

An incremental boundary study on parafoveal preprocessing in children reading aloud: Parafoveal masks overestimate the preview benefit

Christina Marx, Stefan Hawelka, Sarah Schuster, and Florian Hutzler

Centre for Cognitive Neuroscience, University of Salzburg, Salzburg, Austria

Parafoveal preprocessing is an important factor for efficient reading and, in eye-movement studies, is typically investigated by means of parafoveal masking: Valid previews are compared to instances in which masks prevent preprocessing. A long-held assumption was that parafoveal preprocessing, as assessed by this technique, only reflects facilitation (i.e., a preview benefit). Recent studies, however, suggested that the benefit estimate is inflated due to interference of the parafoveal masks, i.e., the masks inflict processing costs. With children from Grades 4 and 6, we administered the novel incremental priming technique. The technique manipulates the salience of the previews by systematically varying its perceptibility (i.e., by visually degrading the previews). This technique does not require a baseline condition, but makes it possible to determine whether a preview induces facilitation or interference. Our salience manipulation of valid previews revealed a preview benefit in the children of both Grades. For two commonly used parafoveal masks, we observed interference corroborating the notion that masks are not a proper baseline. With the novel incremental boundary technique, in contrast, one can achieve an accurate estimate of the preview benefit.

Keywords: Eye movement control; Parafoveal preprocessing; Reading.

From an adult's perspective it is often forgotten that we did not acquire the remarkable feat of reading effortlessly. The efficiency with which most of us read is due to, among many other aspects, parafoveal preprocessing: We do not only process the word which we are currently fixating, but also preprocess the upcoming, parafoveal word. This process leads to a preview benefit for the recognition of preprocessed words. For adult readers, this benefit has been estimated to be of a

magnitude of about 30–50 ms compared to instances where parafoveal preprocessing a word is not possible. Thus, parafoveal preprocessing accelerates word recognition and plays a pivotal role for fast and fluent reading (Rayner, 1998, 2009; Rayner, Liversedge, & White, 2006). Little is known, however, about the emergence and development of parafoveal preprocessing in beginning readers. The objective of the present study is to examine whether the common method to assess

Correspondence should be addressed to Stefan Hawelka, Centre for Cognitive Neuroscience, University of Salzburg, Hellbrunnerstraße 34, 5020 Salzburg, Austria. E-mail: stefan.hawelka@sbg.ac.at

We would like to thank the children who participated in the study and the principals and teachers who granted us the permission to conduct the study in their schools. We are grateful to Ramona Zintl for her help in data collection.

No potential conflict of interest was reported by the authors.

This work was supported by the Austrian Science Fund (FWF) [grant number P25799].

© 2015 The Author(s). Published by Taylor & Francis.

This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. The moral rights of the named author(s) have been asserted.

parafoveal preprocessing, that is, the invisible boundary paradigm (Rayner, 1975) is suitable for studying the process in children.

Most of what we currently know about parafoveal preprocessing is based upon studies with adult readers (mostly university students; see Schotter, Angele, & Rayner, 2012 for a recent review). There are comparatively few eye movement studies with children (see Blythe & Joseph, 2011 for a review of the existing evidence). These studies showed that more experienced (i.e., older) children exhibit faster reading times, a higher skipping probability, a smaller probability of re-fixations, fewer fixations, and fewer regressions compared to less experienced (i.e., younger) children. Furthermore, the results of these studies suggest that developmental changes in eye movement behaviour reach adult characteristics around the age of approx. 12 years (Blythe, Liversedge, Joseph, White, & Rayner, 2009; Blythe et al., 2006; Häikiö, Bertram, Hyönä, & Nieme, 2009; Huestegge, Radach, Corbic, & Huestegge, 2009; Rayner, 1986).

As yet, the primary focus of eye movement studies with children has been on foveal word recognition (e.g., Blythe, Häikiö, Bertam, Liversedge, & Hyönä, 2011; Blythe et al., 2006; Huestegge et al., 2009; Joseph, Liversedge, Blythe, White, & Rayner, 2009). Comparatively few eye movement studies investigated parafoveal preprocessing in children. A longitudinal eye movement study by Huestegge et al. (2009) found a gain in reading speed of about 40% from Grade 2 to Grade 4 (in German-speaking children). However, the authors did not determine whether (and to what extent) this gain was due to more efficient foveal word recognition or (additionally) due to the emergence of parafoveal preprocessing. Recently, Zoccolotti et al. (2013) reported that 12-year-old children read words faster when they were presented in a list format compared to words presented in isolation (dyslexic children of the same age did not exhibit this benefit). This finding indicates that 12-year-old, typically developing children indeed preprocess parafoveal information about the upcoming word and utilise it to foster word recognition when the word is foveated.

Further evidence for the development of children's capability to extract parafoveal information during reading was provided with the gaze-contingent moving-window technique (Häikiö et al., 2009; Rayner, 1986). This technique displays mutilated text outside a specified window to the left and the right of the reader's current fixation

(e.g., masking all letters with x's). Within the window the text is presented normally (i.e., unmasked). By systematically altering the size of the window, this technique assesses the *perceptual span* of a reader. The span is the minimal size of the window with which a person can read at his/her usual speed (McConkie & Rayner, 1975). Rayner (1986) reported that the perceptual span of 2nd and 4th Graders is substantially smaller than those of adult readers. Sixth Graders, in contrast, exhibit a close to adult-like span size (see also Häikiö et al., 2009).

Most evidence about the parafoveal preview benefit, as aforementioned, is based on skilled adult readers. Ashby, Yang, Evans, and Rayner (2012), for example, investigated parafoveal processing during silent and oral reading by changing the size (one word versus three words) of a moving window. The outcome revealed that parafoveal preprocessing facilitated reading in both oral and silent reading (i.e., reading speed was faster with the three than with the one-word window). The parafoveal benefit, however, was more pronounced in silent reading. This suggests that the additional demands of oral reading reduce parafoveal preprocessing.

The bulk of what we know about the preview benefit, however, stems from eye movement studies which applied another gaze-contingent display change technique, that is, the *invisible boundary paradigm* (Rayner, 1975). Within this paradigm, a boundary is placed before a target word. As long as the reader's gaze is in front of the boundary, the target word is substituted by an experimentally manipulated preview (e.g., by a mask). When the readers move their gaze towards the target—in so doing crossing the boundary—the manipulated preview is replaced with the actual target word. Commonly used parafoveal masks with this paradigm are the same-shape/different letter mask (i.e., a sequence of different letters which preserves the shape of the target word; henceforth abbreviated as SSDL-mask) and the X-mask (a string of X's with the same length as the target word). The magnitude of the effect of parafoveal preprocessing is estimated by subtracting the reading time of the target words after preprocessing valid previews from the reading time after previewing masks. With this technique, Ashby and Rayner (2004) and Ashby and Martin (2008), for example, showed that readers can extract phonological information (i.e., the syllable structure) from a parafoveal word (see Discussion).

A requirement for an exact (and valid) estimation of the preview *benefit* with the boundary paradigm is that the mask (i.e., the *baseline* condition) does not induce processing costs (i.e., does not interfere with the foveal processing of the target word). Put differently, the baseline condition must be *neutral*. Recent studies, however, challenge the neutrality of the most commonly used parafoveal masks: A study from our lab provided evidence that previewing X-masks interferes with the foveal processing of target words (Hutzler et al., 2013). In this study, we simultaneously recorded eye movements and EEG (i.e., fixation-related brain potentials; Hutzler et al., 2007). The findings showed that the parafoveal X-masks markedly delayed the emergence of the neural signature of an effect (i.e., the old/new effect; Friedman, 1990) compared to a condition which did not present a preview at all (i.e., the presentation of isolated words). As for random-letter masks, Kliegl, Hohenstein, Yan, and McDonald (2013) reported interference with foveal word recognition. They assessed the duration of fixations which were either in close proximity or at a remote distance of masked target words. The rationale is that if fixations are close to the parafoveal mask, then the parafoveal preview is highly visible (i.e., has a high *salience*). If the fixation is at a large distance from the target word, then its salience is low. Higher salience of parafoveal masks increased the processing time for the subsequently fixated (unmasked) target words compared to instances in which the masks were less salient—a clear indication that the mask interfered with foveal word recognition. The authors concluded that the joint application of the invisible boundary paradigm and parafoveal masks produces a complex mixture of benefits (for valid preview) and costs (for masks).

The rationale to relate the processing times of a stimulus (*target*) to the salience of a preprocessed stimulus (*prime*) was originally put forward by Jacobs, Grainger, and Ferrand (1995). The authors introduced an ingenious paradigm for the study of *priming* (which also faced the question of an adequate baseline): The *incremental priming technique*. The technique gradually (and systematically) manipulates the salience of the primes: If increasing salience of the primes lead to a prolongation of the processing times of the targets, then the primes interfered with target processing. Conversely, if increasingly higher salience of the primes results in a decrement of processing times, then the primes were facilitatory. The present

study combines the rationale of incremental priming with the boundary paradigm. We manipulated the salience of parafoveal previews (valid previews, SSDL-masks and X-masks) by gradually reducing the visual integrity of the preview (i.e., displacing a certain amount of black pixels of the preview). We related the various salience levels of the previews to our indices of processing time [first fixation duration (FFD) and gaze duration (GD)]. In so doing, we can assess the suitability of parafoveal masks and the salience manipulation for the study of parafoveal preprocessing in children.

METHOD

Participants

A total of 58 Austrian (i.e., German-speaking) children participated. They were recruited from five different schools (from the city of Salzburg and the surrounding area). Data collection was conducted in the month of May, that is, during the pre-final month of the school year. Thus, (subtracting the holiday periods) our younger readers had about 34, our older readers about 52 month of formal reading instruction. (Note that in Austrian Kindergartens no reading instruction is administered.) Four children were excluded from the study; one because of an expressive language disorder (stuttering), and three because they read too slowly (i.e., they had a reading quotient of less than 85 on a test for reading speed; see later). The final sample consisted of 27 Grade-4 children (10 boys/17 girls) and 27 Grade-6 children (17/10). The mean age of the children was 10 and 12 years, respectively ($SD = 4$ and 7 months).

To prevent the inclusion of below-average readers, we administered standardised tests for reading speed, that is, the Salzburger Lese Screenings (SLS1-4, Landerl, Wimmer, & Moser, 1997; SLS5-8, Auer, Gruber, Mayringer, & Wimmer, 2005). These paper-and-pencil tests present lists of sentences. The sentences are either semantically correct (e.g., “A week has seven days”) or a gross violation of common knowledge (e.g., “Strawberries are blue”). The children had to read the sentences silently and mark the sentences for correctness. The measure was the number of correctly marked sentences within a time limit of 3 min. Children who scored below the normal range of reading speed (compared to their respective age norms) were not included in the study, i.e., when their reading quotient was more than 1 SD

(15) below the norm mean (100). Our final samples of 4th and 6th Graders performed equally compared to the respective age norms with reading quotients of $M = 110$ and 109 , respectively ($SD = 11$ and 16 ; $t < 1$). For the comparison of the two groups in terms of absolute reading speed, we converted the test scores in a word per min measure (*wpm*). The 4th Graders read on average 88 wpm; the mean of the 6th Graders was 129 ; $SD = 15$ and 34 , respectively; $t(52) = 5.75$, $p < .001$.

Material

The experimental manipulation of the target word was twofold. First, we manipulated the type of preview (three types): valid preview ($n = 30$), X-mask or SSDL-mask ($n = 30$ each). The former mask consisted of x's, but preserved the common capitalisation of the initial letter of German nouns [e.g., target: *Blitz* (lightning); mask: *Xxxxx*]. The latter presented different letters, but preserved the word shape of the target word [e.g., target: *Kopf* (head); mask: *Pnql*]. Second, we manipulated the *saliency* of the parafoveal preview. Figure 1 presents an example. *Saliency* refers to the degree of visual degradation (three levels). Degradation is the random exchange of a certain amount of the black pixels from the bitmap of the preview with white pixels. The same amount of the white pixels surrounding the letters was replaced by black pixels. The amount of displaced pixels were 0%, 10%, and 20% for our three levels of degradation (henceforth, we refer to the levels as high, medium, and low saliency). The amounts of pixels displacements were chosen upon the outcome of pilot studies (with samples of University students).

Susi wohnt in einem großen Zwmn neben der Schule.
 Susi wohnt in einem großen Zwan neben der Schule.
 Susi wohnt in einem großen Zwm neben der Schule.
 Susi wohnt in einem großen Haus neben der Schule.

Figure 1. Example of a sentence with a SSDL-mask as parafoveal preview. The target word was Haus (house). Top-to-bottom, the example shows the three levels of saliency of the parafoveal preview (i.e., visual degradation of 0%, 10%, and 20%, respectively). The last line of the Figure illustrates the location of the invisible boundary (dashed line) and the unmasked and undegraded target word which appeared after crossing the boundary. Note that the bitmaps of the sentences were optimized for a low screen resolution (640×480 pxl; which made possible the high refresh rate of 200 Hz). The depiction appears blurry at higher resolutions.

The visual degradation was administered with an in-house *R-script* and the *pixmap*-package of Bivand, Leisch, and Mächler (2008). Note that the target word and all words thereafter were degraded (see Figure 1).

The combination of the three preview types (i.e., valid, X-mask, SSDL) and the three saliency levels resulted in a total of nine conditions (i.e., nine preview-by-saliency combinations). Each of these nine conditions comprised 10 words, i.e., we had 90 target words (exclusively nouns; mean length: five letters; range: 4–6). The target words were embedded in sentences; one target per sentence (i.e., $N = 90$ experimental sentences). The target words were, according to a Latin square design, rotated between the nine experimental conditions. This was conducted in such a way that each word was presented once in each of the experimental conditions (i.e., we had nine different experimental sequences). Each of the sequences of 90 sentences was presented to an equal number of participants (three children per Grade). The consequence of this counterbalancing was that a particular target word was presented only six times (three times for each of the two Grades) with a specific combination of the *type of preview* and *degree of saliency* manipulations.

The lengths of the experimental sentences ranged from 6 to 12 words ($M = 8.84$, $SD = 1.11$). The target words had a mean frequency (occurrences per million) of 105 according to the SUBTLEX-DE norms (Brysbaert et al., 2011). Sentences were constructed in such a way that at least three words preceded and at least one word followed the target word ($M = 5.4$ and 2.5 , respectively). The pre-target words were medium-length and (on average) high-frequency adjectives. The mean length of the pre-target word was 5.26 letters ($SD = 0.84$; range: 4–8). The mean frequency of their lemma-form (i.e., the uninflected form of the word) was 204 per million (word-form: $M = 85$ per million). The sentences were typed in a bold and mono-spaced font type; black on white background. Each character had a width of 10 pixels on the display screen (whose specifications are provided in the apparatus section). From the 50 cm viewing distance a single character had a width of $\sim 0.5^\circ$ of visual angle.

Apparatus

Eye movements were recorded (monocular for the right eye; sampling rate 500 Hz) with an EyeLink 1000 (SR Research, Canada). We used the

Desktop mount configuration with the “remote” set-up which compensates for head movements (by tracking a target sticker on the children’s forehead). The children sat at a viewing distance of approx. 50 cm to the 17 inch CRT-monitor (640 × 480 pixel resolution, 200 Hz frame rate).

Procedure

Prior to the eye tracking, we administered the reading speed (pencil-and-paper) test in the classrooms of the children. The eye tracking was conducted in a separate room (duration approx. 15 min). First, we performed a horizontal 3-point calibration routine to familiarise the children with calibrating the eye tracking system; the routine was repeated until the child achieved an average tracking error below 0.5° of visual angle. Then, five familiarisation trials for the sentence reading task were administered after which calibration was repeated; now with a more stringent criterion (average tracking error <0.3°). Then, we presented the 90 experimental sentences. A trial started with a *fixation check*, that is, the presentation of a fixation cross at the left side of the screen (vertically centred). Calibration was repeated when the fixation check failed (but not later than the presentation of 45 sentences). In case that the system had detected a fixation (minimum duration: 100 ms) on the fixation cross, the sentence was presented. Display changes were realised with the invisible boundary technique (Rayner, 1975). The boundary was at the very end of the pre-target word (see Figure 1). If the sentence presented a manipulated preview (visually degraded and/or masked), then crossing the boundary triggered the presentation of the unmutated target word [and the unmutated display of the subsequent (post-target) words; see Figure 1]. Note that crossing the boundary in the valid preview condition with the highest salience (i.e., 0% pixel displacement) triggered the (re-)appearance of the pre-boundary stimulus, i.e., there was no (physical) change. The children read the sentences aloud. (We aimed at comparability with future studies with younger readers for whom reading aloud is the “default”.) The experimenter noted reading errors.

Data treatment

We considered FFD as the dependent measure of main interest for the present study since the effect of parafoveal preprocessing will be most evident in

the initial fixation on the target words (FFD are sometimes considered as an “early measure”; e.g., Perea & Pollatsek, 1998). Additionally, we report GD, single fixation probability and initial landing position. For analysis, we considered only trials in which the target word was fixated during first pass reading. This criterion resulted in the exclusion of 3% of the trials, i.e., 148 from the total of 4,860 trials. This figure also includes trials in which the eye tracker did not register a fixation on the target word within a time limit of 60 ms after crossing the boundary (e.g., due to data loss or tracking error). Furthermore, we excluded trials when the duration of the first fixation on the target word was shorter than 80 ms or longer than 1200 ms. These criteria led to the exclusion of further 2.1% (100 out of the remaining 4,712) of the trials for the analysis of FFD. For the measure of GD, we considered durations of less than 120 ms or greater than 2,000 ms (Grade 6), or 2,400 ms (Grade 4) as outliers. This criterion led to the exclusion of another 1.3% of the trials (61 of the remaining 4,612) from the analysis of GD. For the analyses, we *log*-transformed FFD and GD (by the natural logarithm), because their distributions were considerably right skewed (which is usual for fixation times). We analysed the effects of the type and salience of the previews with Analyses of variance (ANOVAs) with the levels of salience (high, medium, and low) and the types of preview (X-mask, SSDL-mask, and valid preview) as within-subject factors and Grade as between subject factor. We conducted F_1 (participants) and F_2 (items) analyses. With regard to the F_2 analyses, missing values (due to the aforementioned exclusion criteria) were replaced with the mean of the respective condition and Grade (otherwise the ANOVA would discard all data points of the respective item, because the analysis considers only complete cases). This procedure led to the replacement of 2.3% of the FFD data and 2.2% of GD data.

Results

Global measures. Table 1 provides the results for reading accuracy and of global eye movement measures. The children from the two Grades did not differ in their reading accuracy (Wilcoxon rank sum test: $W = 363$, $p = .98$). With regard to the eye movement measures, both groups exhibited a similar mean number of fixations per sentence, a comparable proportion of regressions

TABLE 1

Means and standard deviations of numbers of misreadings and global eye movement measures of the children from Grade 4 and Grade 6

	Grade 4		Grade 6	
	M	SD	M	SD
<i>N</i> of misreadings	8.04	9	7.22	5
<i>N</i> of fixations per sentence	14.5	2.0	14.8	2.5
Fixation duration (ms)	328	50	283	37
Forward saccade length (letters)	4.0	0.6	4.2	0.7
% of regressions	17	5	19	7

and similar mean forward saccade lengths (all group differences *n.s.*; $W_s > 299$, $p_s > .25$). The children of Grade 6 exhibited substantially shorter fixation durations (~45 ms) than the children of Grade 4; $t(52) = 3.8$, $p < .001$; which is a reduction of fixation duration of approx. 14%.

Target words. A first analysis restricted to the target words revealed that they were seldom skipped ($M < 3\%$ for both Grades). There was a small (and non-significant) group difference for the mean number of fixations during the first pass reading of the target words (Grade 4: $M = 2.00$; Grade 6: $M = 1.86$; $W = 450.5$, $p = .13$). The probabilities that the target words received a single fixation were 34% and 41% for the children from Grades 4 and 6, respectively. An ANOVA (F_1) revealed that this difference was not reliable; main effect of Grade: $F_1(2, 52) = 2.1$, $p = .15$. Moreover, neither type of preview nor the levels of salience influenced single fixation probability and there were no reliable interactions between the factors; all $F_1 < 1$.

Next, we note that our salience manipulation of the previews (by visual degradation) might have “blurred” the inter-word spacings, thereby reducing the informational value of word length for programming the saccade to the target word (see Figure 1). Thus, we examined whether our salience manipulation influenced saccadic targeting. To this end, we conducted an ANOVA with the initial landing position on the target word as dependent measure, Grade as between subject-factor and the level of salience and word length as within-subject factors. The rationale is that word length would not influence the initial landing position, if the visual degradation indeed compromised the perception of the inter-word spacings. As evident from Figure 2, the children initially

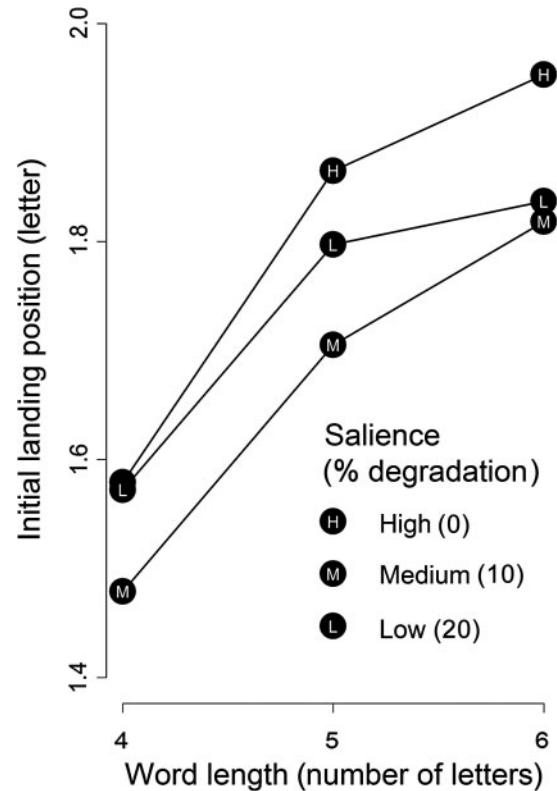


Figure 2. The mean initial landing position in relation to word length for the high, medium, and low salience previews (combined over Grades and types of mask; see main text).

fixated the target words, on average, between the 1st and the 2nd letter and the effect of word length on initial landing position was rather small. However, the main effect of word length was (highly) reliable; $F_1(2, 320) = 29.2$, $F_2(2, 1076) = 221.8$, $p_s < .001$. It did not differ between Grades (main effect of Grade and the Grade by length interaction: all F_1 and $F_2 < 1$). With regard to salience, there was a slight tendency towards more central initial landing positions for the high salience (i.e., undegraded) previews which was reflected in a reliable main effect of salience; $F_1(2, 104) = 5.0$, $p < .01$ and $F_2(2, 1076) = 30.1$, $p < .001$. The effect did not interact with word length or Grade, nor were there any other reliable interactions (all F_1 and $F_2 < 1$). We consider this finding indicative that our manipulation of the salience of the previews had little influence on saccadic targeting of the target words (but see Discussion).

The main findings of our preview by degradation manipulation on FFD and GD are depicted in Figure 3; the findings for the Grade-4 children are shown in the upper panel, those for the Grade-6 children in the lower panel. (Means and standard

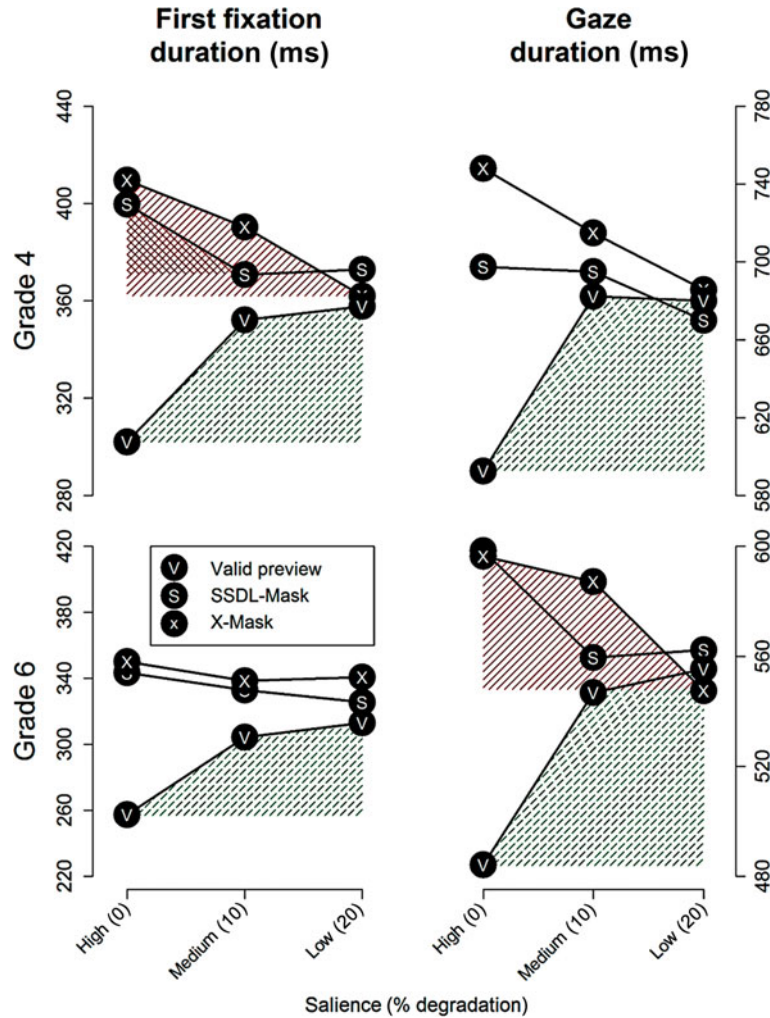


Figure 3. The mean FFD and GD of the children from Grade 4 (upper panel) and Grade 6 in relation to the type and the salience of the parafoveal preview. For the purpose of illustration, we highlighted the areas under the lines for which planned comparisons (i.e., simple effects) revealed significant effects of the salience of the preview. The red (and solid line) shadings depict the effect of the parafoveal masks. The green (and dashed line) shadings depict the effects of the valid preview. SSDL, Same shape/different letter. [To view this figure in colour, please visit the online version of this Journal.]

deviations are provided in Table 1A of the Appendix.) The Grade-6 children exhibited shorter FFD and GD than the Grade-4 children (note that the y-axes of the Figure are scaled differently for the two Grades). The ANOVAs revealed the respective main effects; FFD: $F_1(1, 52) = 10.6$, $F_2(1, 178) = 52.7$; GD: $F_1(1, 52) = 6.6$, $F_2(1, 178) = 74.0$, all $ps < .001$. Figure 2 further shows that the preview of masks elicited, on average, higher processing times than the valid previews. Accordingly, the main effects of type of preview were reliable; FFD: $F_1(2, 104) = 38.3$, $F_2(2, 356) = 49.3$, and GD: $F_1(2, 104) = 19.0$, $F_2(2, 356) = 20.1$, $ps < .001$. Furthermore, the interactions between type of preview and degree of

salience were significant; FFD: $F_1(4, 208) = 12.8$, $F_2(4, 712) = 11.3$; GD: $F_1(4, 208) = 9.0$, $F_2(4, 712) = 9.8$, $ps < .001$. In the following we report the effects of the levels of salience separately for the valid preview condition and the parafoveal masks.

Valid preview. The effect of salience was significant for both measures; FFD: $F_1(2, 104) = 20.2$, $F_2(2, 356) = 18.7$; GD: $F_1(2, 104) = 12.6$, $F_2(2, 356) = 12.3$, $ps < .001$. As evident from Figure 3, the effect was due to increasingly longer FFD and GD with decreasing salience (i.e., with increasing degradation). For FFD, the effect was of a comparative size for both Grades as indicated by the absence of an interaction of Grade by salience;

FFD: both F_1 and $F_2 < 1$. In absolute terms, the magnitude of the effect (i.e., the preview benefit) was approx. 60 ms (for both Grades). For GD, the analyses revealed a non-significant interaction of Grade by salience in the analysis over participants; $F_1 < 1$, but a marginally significant interaction in the analysis over items; $F_2(2, 356) = 2.6, p = .08$. As evident from Figure 3, the younger readers exhibited—in absolute terms—a higher preview benefit (approx. 90 ms) than the older readers (approx. 70 ms; see Discussion).

Parafoveal masks. Note that the analysis comprises (in contrast to the analysis of the valid previews) two different previews; the SSDL-masks and the X-masks. The main effect of salience was significant for both FFD and GD; $F_1(2, 104) = 4.7, F_2(2, 365) = 4.5$; and $F_1(2, 104) = 4.1; F_2(2, 356) = 4.0$, respectively; $ps < .05$. As evident from Figure 3, these effects were due to, on average, decreasing FFD and GD with decreasing salience (i.e., with increasing degradation). Furthermore, Figure 3 gives the impression that the main effect of salience was carried primarily by the X-mask, and by the Grade-4 children in case of FFD, but by the Grade-6 children in case of GD. However, the three-way interactions between the type of preview, the level of salience, and Grade were non-significant; FFD: $F_1(2, 104) = 1.2; F_2 < 1$; GD: F_1 and $F_2 < 1$; The two-way interactions between salience and Grade were also not significant; all F_1 and $F_2 < 1$. With regard to differences between the two types of parafoveal masks, all the respective interactions (i.e., type of preview by salience, type of preview by Grade) were non-significant, all F_1 and $F_2 < 1.3$.

DISCUSSION

The present study examined whether parafoveal masking, which is the common method in eye movement research to study parafoveal preprocessing, is suitable for investigating preview benefits in children. To this end, we studied the effect of two common masks, that is, the X-mask and the SSDL-mask in children from Grades 4 and 6 (age: 10 and 12 years, respectively). Additionally, a novel manipulation of previews was applied, that is, a salience manipulation by means of visual degradation. Unlike parafoveal masks, visual degradation enables manipulating the parafoveal preview in a gradual manner, that is, the manipulation of the preview is not binary (i.e., all-or-none)

as with masks. The manipulation of the salience of the parafoveal previews was inspired by the rationale underlying the *incremental priming technique* of Jacobs et al. (1995). As discussed in more detail later, this technique allows researchers to pin down the direction of the influence of an experimental manipulation, that is, one can determine whether the manipulation exerts facilitation or interference. Moreover, the technique does not require a baseline condition. The present (and novel) application of combining the incremental “priming” technique with the invisible boundary paradigm revealed that the application of parafoveal masks to study parafoveal preprocessing in children could lead to an overestimation of the magnitude of the effect of parafoveal preprocessing.

The effect of parafoveal masks

Interference of the parafoveal masks with foveal word recognition was inferred from increasingly longer fixation and GDs with increasing salience of the masks. Such an interference was particularly evident for the FFDs of our younger readers (Grade 4) and for the GDs of the older readers (Grade 6). Put differently, the masks inflicted processing costs (Kliegl et al., 2013). Any such instance (regardless of its statistical reliability in its own right) would lead to an overestimation of the preview benefit. Our findings demonstrate that a comparison of valid previews with parafoveal masks does not result in an accurate estimate of the extent to which young readers profit from valid previews. To illustrate, for our younger readers the interference by the masks, i.e., the difference between the fixation durations for high-salience and low-salience previews of the masks was about 40 ms for FFD. This is more than half of the magnitude of the benefit of previewing valid information (as indexed by our salience manipulation of the valid previews). If one would estimate the extent of the preview benefit by contrasting valid versus invalid previews, one would overstate the preview “benefit”. In the data from the present sample of children, these overstated estimates would have been approx. 90–100 ms. The actual benefits were about 50–60 ms. Thus, parafoveal masks should not be applied as a baseline, because *neutrality* is a prerequisite for a proper baseline condition.

Only recently, the issue of an appropriate baseline in eye movement studies using parafoveal

masks received renewed attention. Hutzler et al. (2013) showed an interfering effect of parafoveal X-masks. Kliegl et al. (2013) reported that random-letter masks interfere with foveal word processing. These studies, however, did not suggest how we may attain better estimates of the preview benefit. The present study's findings, on the one hand, corroborate the evidence that masks are not a suitable baseline for the study of parafoveal preprocessing. On the other hand, it suggests a possible solution of the baseline problem of eye movement research on the preview benefit.

The asset of manipulating salience

Manipulating the salience of valid previews provides the solution for the shortcoming of parafoveal masks. With the *incremental* boundary technique, valid previews can serve as their own baseline (i.e., a within-condition baseline). Two basic approaches can be taken. First, in order to estimate the general effect (i.e., facilitation versus interference) of a certain parafoveal preview, it is sufficient to determine whether increasing salience of the preview leads to prolonged or diminished processing times. If increasing salience results in diminished processing times, then the parafoveal information facilitated the subsequent foveal processing. If, to the contrary, increasing salience results in prolonged processing times, then the parafoveal information interfered with foveal processing. In the present study, the salience manipulation of valid previews provided clear evidence that young readers benefit from valid parafoveal information. The second approach makes it possible to judge the absolute extent of the influence of a parafoveal preview. A prerequisite for that is to find a "zero" information-extraction salience level. As evident from Figure 3, the (inhibitory) effect of the masks as well as the (facilitatory) effect of the valid previews converged at the lowest salience level (i.e., resulted in similar processing times). If the requirement of convergence is met, then it is safe to conclude that this level of salience prevents the extraction of (useful) parafoveal information.

Thus, manipulating the salience of the preview is a sensitive method to study preview effects. However, the current manipulation of salience could probably be further improved. The applied method of visual degradation replaced the pixels of the bitmapped parafoveal word or mask to the white space around the letters without any

Susi wohnt in einem großen Haus neben der Schule

Figure 4. The current manipulation of the parafoveal previews by visual degradation placed pixels of the degraded words in the spaces between words—possibly reducing the informative value of the interword spaces. This Figure provides an example of an improved manipulation where the visual information of interword spacings is kept intact by restricting the visual degradation to the boundaries of the degraded words (compare with Figure 1).

particular restrictions. Thus, it happened that pixels from the first and the last letters of the target words were placed in the inter-word spaces (see Figure 1)—possibly diminishing the informative value of word length for eye movement control. We did not observe notably detrimental effects on the initial landing position in relation to our visual manipulation. We concede, however, that the manipulation could be adapted with this issue in mind. Figure 4 displays the same sentence as Figure 1. Similar to the current manipulation, pixels of upcoming words were displaced. The difference is that the displacement was restricted to the word boundaries and hence the inter-word spacings were not occupied by displaced pixels—retaining the information provided by the white spaces. Future studies on parafoveal preprocessing with the incremental boundary technique may resort to this particular manner of degradation, but even further improvements are conceivable.

The development of preview benefit

The primary aim of the present study was to assess the suitability of parafoveal masks for the study of the preview benefit in children. However, we briefly discuss the primary findings of the eye movement measures of our study in this section. We start with the notion that the present groups of children from Grades 4 and 6 differed substantially in their average reading speed with a reading rate of approx. 90 and 130 words per min, respectively. These measures are from the paper-and pencil reading speed screening test (administered to prevent the inclusion of below-average readers) which, in contrast to our experimental sentence reading task, required silent reading. One could speculate that this difference in reading speed is, at least partially, due to less parafoveal preprocessing in the younger readers. By means of our salience manipulation, we were able to estimate the absolute extent of the preview benefit. Surprisingly, we observed substantial preview benefits for both age

groups on FFD. Even the 4th Graders exhibited a preview benefit of approx. 60 ms (~15% of the children's mean fixation duration). The extent of the preview benefit for 6th Graders was—in absolute terms—of similar size (but it was ~20% of their mean fixation duration). For GD, the preview benefit was—in absolute terms—larger in the younger than in the older readers (~90 and ~70 ms, respectively). However, in relation to their different mean GD (substantially higher in the younger readers), the benefit corresponds to a reduction of approx. 13% in both groups.

As stated in the Introduction, as yet little is known about the development of parafoveal preprocessing in young readers. We anticipated preview benefits for our 6th Graders on the basis of Zoccolotti et al.'s (2013) finding that 12 year olds read words faster, when they are presented in list format compared to words presented in isolation. The extent of the preview benefit in our 4th Graders, however, is surprising since relatively small perceptual spans were reported for younger readers. Häikiö et al. (2009) investigated, by means of the moving-window paradigm, how many characters (i.e., number of letters) to the right of fixation can be extracted from a single fixation. The authors reported that the letter-identity span of 10 year olds (as our 4th Graders) encompassed only seven letters. The span of 12 year olds (as our 6th Graders) encompassed, similar to their adult participants, nine letters. In the same vein, Rayner (1986) reported that the span of 8- and 10-year-old children is substantially smaller than the span of adult readers, whereas the span of 12-year-old is almost adult-like.

Why then did our youngest readers exhibit such a substantial preview benefit or, put differently, why did we observe comparatively little differences (with regard to the preview benefit and global eye movement measures) between the children from Grade 4 and Grade 6? We can only speculate and must leave the issue for future studies. First, one could assume that the requirement of reading aloud diminished effects which would express themselves stronger during silent reading in the Grade-6 children (Ashby et al., 2012). However, we think that this explanation is doubtful since a preview benefit of approx. 50 ms is already quite adult-like (if one gives full credit to the studies which based the assessment of the preview benefit on parafoveal masks). Another explanation could be that the preview benefit arises from preprocessing primarily the very first letters of an upcoming word, which

would not require a particularly large perceptual span. Previewing the initial two or three letters can constrain the set of potential upcoming words (e.g., Gagl, Hawelka, Richlan, Schuster, & Hutzler, 2014). It can also provide information of the syllable structure of the upcoming word (shown for adult readers by Ashby & Rayner, 2004; see also Ashby & Martin, 2008). The first syllable (of multi-syllabic words) is considered as an access unit to the phonological lexicon, especially for reading a regular orthography (e.g., Spain: Carreiras, Alvarez, & de Vega, 1993; German: Conrad, Carreiras, Tamm, & Jacobs, 2009; Hawelka, Schuster, Gagl, & Hutzler, 2013; Hutzler et al., 2004).

Orthographic regularity may also account for other differences to previous English-based findings (e.g., Rayner, 1986). To illustrate, our children exhibited a relatively low single fixation probability. This is, however, not too surprising if one takes into account that a very regular orthography, such as German, does not impose a similar incentive for lexical (i.e., whole-word) recognition as the irregular English orthography (because grapheme-phoneme coding reliably results in the correct pronunciation of a word). Indeed, a very recent eye movement study, comparing German and English children, provided evidence that German children exhibit a higher reliance on small-unit decoding than their English peers (Rau, Moll, Snowling, & Landerl, 2015). This could also explain our finding that the children initially fixated word beginnings which is conducive for small-unit, serial decoding. Hawelka, Gagl, and Wimmer (2010) reported that German dyslexic readers, who exhibit an over-reliance on serial decoding, preferentially fixate word beginnings (see also Gagl, Hawelka, & Hutzler, 2014; MacKeben et al., 2004). Rau, Moeller, and Landerl (2014) recently showed that the transition from sublexical decoding to predominantly lexical word recognition is a process over several years for children learning to read the regular German orthography. This may also explain the similar mean forward saccade length (of about four letters) in our two groups of children. The higher reading efficiency of our older readers, however, was reflected in substantially shorter mean fixation durations (see also Gagl, Hawelka, & Wimmer, *in press*).

Conclusion

The present study demonstrated that an essential prerequisite for parafoveal masks, that is,

“neutrality” towards the effect in question, is not fulfilled. We confirmed this by means of the invisible boundary paradigm combined with a salience manipulation of the parafoveal previews (i.e., the *incremental boundary paradigm*). For valid previews, we estimated a preview benefit of about 60 ms in FFD based on the comparison of high-salience and low-salience previews (*within-condition* baseline). If we had estimated the preview benefit by the contrast of valid previews versus the parafoveal masks, then we would have overestimated the benefit substantially. Future studies on the emergence of parafoveal preprocessing in beginning readers may consider a salience manipulation of valid previews as an alternative to using parafoveal masks.

REFERENCES

- Ashby, J., & Martin, A. E. (2008). Prosodic phonological representations early in visual word recognition. *Journal of Experimental Psychology: Human Perception and Performance*, *34*, 224–236. doi:10.1037/0096-1523.34.1.224
- Ashby, J., & Rayner, K. (2004). Representing syllable information during silent reading: Evidence from eye movements. *Language and Cognitive Processes*, *19*, 391–426. doi:10.1080/01690960344000233
- Ashby, J., Yang, J., Evans, K. H. C., & Rayner, K. (2012). Eye movements and the perceptual span in silent and oral reading. *Attention, Perception, & Psychophysics*, *72*, 634–640. doi:10.3758/s13414-012-0277-0
- Auer, M., Gruber, G., Mayringer, H., & Wimmer, H. (2005). *Salzburger Lese-Screening für die Klassenstufen 5–8 (SLS 5-8)* [Salzburger screening test for reading fluency]. Bern: Huber.
- Bivand, R., Leisch, F., & Mächler, M. (2008). Pixmap: Bitmap images (“Pixel maps”); R Package, Version 0.4-9). Retrieved from <http://CRAN.R-Project.org/package=Pixmap>
- Blythe, H. I., Häikiö, T., Bertam, R., Liversedge, S. P., & Hyönä, J. (2011). Reading disappearing text: Why do children refixate words? *Vision Research*, *51*(1), 84–92. doi:10.1016/j.visres.2010.10.003
- Blythe, H. I., & Joseph, H. S. S. L. (2011). Children’s eye movements during reading. In S. P. Liversedge, I. D. Gilchrist, & S. Everling (Eds.), *The Oxford handbook of eye movements* (pp. 643–662). Oxford: Oxford University Press.
- Blythe, H. I., Liversedge, S. P., Joseph, H. S. S. L., White, S. J., Findlay, J. M., & Rayner, K. (2006). The binocular coordination of eye movements during reading in children and adults. *Vision Research*, *46*, 3898–3908. doi:10.1016/j.visres.2006.06.006
- Blythe, H. I., Liversedge, S. P., Joseph, H. S. S. L., White, S. J., & Rayner, K. (2009). Visual information capture during fixations in reading for children and adults. *Vision Research*, *49*, 1583–1591. doi:10.1016/j.visres.2009.03.015
- Brybaert, M., Buchmeier, M., Conrad, M., Jacobs, A. M., Bölte, J., & Böhl, A. (2011). The word frequency effect: A review of recent developments and implications for the choice of frequency estimates in German. *Experimental Psychology*, *58*, 412–424. doi:10.1027/1618-3169/a000123
- Carreiras, M., Alvarez, C. J., & de Vega, M. (1993). Syllable frequency and visual word recognition in Spain. *Journal of Memory and Language*, *32*, 766–780. doi:10.1006/jmla.1993.1038
- Conrad, M., Carreiras, M., Tamm, M., & Jacobs, A. M. (2009). Syllables and bigrams: Orthographic redundancy and syllabic units affect visual word recognition at different processing levels. *Journal of Experimental Psychology: Human Perception and Performance*, *35*, 461–479. <http://dx.doi.org/10.1037/a0013480>
- Gagl, B., Hawelka, S., Richlan, F., Schuster, S., & Hutzler, F. (2014). Parafoveal preprocessing in reading revisited: Evidence from a novel preview manipulation. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *40*, 588–595. doi:10.1037/a0034408
- Gagl, B., Hawelka, S., & Hutzler, F. (2014). A similar correction mechanism in slow and fluent readers after suboptimal landing positions. *Frontiers Human Neuroscience*, *8*, 355. doi:10.3389/fnhum.2014.00355
- Gagl, B., Hawelka, S., & Wimmer, H. (in press). On sources of the word length effect in young readers. *Scientific Studies of Reading*.
- Friedman, D. (1990). Erps during continuous recognition memory for words. *Biological Psychology*, *30*(1), 61–87. doi:10.1016/0301-0511(90)90091-A
- Hawelka, S., Gagl, B., & Wimmer, H. (2010). A dual-route perspective on eye movements of dyslexic readers. *Cognition*, *115*, 367–379. doi:10.1016/j.cognition.2009.11.004
- Hawelka, S., Schuster, S., Gagl, B., & Hutzler, F. (2013). Beyond single syllables: The effect of first syllable frequency and orthographic similarity on eye movements during silent reading. *Language and Cognitive Processes*, *28*, 1134–1153. doi:10.1080/01690965.2012.696665
- Häikiö, T., Bertram, R., Hyönä, J., & Nieme, P. (2009). Development of letter identity span in reading: Evidence from the eye movement moving window paradigm. *Journal of Experimental Child Psychology*, *102*, 167–181. doi:10.1016/j.jecp.2008.04.002
- Huestegge, L., Radach, R., Corbic, D., & Huestegge, S. M. (2009). Oculomotor and linguistic determinants of reading development: A longitudinal study. *Vision Research*, *49*, 2948–2959. doi:10.1016/j.visres.2009.09.012
- Hutzler, F., Bergmann, J., Conrad, M., Kronbichler, M., Steneken, P., & Jacobs A. M. (2004). Inhibitory effects of first syllable-frequency in lexical decision: An event-related potential study. *Neuroscience Letters*, *372*, 179–184. doi:10.1016/j.neulet.2004.07.050
- Hutzler, F., Braun, M., Vo, M. L., Engl, V., Hofmann, M., Dambacher, M., ... Jacobs, A. M. (2007). Welcome to the real world: Validating fixation-related

- brain potentials for ecologically valid settings. *Brain Research*, 1172(1), 124–129. doi:10.1016/j.brainres.2007.07.025
- Hutzler, F., Fuchs, I., Gagl, B., Schuster, S., Richlan, F., Braun, M., & Hawelka, S. (2013). Parafoveal X-masks interfere with foveal word recognition: Evidence from fixation-related brain potentials. *Frontiers in Systems Neuroscience*, 7(33), 1–10. doi:10.3389/fnsys.2013.00033
- Jacobs, A. M., Grainger, J., & Ferrand, L. (1995). The incremental priming technique: A method for determining within-condition priming effects. *Perception & Psychophysics*, 57, 1101–1110. doi:10.3758/BF03208367
- Joseph, H. S. S. L., Liversedge, S. P., Blythe, H. I., White, S. J., & Rayner, K. (2009). Word length and landing position effects during reading in children and adults. *Vision Research*, 49, 2078–2086. doi:10.1016/j.visres.2009.05.015
- Kliegl, R., Hohenstein, S., Yan, M., & McDonald, S. A. (2013). How preview space/time translates into preview cost/benefit for fixation durations during reading. *The Quarterly Journal of Experimental Psychology*, 66, 581–600. doi:10.1080/17470218.2012.658073
- Landerl, K., Wimmer, H., & Moser, E. (1997). *Salzburger Lese- und Rechtschreibtest: Verfahren zur Differentialdiagnose von Störungen des Lesens und Schreibens für die 1. und 4. Schulstufe* [Salzburger reading and spelling test: Standardized measure to diagnose subcomponents of reading and spelling]. Bern: Huber.
- McConkie, G. W., & Rayner, K. (1975). The span of the effective stimulus during a fixation in reading. *Perception & Psychophysics*, 17, 578–586. doi:10.3758/BF03203972
- MacKeben, M., Trauzettel-Klosinski, S., Reinhard, J., Dürrwächter, U., Adler, M., & Klosinski, G. (2004). Eye movement control during single-word reading in dyslexics. *Journal of Vision*, 4, 388–402. doi:10.1111/j.1755-3768.2009.01523.x
- Perea, M., & Pollatsek, A. (1998). The effects of neighborhood frequency in reading and lexical decision. *Journal of Experimental Psychology: Human Perception and Performance*, 24, 767–779. doi:10.1037/0096-1523.24.3.767
- Rau, A. K., Moeller, K., & Landerl, K. (2014). The transition from sublexical to lexical processing in a consistent orthography: An eye-tracking study. *Scientific Studies of Reading*, 18, 224–233. doi:10.1080/10888438.2013.857673
- Rau, A. K., Moll, K., Snowling, M. J., & Landerl, K. (2015). Effects of orthographic consistency on eye movement behavior: German and English children and adults process the same words differently. *Journal of Experimental Child Psychology*, 130(1), 92–105. doi:10.1016/j.jecp.2014.09.012
- Rayner, K. (1975). The perceptual span and peripheral cues in reading. *Cognitive Psychology*, 7(1), 65–81. doi:10.1016/0010-0285(75)90005-5
- Rayner, K. (1986). Eye movements and the perceptual span in beginning and skilled readers. *Journal of Experimental Child Psychology*, 41, 211–236. doi:10.1016/0022-0965(86)90037-8
- Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, 124, 372–422. doi:10.1037/0033-2909.124.3.372
- Rayner, K. (2009). Eye movements and attention in reading, scene perception, and visual search. *The Quarterly Journal of Experimental Psychology*, 62, 1457–1506. doi:10.1080/17470210902816461
- Rayner, K., Liversedge, S. P., & White, S. J. (2006). Eye movements when reading disappearing text: The importance of the word to the right of fixation. *Vision Research*, 46, 310–323. doi:10.1016/j.visres.2005.06.018
- Schotter, E. R., Angele, B., & Rayner, K. (2012). Parafoveal processing in reading. *Attention, Perception and Psychophysics*, 74(1), 5–35. doi:10.3758/s13414-011-0219-2
- Zoccolotti, P., De Luca, M., Lami, L., Pizzoli, C., Pontillo, M., & Spinelli, D. (2013). Multiple stimulus presentation yields larger deficits in children with developmental dyslexia: A study with reading and RAN-type tasks. *Child Neuropsychology*, 19, 639–647. doi:10.1080/09297049.2012.718325

APPENDIX

TABLE 1A

Means and standard deviations for FFD and GD in relation to the type of preview and the salience (i.e., degree of degradation) for the Grade 4 and Grade 6 children

Condition	Salience (% deg. ^a)	Grade	FFD		GD	
			M	SD	M	SD
Valid preview	High (0)	4	302	65	593	200
		6	257	53	484	170
	Medium (10)	4	352	71	682	234
		6	304	58	547	199
	Low (20)	4	358	63	680	205
		6	313	64	555	179
SSDL-mask	High (0)	4	400	89	697	262
		6	343	56	598	183
	Medium (10)	4	371	88	695	258
		6	333	62	560	164
	Low (20)	4	373	60	670	247
		6	325	60	562	144
X-mask	High (0)	4	409	97	748	278
		6	350	71	596	173
	Medium (10)	4	390	81	715	231
		6	338	59	587	164
	Low (20)	4	362	77	686	190
		6	341	70	548	166

^aDegradation.