reliable parafoveal-on-foveal effects in other studies (e.g., Drieghe et al., 2008; Inhoff et al., 2000; Pynte, Kennedy, & Ducrot, 2004; Vitu et al., 2004). Given that effects showed up delayed on word *n*+1, we tentatively suggest that in the present study previews were not only processed on a coarse level of orthography but that the difficulty information was based on higher-level word processing, most likely its lexical frequency.

Delayed effects of preview difficulty after the boundary replicated findings with the *n*+2-boundary paradigm (Kliegl et al., 2007; Risse & Kliegl, 2011, 2012). Varying the preview of word *n*+2 two words to the right of fixation consistently resulted in an effect of the preview difficulty of word *n*+2 on word *n*+1. We termed this a delayed parafoveal-on-foveal effect because it was not associated with the validity of the word *n*+2 preview or with the *n*+2 target-word difficulty after the display change but only with its difficulty before the boundary. Going beyond these findings, the present experiments showed similar delayed effects, but in the classical *n*+1-boundary paradigm. Moreover, effect sizes suggested that this delayed preview effect is of similar size than the preview-benefit effect and thus a substantial part of parafoveal processing during reading.

Interpreting the preview-difficulty effect on word *n*+1 as a delayed effect implies that it originates from the processing situation before the display change. The fact that in the *n*+2-boundary paradigm there was no evidence for properties of word *n*+2 after the display change in the first fixation after the eyes crossed the boundary (i.e., on word *n*+1) is in agreement with this interpretation. Alternatively, one could argue that the preview-difficulty effect reflects asymmetric preview-to-target switch costs due to stronger inhibition of high-frequent word competitors in case of a low-frequent preview (cf. Arbuthnott, 2008). Target words with higher-frequency neighbors (i.e., words that differ only in a single letter but are more frequent than the target word) received longer total reading times, were reread more often, and lead to greater spillover effects in fixation durations on the next word in sequence in comparison to frequency-matched target words without higher-frequency neighbors (Perea & Pollatsek, 1998). However, a comparable slowing was not obtained when a high-frequency neighbor was presented in parafoveal vision that was later replaced by a low-frequency target word (Williams, Perea, Pollatsek, & Rayner, 2006). Greater preview benefit could be gained from the high-frequency neighbor than from a nonword sharing the same number of letters with the target word. This indicates that the lexical difficulty of the preview was parafoveally extracted but did not interfere with target-word recognition after the display change.

Further support for a temporal delay of the preview difficulty comes from quantile-regression analyses of the time course of the two preview effects across the distribution of fixation durations on the target word *n*+1. In contrast to the preview validity, the preview difficulty was significant already for the shortest fixation durations. Thus, the cost from preprocessing a difficult preview during preboundary fixations affected the very early saccadic decisions on the target word whereas the benefit from valid preview information impacted later. Early effects of parafoveal preview have also been reported in a study estimating the divergence point of survival curves for distributions of FFDs for high- and low-frequency target words *n*+1 (Reingold, Reichle, Glaholt, & Sheridan, 2012). The very early effect of preview difficulty in the present study, however, suggests that it had started on word *n* (i.e., as a parafoveal-on-foveal effect) but was delayed into fixations on the next word *n*+1. To the contrary, the late effect of preview validity nicely fits with its interpretation as preview benefit resulting from integrating valid preview information that can start only after the target word is fixated.

In summary, research on eye movements during reading has revealed a complex nature of what constitutes the duration of reading fixations. In the context of integrating foveal and parafoveal information across the perceptual span, fixation durations seem to reflect (1) the foveal processing difficulty which is reduced by means of parafoveal preview benefit, (2) delayed preview-difficulty effects suggesting a head-start of processing the word already on the previous fixations, (3) lag- or spillover effects of the difficulty of the parafoveal word *n*-1 to the left of fixation (e.g., Kliegl et al., 2006; Schroyens et al., 1999), and (4) immediate parafoveal-on-foveal effects of the upcoming word *n*+1 to the right of fixation (Hyönä & Bertram, 2004; Inhoff et al., 2000; Kennedy et al., 2002; Kliegl et al., 2006). With respect to the inconsistencies in finding the latter, the readers' strategic trade-off between a word's difficulty and its fixation probability has recently been shown to be a limiting condition

(Wotschack & Kliegl, 2012). The present results suggest that another reason might be the delay of such effects into fixations on the next word *n*+1.

Implications for computational models of eye-guidance during reading

All reading models – at least since Morrison (1984) – consider the possibility of processing not-yet-fixated words in parafoveal vision and can account for preview benefit. Computational models such as E-Z Reader (e.g., Pollatsek, Reichle, & Rayner, 2006; Reichle, Rayner, & Pollatsek, 2003) and SWIFT (Engbert et al., 2005) differ, for example, in that attention is either shifted serially from word to word or is distributed in a gradient fashion across the words inside the perceptual span. Despite this major difference, the implementation of parafoveal preview with respect to word identification is similar. Most reading models assume a two-stage process of lexical access, which has to be completed before a word is identified (e.g., Engbert, Longtin, & Kliegl, 2002; Reichle et al., 1998). Parafoveal processing contributes information to the word recognition process (e.g., it activates word entries in the mental lexicon), and this information is available as a processing advantage when the word is finally fixated, reducing its maximum word-identification time (i.e., preview benefit).

The present results suggest, however, that there is also an additional effect, in terms of an additional cost, on a given fixation due to parafoveal processing difficulties detected before the word was fixated. This delayed preview effect indicates that the influence of parafoveal processing on the when-decision of the next eye movement is not always immediate. In fact, this emphasizes an additional aspect of reading models, namely the coupling between the temporal control of saccade programming and attention allocation. In E-Z Reader, for example, word processing is serial and partial processing-success of the attended word (completion of L1-stage) directly triggers the next saccade program. A strong and direct coupling between cognitive processing and oculomotor timing, therefore, predicts that processing difficulties translate immediately into the eye movement record. Thus, the fact that preview effects are delayed seems to contradict the approach of direct cognitive control of eye movements during reading.

Yet, computational models are even more complex than this. For example, E-Z Reader takes into account that visual information at the new fixation location needs about 50-90 ms to arrive in the respective cortical brain areas responsible for lexical word-identification (e.g., Foxe & Simpson, 2002). Such updating delays may be one reason why the parafoveal preview can have a sustainable effect after it was replaced by the target word. In E-Z Reader this transmission time (the V stage) could be used to continue processing the old representation that reflects the processing situation at the past fixation location until the new representation arrives. Under certain circumstances, this process may trigger a saccade program and the old representation should show an effect on the early saccade-programming decisions. Whether the process would also affect the fixation duration distribution in later quantiles, as suggested in the time-course analysis, is unclear and requires model simulations.

The importance of word representations during reading has also been highlighted in a study in which words disappeared 60 ms after fixation onset and readers were looking at a blank space (Liversedge et al., 2004; Rayner, Liversedge, & White, 2006). If there was sufficient time to activate a stabile representation of the fixated word, fixation durations showed effects of the word’s processing difficulty even though it was removed. Delayed preview effects further suggest that, during each reading fixation representations are also established of the parafoveal word *n*+1 (and even of word *n*+2, see Risse & Kliegl, 2012), and that such representations affect fixation durations still after a saccade moved the eyes to a new location. Thus, the present results confirm the impact of word representations on reading and stress the need for more careful consideration of their sustainability in understanding the full dynamics of processing inside the perceptual span.

The SWIFT model offers a parallel word-processing framework in which processing difficulties rather indirectly control an otherwise autonomous saccadic timer. Findings of temporal delays in the oculomotor response to online processing difficulties are in good agreement with the assumption of indirect control as they suggest that some portion of saccades (i.e., mostly before the boundary) were independently generated without being affected by current (parafoveal) difficulties. However, at its contemporary stage SWIFT uses only foveal information to inhibit saccade programs and provides no particular mechanism to account for parafoveal-on-foveal effects. That means that even though SWIFT is a parallel reading model at present it explains parafoveal-on-foveal effects as a result of differences in saccade-target selection. Parafoveal difficulty affects processing in SWIFT through a tradeoff between foveal fixation time and refixation probability modulating the likelihood to find rather long than short single-fixation durations on the pretarget word *n* in the presence of a difficult parafoveal word *n*+1. However, extending foveal to parafoveal inhibition such effects may be directly implemented into the model without conflicting with its primary assumptions. The delay in preview effects could then be modulated by the fact that more eccentric information takes longer to accumulate and often inhibits the next saccade after word *n* has already been left.

In a more recent version of the SWIFT-model (Schad & Engbert, 2012; see also Trukenbrod & Engbert, submitted), control of the random saccade timer is achieved through the implementation of discrete random walks to model the time between two successive saccades. In this framework, processing difficulty continuously (and immediately) affects the fixation duration by changing the rate of the random-walk process accordingly. This somehow acts as a monitoring system continuously guarding the processing success during reading. Parafoveal difficulties that have been detected at some point may remain in the memory of the monitoring system. Irrespective of whether the processing difficulty is perceptually still available, traces of the preview difficulty should be observed even after its replacement. It is an intriguing empirical question which approach can better account for the specific time course of preview effects in fixation durations after the boundary, and its answer could be valuably supported by informative simulations within the computational models.

Conclusion

The findings from the present experiments suggest that parafoveal preview benefit in the boundary paradigm may in part be due to a delayed effect of the preview difficulty before the boundary. Parafoveal processing difficulty appears to have a direct but possibly delayed influence on the oculomotor decisions during reading that is independent of the preview validity that benefits the later foveal processing. The time course of preview effects observed in the present experiments supports the notion of preview effects that were initiated during preboundary fixations and indicates that past processing situations have sustained effects at least for an early time period after changing the fixation location. Delayed preview effects describe a novel aspect about how foveal and parafoveal information is integrated across the perceptual span and place new constraints on the spatio-temporal coordination of attention, word recognition, and eye movements during reading.

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Footnotes

1. Reported effects were also significant for more complex models containing more variance components (e.g., random slopes). Note that data and R scripts are available at the Potsdam Mind Research Repository (http://read.psych.uni-potsdam.de/pmr2/).

2. We used the R package “quantreg” version 4.62 (Koenker, 2011) to estimate the quantile regressions. The results for SFD and GD were similar. As most fixations on word *n*+1 were single fixation cases, all first-pass fixation duration measures shared a very large subset of the data.