Development of parafoveal processing within and across words in reading: Evidence from the boundary paradigm

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In this study we used the boundary paradigm to examine whether readers extract more parafoveal information within than across words. More specifically, we examined whether readers extract more parafoveal information from a compound word's second constituent than from the same word when it is the noun in an adjective–noun phrase (kummitustarina “ghost story” vs. lennokas tarina “vivid story”). We also examined whether the processing of compound word constituents is serial or parallel and how parafoveal word processing develops over the elementary school years. Participants were Finnish adults and 8-year-old second-, 10-year-old fourth-, and 12-year-old sixth-graders. The results showed that for all age groups more parafoveal information is extracted from the second constituent within compounds than from the noun in adjective–noun phrases. Moreover, for all age groups we found evidence for parallel processing of constituents within compounds, but only when the compounds were of high frequency. In sum, the present study shows that attentional allocation extends further to the right and is more simultaneous when words are linguistically and spatially unified, providing evidence that attention in text processing is flexible in nature.

Keywords: Reading development; Parafovea; Perceptual span; Boundary paradigm; Eye movements; Children; Finnish.

Readers extract information not only from words they fixate, but also from words to the right of fixation (see Rayner, 1998, for a review). This holds true also when the word is the second constituent of a compound word (e.g., “ware” in “kitchenware”). More specifically, it has been found that during the fixation on a compound's first constituent (e.g., “kitchen”), not only information from that constituent but also information from the compound's second constituent (e.g., “ware”) is extracted (e.g., Hyöna, Bertram, & Pollatsek, 2004; Juhasz, Pollatsek, Hyöna, Drieghe, & Rayner, 2009; White, Bertram, & Hyöna, 2008). Earlier studies thus indicate that spatial attention not only is restricted to the currently fixated constituent (word), but can also be extended to the parafoveal constituent (word) as well. The current study investigated whether (a) there is a difference between the amount of information extracted from the parafovea within and across words; (b) whether foveal and...
parafocal information can be processed in parallel; and (c) how parafocal processing skills develop during the elementary school years.

It has been established that especially visual-orthographic features of the word to the right of fixation are extracted (e.g., Altarriba, Kambe, Pollatsek, & Rayner, 2001; Balota, Pollatsek, & Rayner, 1985; Pollatsek, Lesch, Morris, & Rayner, 1992; Rayner, 1975; Rayner, Balota, & Pollatsek, 1986). Withholding visual-orthographic information for the word to the right of a fixated word, called the parafocal word, has therefore detrimental effects on reading. This has been shown in several studies using the boundary paradigm (e.g., Altarriba et al., 2001; Pollatsek et al., 1992), a paradigm (introduced by Rayner, 1975) in which letters of a parafocal word are initially replaced by visually similar or dissimilar letters. During the saccade crossing an invisible boundary placed to the left of the parafocal word, the word is changed to the correct form. Because vision is suppressed during saccades, the reader does not become aware of the actual change. The size of the change effect depends on the number of letters initially replaced and on whether the replaced letters are visually similar or dissimilar to the correct letters, with larger effect sizes in the case of dissimilar letters and more letters being changed (e.g., Altarriba et al., 2001; Inhoff, 1989). The change effect indicates that readers take advantage of the parafocally presented word. Hence the change effect is also referred to as the parafocal preview benefit.

Until recently, the change effect has been studied across words separated by a space, but Hyönä et al. (2004) manipulated parafocal words that are part and parcel of a bigger word unit—namely, the second constituents of biconstituental compound words. In Finnish, the language used in the present study and in that of Hyönä et al. (2004), constituents within a compound are always concatenated (i.e., unspaced). Hyönä et al. found a substantial 85-ms preview benefit in gaze duration for the second constituent in the identical condition,1 a much larger effect than effects that were found in any of the studies examining preview benefit across two separate words. In fact, similar manipulations across words (i.e., preserving two letters after the boundary and replacing the remaining letters with visually similar ones) yielded practically no change effects whatsoever in the majority of studies (see Hyönä et al., for a survey). However, in order to directly compare preview benefits within and across words, one would need to match frequency and length of the foveal and parafocal word, since both may influence the amount of parafocal information extracted (see Henderson & Ferreira, 1990).

Juhasz et al. (2009, Experiment 2) did exactly this; they compared the amount of parafocal information extracted from the second constituent of spaced compounds with the amount of parafocal information extracted from the noun in adjective–noun pairs, while matching for the relevant characteristics of the foveal and parafocal word. They found larger than regular (e.g., Pollatsek et al., 1992) preview benefits for both conditions, but no difference between them. These results imply that the allocation of attention is regulated by linguistic unification. More precisely, both spaced compounds and adjective–noun phrases are linguistically unified in the sense that the first part (either the first constituent or the adjective) modifies the second, or, to put it differently, the meaning of the first part is dependent on and/or has to be related to the meaning of the second. This tight linguistic dependency (in comparison to word sequences used in previous studies) may have led to larger than regular preview benefits in Experiment 2 of Juhasz et al. In addition, Juhasz et al. (Experiment 1) found a larger preview benefit for the second constituent of concatenated (i.e., unspaced) compounds than for the second constituent of spaced compounds. This result showed that also spatial unification has a role to

1 The effect size of 85 ms was not reported in the Hyönä et al., but calculated here for purposes of comparison with studies examining preview benefits across words. It should be noted that—due to technical problems—the analyses are based on a subset of the participants (11) only, but since it is rather similar to the effect we find in this study (to anticipate, the gaze duration change effect for the second constituent here is 86 ms), we believe it is quite reliable.
play in the allocation of visual attention during reading, with more attentional resources allocated to the second constituent when it is attached to the first one.

Although not directly tested, the results of Juhasz et al. (2009) imply that larger preview effects may be found within compound words with concatenated constituents than across words, even when the two-word sequences comprise adjective–noun phrases. The current study extends the Juhasz et al. study by investigating whether larger parafoveal preview benefits may be observed for the second constituent within concatenated compounds than for the noun in adjective–noun phrases, while tightly controlling for lexical factors such as word frequency and word length. Given the results of Juhasz et al., we predict that parafoveal preview benefits (i.e., the size of the change effect) are larger for the second constituent of concatenated compound words than for the noun in the adjective–noun phrases.

Another issue we address in this study is whether characteristics of the parafoveal word $N + 1$ can affect fixation times on word $N$. So far, most boundary studies (e.g., Altarriba et al., 2001; Hyönä et al., 2004; Pollatsek et al., 1992) suggest that the preview of word $N + 1$ only affects fixation time of word $N + 1$. However, there are a few studies that suggest that a preview of word $N + 1$ affects fixation time of word $N$ as well (e.g., Kennedy, 2000; Kennedy, Pynte, & Ducrot, 2002; Kliegl, Risse, & Laubrock, 2007; White, 2008). Kennedy has coined this effect the parafoveal-on-foveal effect. Kennedy and colleagues have argued that parafoveal-on-foveal effects reflect parallel word processing, since influences of properties of word $N + 1$ on processing word $N$ can only be explained if one assumes that both words are processed simultaneously. Consequently, it has been argued that a serial model like the E-Z Reader model (e.g., Reichle, Rayner, & Pollatsek, 2003) cannot account for parafoveal-on-foveal effects, since one of the basic assumptions of this model has been that words are attended and processed one at a time (e.g., Kennedy & Pynte, 2005), be it that more recent versions of the model have incorporated a preattentive mechanism that allows for early extraction of parafoveal visual-orthographic information (e.g., Pollatsek, Reichle, & Rayner, 2006; Reichle et al., 2003). Moreover, advocates of the E-Z Reader model have argued that parafoveal-on-foveal effects are by and large caused by mislocated fixations (Drieghe, Rayner, & Pollatsek, 2008). That is, as a result of saccadic undershooting a fair number of fixations intended to land on word $N + 1$ land in fact on word $N$, and these mislocated fixations are thought to account for the observed parafoveal-on-foveal effects. In other words, if one would like to argue that a parafoveal-on-foveal effect is real, one would need to exclude the possibility that it is driven by mislocated fixations only.

Until now, most studies have examined whether parafoveal-on-foveal effects occur across separate words (e.g., Kennedy, 2000; Kennedy et al., 2002). We think that—for several reasons—parafoveal-on-foveal effects are more likely to be observed when words are concatenated (unspaced) as is the case in Finnish compound words. As argued above, the constituents of a concatenated compound word are both linguistically and spatially unified. Since previous results (Juhasz et al., 2009) suggest that linguistic unification regulates the allocation of attention and that attention may be allocated to nonfixated text to a greater degree within a spatially unified than a nonunified visual object, we think it is possible that during concatenated compound word processing attention stretches not only further but also earlier into the parafovea. In other words, we argue that if genuine parafoveal-on-foveal effects are to be found, they ought to be observed within concatenated compound words.

Despite the greater likelihood of finding parafoveal-on-foveal effects within compounds, the three Finnish boundary studies on compounds conducted so far have not found solid evidence for a parafoveal-on-foveal effect (Hyönä et al., 2004; Pollatsek & Hyönä, 2005; White et al., 2008). Yet, it should be noted that in the White et al. study there was a numerical trend for a parafoveal-on-foveal effect in gaze duration on the first constituent. When one considers a more inclusive measure such as the selective regression...
path duration (including all fixations on the first constituent before saccading to the second constituent—that is, before the change has taken place), we do in fact find a significant parafoveal-on-foveal effect, \( F_1(3, 81) = 3.36, p = .02, \]
\( F_2(2.44, 134) = 2.79, p = .05 \) (this result was not reported in original article). To be more precise, in the White et al. study the no-change condition (e.g., *vaniljakastike* “vanilla sauce”) yielded shorter selective regression path durations on the first constituent (*vanilja*, 323 ms) than was the case in the change conditions (semantically related *vaniljasinappi* “vanilla mustard”, 370 ms; semantically unrelated *vaniljarovasti* “vanilla priest”, 353 ms; pronounceable nonword *vanilja-seoklii*, 381 ms). In addition, Hyöna et al. found a numerical trend (15 ms) for a parafoveal-on-foveal effect for compounds with a predictable second constituent, which was marginally significant over participants, but not over items. The 9-ms parafoveal-on-foveal effect in the Pollatsek and Hyöna (2005) study was not significant. For English, Juhasz et al. (2009) found a similar numerical trend (15 ms) in Experiment 1, which was also marginally significant over participants, but not over items. Taken together, the earlier boundary studies suggest that parafoveal-on-foveal effects within compounds may exist, but the evidence is not compelling. Moreover, we would like to point out that the suggestions for parafoveal-on-foveal effects mentioned above are not semantic in nature. Thus, even though the White et al. study (2008) showed a selective regression path duration effect on the first constituent, there was no significant benefit for the semantically related condition in comparison to the semantically unrelated or pronounceable nonword condition (for all contrasts, \( ps > .2 \)). In other words, it is likely that if parallel constituent processing does take place, the type of information extracted from the second constituent while fixating the first is orthographic in nature.

Why is the evidence of earlier boundary studies for parafoveal-on-foveal effects within compounds not compelling? This may be due to lack of statistical power, the fact that more inclusive dependent measures like selective regression path duration were not considered, and/or because the properties (e.g., frequency and age of acquisition) of the selected items were such that evidence for parallel processing did not reach significance. In order to overcome these potential problems, in the present study we selected a sizeable number of items and considered all the possible dependent measures that could inform us about parafoveal-on-foveal effects. With respect to the item selection, we selected compound words that were early acquired and relatively frequent. Words with such properties are generally easier to process (e.g., Gerhand & Barry, 1998; Inhoff & Rayner, 1986), which may affect how attention is allocated within a word. For instance, it could well be that long low-frequency words make readers zoom in quickly on the beginning of the word to search for sublexical units that may come to aid in processing the words. In order to further explore this option, we ran post hoc analyses in which we divided the compounds into a less frequent and more frequent group.

The studies discussed above have examined parafoveal processing among skilled adult readers. In general, there are surprisingly few studies examining parafoveal processing in children. The current study will extend on the adult studies by investigating how parafoveal information processing develops during elementary school years. In particular, we were interested in whether parafoveal processing within and across words is different for children and, if so, at what point in reading development differences start to appear. Second, we wanted to investigate whether children also engage in parallel constituent processing.

With respect to the first issue, it has been shown that second-graders (7 years of age for English-speaking, 8 years of age for Finnish-speaking children) extract less parafoveal information than adults (Häikio, Bertram, Hyöna, & Niemi, 2009; Rayner, 1986), whereas sixth-graders (11 years of age for English-speaking, 12 years of age for Finnish-speaking children) extract as much parafoveal information from the right of fixation as adults, be it word length information (approx. 14 characters to the right for sixth-graders and adults, approx. 11 characters to the right for second-graders; Rayner, 1986),
letter feature information (approx. 11 characters to the right for sixth-graders and adults, approx. 7 characters to the right for second-graders; Rayner, 1986), or letter identity information (approx. 9 characters to the right for sixth-graders and adults, approx. 5 characters to the right for second-graders; Häikio et al., 2009). However, these studies have only examined parafoveal processing across words, and we do not know whether parafoveal information extraction within and across words differs as a function of reading development. Because beginning readers do not utilize the parafoveal area to the same extent as skilled readers, it is possible that for them there is no difference between parafoveal processing within and across words. On the other hand, it may be the case that also the youngest readers allocate attention to the whole word, even when the word is long, leading to more extensive parafoveal processing within than across words.

With respect to the second issue, we think that with the selection of frequent, early-acquired compounds we may find evidence for parallel processing within compound words for adults as well as for sixth-graders (given that they resemble adults in other aspects of parafoveal processing, see Häikio et al., 2009; Rayner, 1986). However, even though second-graders may extend attention to the end of the compound word, it seems unlikely that we would find evidence for parallel constituent processing, given the fact that even in adult studies no solid evidence for such effects has been found. Also, we may assume that the high-frequency compounds we selected are less frequent for younger children, since they have been exposed to written language to a much smaller extent than have older children or adults. In the present study, we examined the above-mentioned two issues by testing adults as well as second-, fourth-, and sixth-grade children in one experiment, using the same materials for all participant groups.

Method

Participants
A total of 79 participants—17 second-graders (9 boys and 8 girls), 17 fourth-graders (7 boys and 10 girls), 19 sixth-graders (11 boys and 8 girls), and 26 adults (5 males and 21 females)—were included in the analyses. The adult participants were university students who took part in the experiment as part of a course requirement. The children attended an elementary school in Turku, a city situated in the south-west of Finland. The second-graders were on average 8;10 years old, the fourth-graders were on average 10;10 years old, and the sixth-graders were on average 12;10 years old. The adults were tested at an earlier time point than the children. At the time of testing (April 2008) the second-graders had received approximately 1 year and 8 months of reading instruction. The child participants received candy as a reward for their participation. Some of the adult participants had participated in an earlier eye movement experiment, but none of them was aware of the research hypotheses. None of the children had participated in an eye movement experiment before. All participants had normal or corrected-to-normal vision. Permission from the children’s parents was acquired prior to the test.

Prior to the experiment proper, the child participants were tested to screen out the weakest readers of each age group. The second-graders were tested with a sentence comprehension task of ALLU (Lindeman, 1998), which is a standardized reading test for primary school children with national norms, and the fourth- and sixth-graders were tested with a word chain task of ALLU (Lindeman, 1998). In the sentence comprehension task, the child sees a drawing (e.g., people sailing) and has to choose which of the four sentences (e.g., “They swim”, “They dive”, “They sail”, or “They dance”) corresponds with the picture. There is a time limit of 120 s, and 1 point is awarded for each correctly chosen sentence. In the word chain test, one must recognize and separate words in a string of letters (e.g., catcomputerprincessstone) by drawing a vertical line at word boundaries (cat|computer|princess|stone) as quickly as possible. There is a time limit of 210 s, and 1 point is awarded for each correctly placed vertical line. For each grade, children with below-average reading skills (according to the test norms) were not included in the experiment.
Apparatus
The adults’ eye movements were recorded with an EyeLink II eyetracker manufactured by SR Research Ltd. (Mississauga, Ontario, Canada). The eyetracker is an infrared video-based tracking system combined with hyperacuity image processing with a spatial resolution of 0.4 degrees. The eye movement cameras are mounted on a headband (one camera for each eye). Two infrared light-emitting diodes (LEDs) for illuminating each eye are placed next to the eye movement cameras. The headband weighs 450 g in total. The cameras sample pupil location and pupil size at the rate of 500 Hz. Recording is performed by placing the camera and the two infrared light sources 4–6 cm away from the eye; in the present study the recording was monocular (the right eye was recorded). Head position with respect to the computer screen is tracked with the help of a head-tracking camera mounted on the centre of the headband at the level of the forehead. Four LEDs are attached to the corners of the computer screen, which are viewed by the head-tracking camera, once the participant sits directly facing the screen. Possible head motion is detected as movements of the four LEDs and is compensated for online from the eye position records. The texts for adults were presented on a 21-inch ViewSonic P225f computer screen, which had a refresh rate of 150 Hz.

Materials
The experiment was conducted in Finnish. Because we wanted to use the same materials for all age groups, we needed to be sure that the words in question were known by second-grade children (aged 8–9 years). To this end, 19 members of the University of Turku community rated the age of acquisition of each candidate word (i.e., compounds in the compound condition and adjectives and nouns in the adjective–noun condition) on a 1 to 7 scale (1 = 0–2 years, 2 = 3–4 years, 3 = 5–6 years, 4 = 7–8 years, 5 = 9–10 years, 6 = 11–12 years, 7 = 13 years or more). Based on these ratings, the words most suitable for second-grade children were chosen (average 2.49; range 1.16–5.74). A word was judged suitable for second-grade children if at least half of the raters rated the word being acquired by the age of 8.2 The final experimental list consisted of 60 nominal compound words paired with 60 adjective–noun pairs. This amounted to a total of 120 target items. The compound-word/adjective–noun pairs served as the target area, which in turn was divided in two sub-areas: T1 (first constituent of compound, or adjective) and T2 (second constituent of compound, or noun in the adjective–noun condition). The second constituent and the noun in the adjective–noun condition (T2) were exactly the same in each pair. T1 was matched on word length and frequency across the stimulus types. The frequency values were extracted from a newspaper corpus containing 22.7 million word forms (Laine & Virtanen, 1999). The experimental materials were embedded in sentences, where the sentence frame was identical in each pair up to word N + 1. For one sentence pair the beginning of the sentence was slightly simplified in the experiment for children, and also the endings of some

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2 Some of the chosen words had on average a higher age of acquisition rating than 8 years but this is most likely a by-product of the age of the raters; the words in question have become popular only relatively recently. To ensure that these words were familiar to second-graders, 6 eight-year-old children who did not take part in the actual experiment were asked to explain the meanings of these words. At least 5 out of 6 children could give a proper definition for the eight compounds, and hence we included them in the experiment proper.
sentences were simplified so that they would be more suitable for the children. The target area never appeared in the beginning or end of the sentence or text line. For adults, the sentences were divided into six lists. For each list, half of the sentences contained a display change, and half of them did not. None of the sentence frames was repeated in the same list, so that each list always contained only one member of each sentence pair. To ensure that each sentence was seen both in the change and in the no change condition, for each list there was a corresponding list that contained the same sentences but in the other change condition (e.g., if Sentence A was presented in the change condition in one list, in the corresponding list it was presented in the no change condition). Each list contained around 20 compound-word/adjective–noun pairs. The lists were matched for T1 and T2 in terms of target word length and frequency. Each list was seen by 4 or 5 participants. For children, the assignment of sentences to different lists was identical to that of adults apart from the fact that for children there were four lists and that there were 30 compound-word/adjective–noun word pairs per list. The four lists and stimulus types were matched on the same criteria as those for adults. Each list was seen by 4 or 5 participants from each grade apart from one list, which was seen by 6 sixth-grade participants. Lexical characteristics of the stimulus materials are presented in Table 1. Each adult saw a total of 160 sentences, and each child saw a total of 108 sentences. For adults, a number of filler sentences were the same for each list, and some of the filler sentences contained a display change (in order to keep the proportion of items with a display change about equal for children and adults). For children, all filler sentences were the same across lists, and none of the fillers contained a display change. Each list was divided in two blocks, and the block order was counterbalanced across participants. Each participant saw only one list. The order of sentences was pseudo-randomized for each participant, but so that no condition appeared more than twice in a row.

An invisible boundary was set at the word/constituent boundary. In the change condition, T2 was changed to its correct form during the saccade crossing the boundary for the first time. The first two letters of T2 were always preserved, and the rest of the characters were replaced with visually similar letters prior to display change (i.e., T2 was always a nonword in the change condition; both pronounceable and unpronounceable nonwords were used.4). Letters were considered visually

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Table 1. Lexical statistics of the experimental materials

<table>
<thead>
<tr>
<th></th>
<th>Compound word</th>
<th>Adjective–noun phrase</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1 frequency (per million)</td>
<td>76.0</td>
<td>71.4</td>
</tr>
<tr>
<td>T1 length (in characters)</td>
<td>6.7</td>
<td>6.7</td>
</tr>
<tr>
<td>T2 frequency (per million)</td>
<td>176.2</td>
<td>176.2</td>
</tr>
<tr>
<td>T2 length (in characters)</td>
<td>5.1</td>
<td>5.1</td>
</tr>
<tr>
<td>Target area length (in characters)</td>
<td>11.8</td>
<td>11.8*</td>
</tr>
<tr>
<td>T1 bigram frequency (per thousand)</td>
<td>7.15</td>
<td>7.84</td>
</tr>
<tr>
<td>T1 initial trigram frequency (per thousand)</td>
<td>0.569</td>
<td>0.721</td>
</tr>
<tr>
<td>Whole word frequency (per million)</td>
<td>4.96</td>
<td>—</td>
</tr>
</tbody>
</table>

Note: T1 = first constituent/adjective. T2 = second constituent/noun. None of the measures are significantly different from each other.

*Does not include space between adjective and noun.

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3 In principle, four lists would have been enough for the purposes of the present study. However, due to incorporating materials from a separate pilot study as fillers, six lists were created. Furthermore, originally adults had 28 compound-word/adjective–noun word pairs per list amounting to 84 word pairs or 168 items altogether. At a later stage we decided to exclude 24 word pairs (48 words), so that we were left with exactly the same materials as those used for the children (60 pairs and 120 items altogether). In this way, we could directly compare child performance and adult performance using the same items in all analyses. Since for adults the 48 excluded items were not evenly distributed over lists, in the end the number of items for each of the six lists was not exactly 40 but 38–43. However, it is important to notice that results of the analyses where all adult items were included and the analyses reported in the present paper did not differ whatsoever.

4 In previous studies examining preview benefit within compounds, the included nonwords were either pronounceable/phonotactically legal (White et al., 2008) or, in most cases, unpronounceable/phonotactically illegal (Hyönä et al., 2004; Juhasz et al., 2009).
similar when they shared the same basic shape (i.e., descenders were replaced with descenders [q replaces j], round letters were replaced with round letters [o replaces e], and ascenders were replaced with ascenders [t replaces l]).

A typical sentence pair can be seen in the example below (an English translation is presented in the parentheses). The target area is in bold, and a slash marks the constituent/word boundary (no bolding or slash was present in the experimental materials). In the change condition, when the participant crossed the boundary, the target area was changed to its correct form (i.e., when fixated, T2 always appeared in the correct form).

**Compound condition**

No change: Ilta pimeni hiljalleen, ja **kummitus/tarina** muuttui todella pelottavaksi.

Change: Ilta pimeni hiljalleen, ja **kummitus/tanlus** muuttui todella pelottavaksi.

(The evening slowly darkened, and the **ghost story** became very frightening.)

**Adjective–noun condition**

No change: Ilta pimeni hiljalleen, ja **lennokas/tarina** muuttui vielä hurjemmaksi.

Change: Ilta pimeni hiljalleen, ja **lennokas/tanlus** muuttui vielä hurjemmaksi.

(The evening slowly darkened, and the **vivid story** became even wilder.)

The sentences were presented in Courier font so that each character position was of equal width. With a viewing distance of about 60 cm, three character spaces subtended approximately 1 degree of visual angle. With respect to the vertical axis, the sentences were always presented halfway between the top and the middle of the screen; with respect to the horizontal axis, the sentences started from the left corner of the computer screen. The materials were presented on a single line, with a maximum of 92 characters on a line.

**Procedure**

Prior to the experiment, the eyetracker was calibrated using a three-point horizontal calibration grid that extended over the entire width of the computer screen. Before each sentence the participant had to fixate on a calibration point in the upper left side of the screen at the same level as the sentences. When the participant was fixating the calibration point, the experimenter pushed a button, which caused the sentence to appear on the screen. Due to calibration problems, 2 fourth-graders, 2 sixth-graders, and 16 adults were excluded from the analyses (not included in the participant N reported above).

Participants were instructed to read the texts silently for comprehension at their own pace, the same way as they would read a magazine or a book. Adults were further told that after varying intervals they would be asked to paraphrase the last sentence to make sure that they attended to what they read. Adult participants answered the queries with 95–100% accuracy. The children were told that after varying intervals they would get a yes/no statement on the last sentence, to which they had to answer by pressing a corresponding button on a gamepad. During the experiment, there were 20 statements in total. Only participants who correctly responded to at least 75% of the statements were included in the analyses. One second grader and one fourth grader were excluded for not meeting this criterion (not included in the participant N reported above). Included participants’ average scores were 91%, 92%, and 93% for second-, fourth-, and sixth-graders, respectively.

A practice session containing eight (adults) or six (children) sentences preceded the first experimental block. There was a short break between the two experimental blocks.

**Results**

Trials where T1 was initially skipped were excluded from the analyses (2% of trials for second-graders,
2% for fourth-graders, 5% for sixth-graders, and 3% for adults). Furthermore, trials where the change occurred more than 6 ms after fixation onset were excluded from the analyses (20% of the remaining trials for second-graders, 16% for fourth-graders, 15% for sixth-graders, and 5% for adults). Because the variances and distributions of the condition means varied quite considerably among age groups, logarithmic transformations were computed for each measure to render the estimates of the condition means more normally distributed and standard deviations more comparable to each other. For each measure, a 4 (age) × 2 (stimulus type) × 2 (preview) three-way analysis of variance (ANOVA) was conducted. In cases where Mauchly’s sphericity test became significant, multivariate analyses of variance (MANOVAs) and Greenhouse–Geisser corrected ANOVAs were also conducted. However, the effects did not change for any measure, so only the ANOVA results are reported here. The means and standard deviations for each measure are presented in Table 2 (nontransformed estimates are presented).

Our main focus was on the Preview × Stimulus Type interactions, which may reveal whether more parafoveal information is extracted from the second constituent within compounds than from nouns in adjective–noun phrases. We assess this by considering a measure that is typically used in boundary studies across words—namely, T2 gaze duration. T2 gaze duration is the sum of all first-pass fixations on the T2 area before it is exited to the left or right. Another measure we considered to assess differences in parafoveal information extraction between conditions is target area gaze duration, the sum of all first-pass fixations on the whole target area (T1 + T2) before it is exited to the left or right. In order to examine whether T1 and T2 are processed in parallel (especially likely for the compound condition), measures assessing

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Table 2. Means and standard deviations for each eye movement measure as a function of age, stimulus type and preview

<table>
<thead>
<tr>
<th>Group</th>
<th>Measure</th>
<th>Change M</th>
<th>SD</th>
<th>No change M</th>
<th>SD</th>
<th>CE</th>
<th>Change M</th>
<th>SD</th>
<th>No change M</th>
<th>SD</th>
<th>CE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade 2</td>
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<td>266</td>
<td>59</td>
<td>268</td>
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<td>52</td>
<td>250</td>
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<td>417</td>
<td>178</td>
<td>392</td>
<td>131</td>
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<td>216</td>
<td>457</td>
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<td>84</td>
<td>341</td>
<td>75</td>
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<td>150</td>
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<td>Target area gaze duration</td>
<td>817</td>
<td>283</td>
<td>707</td>
<td>246</td>
<td>110</td>
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<td>709</td>
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<td>T1 first fixation duration</td>
<td>236</td>
<td>37</td>
<td>247</td>
<td>34</td>
<td>–11</td>
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<td>31</td>
<td>235</td>
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<td>436</td>
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<td>55</td>
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<td>44</td>
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<td>265</td>
<td>59</td>
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<td>48</td>
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<td>290</td>
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<td></td>
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<td>52</td>
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<td></td>
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<td>124</td>
<td>475</td>
<td>107</td>
<td>33</td>
<td>579</td>
<td>174</td>
<td>417</td>
<td>82</td>
<td>162</td>
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</tbody>
</table>

Note: T1 = first constituent/adjective. T2 = second constituent/noun. CE = change effect (change–no change).

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6 McConkie and Loschky (2002) demonstrated that a display change remains undetected if it occurs less than 6 ms after the end of the saccade.
the reading of T1 before change (T1 first fixation duration and T1 gaze duration) were considered. T1 gaze duration is the sum of all first-pass fixations on the T1 area before it is exited to the left or right. Figure 1 visualizes the different eye fixations before change (T1 first fixation duration, T1 gaze duration, and T1 target area gaze duration were considered. T1 gaze duration) were considered. T1 gaze duration is the sum of all first-pass fixations on the T1 area before it is exited to the left or right. Figure 1 visualizes the different eye fixations before change (T1 first fixation duration, T1 gaze duration, and T2 gaze duration were considered. T2 gaze duration) were considered. T2 gaze duration is the sum of all fixations on the T2 area after the target area gaze duration (both T1 and T2) was considered. T1 first fixation duration and T2 gaze duration were longer in the adjective–noun condition, and T1 gaze duration was longer in the compound condition. There was a main effect of age for each measure (all ps < .001), reflecting the fact that reading becomes faster with age during the elementary school years.

**T1 first fixation duration**

There was no effect of preview, Fs < 1. The Preview × Age interaction was significant by participants, $F_1(3, 75) = 3.19$, $p = .03$, $\eta_p^2 = .11$, but not by items, $F_2(3, 177) = 1.78$, $p > .1$, $\eta_p^2 = .03$. There were no other interactions, all Fs < 1.

**T1 gaze duration**

There was a significant main effect of preview, $F_1(1, 75) = 14.15$, $p < .001$, $\eta_p^2 = .16$, $F_2(1, 59) = 7.12$, $p = .01$, $\eta_p^2 = .11$. The main effect was qualified by a Stimulus Type × Preview interaction that was marginal by participants, $F_1(3, 75) = 2.80$, $p < .1$, $\eta_p^2 = .04$, and significant by items, $F_2(1, 59) = 4.36$, $p = .04$, $\eta_p^2 = .07$. When the stimulus types were assessed separately, a main effect of preview was observed for compounds, both ps < .005, but not for adjective–noun pairs, both ps > .2. T1 was fixated longer in compounds when there was a change in T2 than when there was no change. The Preview × Age interaction was significant by participants, $F_1(1, 75) = 3.33$, $p = .02$, $\eta_p^2 = .12$, but not by items, $F_2(3, 177) = 1.82$, $p > .1$, $\eta_p^2 = .03$. There was no Stimulus × Age interaction, $F_1(3, 75) = 1.34$, $p > .2$, $\eta_p^2 = .05$, $F_2(3, 177) = 2.26$, $p = .08$, $\eta_p^2 = .04$, and no three-way interaction, both Fs < 1.

**T2 gaze duration**

There was a significant main effect of preview, $F_1(1, 74) = 198.13$, $p < .001$, $\eta_p^2 = .73$, $F_2(1, 57) = 190.22$, $p < .001$, $\eta_p^2 = .77$, which was qualified by an interaction between stimulus type and preview, $F_1(1, 74) = 41.50$, $p < .001$, $\eta_p^2 = .56$, $F_2(1, 57) = 30.08$, $p < .001$, $\eta_p^2 = .35$. The interaction reflected the fact that the preview effect was larger for compounds (86 ms) than adjective–noun pairs (37 ms) even though the preview effect was significant for both compounds and adjective–noun pairs, all ps < .001. For all groups, T2 was gazed longer in both the compound and adjective–noun condition when there was a change than when there was no change. The three-way interaction was marginal by participants, $F_1(3, 74) = 2.41$, $p = .07$, $\eta_p^2 = .09$, but...
not by items, $F_2(3, 171) = 2.10, p > .1, \eta^2_p = .04$. There were no other interactions, all $Fs \leq 1$.

**Target area gaze duration**

There was a significant main effect of preview, $F_1(1, 75) = 149.78, p < .001, \eta^2_p = .67$, $F_2(1, 59) = 96.10, p < .001, \eta^2_p = .62$, which was qualified by a significant Stimulus Type x Preview interaction, $F_1(1, 75) = 39.29, p < .001, \eta^2_p = .34$, $F_2(1, 59) = 33.60, p < .001, \eta^2_p = .36$. The preview effect was significant for both stimulus types, all $ps < .005$, but again, for all groups, it was larger for compounds (177 ms) than for adjective–noun pairs (52 ms). The target area was read slower in both the compound and adjective–noun condition when there was a change than when there was no change. There was also a marginal Stimulus Type x Age interaction, $F_1(3, 75) = 2.31, p = .08, \eta^2_p = .09$, $F_2(3, 177) = 2.24, p = .09, \eta^2_p = .04$. When assessed separately, a main effect of stimulus type emerged for second-graders $F_1(1, 16) = 5.25, p = .04, \eta^2_p = .25$, $F_2(1, 59) = 2.90, p = .09, \eta^2_p = .05$, but not for the other age groups, all $ps > .2$. The second-graders fixated the target area longer in the compound than in the adjective–noun condition. There was neither a Preview x Age interaction, $F_1(3, 75) = 1.67, p > .1, \eta^2_p = .06$, $F_2(3, 177) = 1.35, p > .2, \eta^2_p = .02$, nor a three-way interaction, both $Fs < 1$.

Post hoc analyses

To summarize the results, a solid main effect of preview was observed for all the gaze duration measures. Most importantly, the change effect on T2 was larger for compounds than for adjective–noun pairs. This suggests that even for the second-graders, the parafoveal preview effect is larger within words than across two words. One possible and rather trivial reason for the change effect being larger for compounds than for adjective–noun pairs may be the initial landing position on T1, which was further in the word for compounds (average character 3.8) than for adjectives (average character 3.4) in the adjective–noun phrases. However, when we divided the trials into two groups based on the initial fixation location on T1, the trials with initial fixations in the beginning of compound words (around the second letter) yielded a much larger preview effect in target area gaze duration (141 ms) than did the trials with initial fixations rather far in the adjectives (around the fifth character, 61 ms). This clearly indicates that the initial fixation location in T1 being on average further in the word in the compound condition than in the adjective–noun condition was not the source of the larger change effects observed for compound words.

Second, in T1 gaze duration there was a solid parafoveal-on-foveal effect for compounds, which was not reliable in previous compound word studies (Hyönä et al., 2004; Juhasz et al., 2009; White et al., 2008). We speculated in the introduction that compound frequency may be a factor that is important in determining whether parafoveal-on-foveal effects are to be observed or not. To further explore this issue, we conducted a post hoc analysis in which we divided the items into a relatively high-frequency compound group (8.82 per million) and a relatively low-frequency compound group (0.53 per million). The means and standard deviations for both frequency groups are presented in Table 3 (nontransformed estimates are presented). In line with our speculations, we found a significant effect of preview in T1 gaze duration for the high-frequency compound group (46 ms, both $ps < .001$) whereas the low-frequency compounds did not exert a preview effect ($-4$ ms, both $ps > .2$), leading to a significant Frequency x Preview interaction, $F_1(1, 75) = 10.87, p = .001, \eta^2_p = .13$, $F_2(1, 58) = 11.42,$

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7 The effect size was on average 60 ms for second-graders, 4 ms for fourth-graders, 47 ms for sixth-graders, and 62 ms for adults. Since there was no interaction between age and preview, we do not want to make an issue of the minimal parafoveal-on-foveal effect for fourth-graders, even though it may well be that their allocation of attention is more serial than that for the other groups. However, it is anyway notable that parafoveal-on-foveal effects can be observed for young readers as well, confirmed by the solid T1 gaze duration effect of 60 ms for second-graders (both $ps < .01$).
Table 3. Means and standard deviations for T1 gaze duration as a function of frequency, age, and preview

<table>
<thead>
<tr>
<th></th>
<th>High frequency</th>
<th></th>
<th>Low frequency</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Change</td>
<td>No change</td>
<td>Change</td>
<td>No change</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
<td>M</td>
<td>SD</td>
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<tr>
<td>Grade 2</td>
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<td>242</td>
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<td>197</td>
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<tr>
<td>Grade 4</td>
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<td>259</td>
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<tr>
<td>Adults</td>
<td>302</td>
<td>195</td>
<td>240</td>
<td>55</td>
</tr>
</tbody>
</table>

Note: CE = change effect (change–no change).

\[ p = .001, \eta_p^2 = .16 \]. There were no other interactions, all \( p > .15 \).

Finally, there is the possibility that the parafoveal-on-foveal effect observed for high-frequency compounds is due to mislocated fixations (Drieghe et al., 2008)—that is, fixations that were intended to land on T2 but instead landed on the ending letters of T1. If so, it may be the case that the attentional focus is already on T2 even though the eyes fixate T1, and this may be the main source for the observed parafoveal-on-foveal effect. In order to rule out this possibility, we performed an analysis for high-frequency compounds for T1 gaze duration in which all the trials were excluded where the last fixation prior to fixing T2 landed on the last two characters (for a similar procedure, see Drieghe et al., 2008). This led to the exclusion of 53% of the trials for second-graders, 41% for fourth-graders, 43% for sixth-graders, and 32% for adults. Against the prediction of the mislocated fixation account, we still found a significant preview effect after the exclusion of the possibly mislocated fixations, \( F(1, 73) = 10.19, p < .005, \eta_p^2 = .12, F(2, 24) = 8.54, p < .01, \eta_p^2 = .26 \). The T1 region in high-frequency compounds\(^9\) was read 34 ms faster when there was no change than when there was a change. This main effect was not qualified by a reliable Preview \( \times \) Age interaction, \( F(3, 73) = 2.13, p > .1, \eta_p^2 = .08, F(3, 72) = 2.44, p = .07, \eta_p^2 = .09 \), indicating that the effect is present across age groups. The analyses thus clearly demonstrate that the preview effect for high-frequent compounds was not due to mislocated fixations.

**Discussion**

The results of the present study clearly showed that the change effect is larger for compound
words than for two separate words for each age group, even for second-graders. It thus seems that more parafoveal information is extracted within words than across words. In other words, attention seems to be allocated to parafoveal text to a greater extent within than across words from Grade 2 onwards. This is in line with earlier studies that have examined the change effect separately across and within words (e.g., Altarriba et al., 2001; Hyönä et al., 2004; Pollatsek et al., 1992). Furthermore, this confirms the implicit prediction of Juhasz et al. (2009) that the change effect is larger for concatenated compounds than for separate words.

For adjective–noun pairs there was no evidence for parafoveal-on-foveal effects for any age group. This indicates that the processing of two separate words proceeds in a serial fashion, as proposed by the E-Z Reader model (e.g., Reichle et al., 2003), which is in line with most of the earlier research (see Rayner, White, Kambe, Miller, & Liversedge, 2003, for a review). For high-frequency compounds, a parafoveal-on-foveal effect was obtained that was not driven by mislocated fixations (Driehge et al., 2008). Moreover, whereas White et al. (2008) found a significant parafoveal-on-foveal effect in selective regression path duration (see the introduction for the analysis), but only nonsignificant numerical trends in gaze duration (see also Hyönä et al., 2004; Juhasz et al., 2009), the present study found a solid preview effect for high-frequency compounds in gaze duration. Most surprisingly perhaps, this effect was found across age groups. This suggests that constituents of a high-frequency compound word are processed in parallel, even by second-grade readers.

The allocation of attention during fixations is a key issue in eye movement research in reading. One of the key questions is whether readers are capable of attending to and identifying more than one word at a time. Serial models posit that as a rule only one word is attended at a time (e.g., Reichle et al., 2003), whereas parallel models assume that the “attentional gradient” may span up to four words around the current fixation (e.g., Engbert, Nuthmann, Richter, & Kliegl, 2005). These conflicting viewpoints may be accommodated by assuming that the attentional span is not fixed but fluctuates as a function of text characteristics and individual differences. The current study supports the idea that certain text characteristics regulate the size of the attentional span and with that also whether constituents in a compound word are processed serially or in parallel. We discuss three factors derived from the present study that can affect the allocation of visual attention.

First, the finding of more parafoveal processing within than across words points to the importance of spatial unification in the allocation of attention during reading. We argue that the reason why Juhasz et al. (2009) did not find a difference between compounds and adjective–noun pairs whereas we did is that we used concatenated compounds whereas they used spaced compounds. Thus, it seems that readers are more likely to span their attention to cover a visual object that is spatially unified than objects that are not spatially unified, resulting in attention stretching further and also earlier into the parafovea in case of unified objects.

Second, we argue that the degree of linguistic unification affects the way attention is allocated, even across words. That is, even though the size of the preview effect across words was smaller than that within words, it was larger than that usually found in boundary studies (see Hyönä et al., 2004, for a summary table). Actually, with the same type of manipulation as in the present study (first two letters preserved and the rest replaced with visually similar letters) it has been hard to find any preview effect in T2 gaze duration at all, whereas in the present study the preview effect for adjective–noun pairs was 37 ms for

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10 One may argue that the changed letters sometimes fall within the foveal rather than the parafoveal area. However, the parafoveal-on-foveal effect is observable even when trials where the last fixation in T1 falls on the last two letters (the so-called mislocated fixations) are excluded. In this case at least four letters from the right of the fixation appear in unchanged format (the two final letters from the first constituent and the two first letters from the second constituent), which means that the changed letters clearly reside in the parafoveal area.
adults and 38 ms, 42 ms, and 33 ms for second-, fourth-, and sixth-grade children, respectively. One study with the same kind of manipulation that did find a solid preview effect across words (20 ms) also used adjective–noun phrases for the two-word condition (Juhasz et al., 2009). Juhasz et al. pointed out that in comparison to other two-word sequences, adjective–nouns phrases are different in the sense that the noun is syntactically predictable after an adjective, as a noun is very likely to follow an adjective. They reasoned that—in comparison to previous studies—the increased predictability of the preview may have caused the larger than usual preview effects. In our experiment, the adjective–noun pair always comprised a noun phrase, in which the adjective is always followed by a noun. Consequently, also in our case the noun is syntactically highly predictable. In other words, the adjective–noun phrases are linguistically unified so the larger than regular preview effects across words may be ascribed to this higher degree of linguistic unification.11

The third factor affecting the allocation of attention is related to lexical properties of the experimental materials. The selection of early acquired and relatively frequent compounds led to larger change effects than in most previous studies (e.g., Hyöna et al., 2004; White et al., 2008). Most importantly, this is the first time a parafoveal-on-foveal effect in gaze duration has been found for compounds, even though previous studies have reported numerical trends going in the same direction (e.g., Hyöna et al., 2004; Juhasz et al., 2009; White et al., 2008). Post hoc analyses of the present data further demonstrated that the parafoveal-on-foveal effect is restricted to frequent compounds. Obviously, we are not the first researchers to show that word frequency affects the way attention is allocated during reading (e.g., Brysbaert, Drieghe, & Vitu, 2005; Henderson & Ferreira, 1990; Rayner, Sereno, & Raney, 1996; White, 2008; White, Rayner, & Liversedge, 2005). For example, Henderson and Ferreira showed that more frequent words allow for more parafoveal information extraction by virtue of low foveal load. However, it needs to be noted that there is no previous evidence demonstrating that word frequency modulates parafoveal-on-foveal effects across words (e.g., Drieghe et al., 2008). How should the parafoveal-on-foveal effect within compound words be interpreted? And why is it that this effect can only be found with higher frequency compounds? In order to answer these questions, we first provide a short survey of the previous findings on Finnish compound processing.

In previous studies we have found evidence for the role of both constituent and whole-word representations in compound-word processing (Bertram & Hyöna, 2003; Hyöna & Pollatsek, 1998; Kuperman, Bertram, & Baayen, 2008; Pollatsek, Hyöna, & Bertram, 2000). That is, these studies have revealed that higher first- and second-constituent frequency as well as higher whole-word frequency come with shorter first- and second-fixation duration and shorter gaze duration. These results have led us to suggest a dual-route model (or a multiple route model in Kuperman et al., 2008), according to which readers attempt to decompose a compound word into its constituents and access the word via these constituents, as well as to map the word directly onto a whole-word representation. In other words, the dual-route model suggests that the reader tries to recognize a compound word—at least in the initial processing stages—simultaneously via the decomposition route and the whole-word route. The larger than average change effects for compounds could be related to this initial period in which the reader allocates attention over the whole word in an attempt to recognize a compound word not only in a decomposed form, but also as a whole unit, regardless of word frequency. However, how much the whole-word route contributes to compound

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11 It may also be argued that English concatenated compounds are linguistically more unified than spaced compounds because new compound formations are typically written with a space, and as the compound meaning becomes more established (going hand in hand with developing more shades of idiosyncrasy as well), they start to be written in a concatenated format. This may also contribute to the larger preview effects in concatenated than spaced compounds observed by Juhasz et al. (2009).
recognition depends on a number of factors, one being whole-word frequency. The more frequent a compound is, the more likely it is that whole-word representations make a significant contribution to the recognition process. As regards attentional allocation, one may assume that with higher frequency compounds attention is for a longer time sustained over the whole compound, whereas for lower frequency compounds—by virtue of a rather unsuccessful whole-word recognition process—attention zooms in more quickly on a smaller lexical unit—that is, the first constituent. This kind of mechanism can explain why changes in the latter part of the word are more disruptive (and appear earlier) in the case of higher frequency than in lower frequency compounds.

Reading skill is also known to affect the allocation of attention (see Häikiö et al., 2009). In the present study, we examined the effect of reading skill on attentional allocation by testing second-, fourth-, and sixth-grade readers as well as adults. To our surprise—and against our hypotheses—we did not find evidence for the view that attentional allocation differs between readers of different age. All age groups extracted more parafoveal information within compounds than across two words, and for all age groups a parafoveal-on-foveal effect was obtained within words (although this claim may be a bit too strong for fourth-graders), but not across words. It thus seems that differences between age groups in the allocation of attention across words (as found here and in Häikiö et al., 2009) are levelled out when words are within a compound word. However, in addition to this it was also the case that the preview benefit for nouns in the adjective–noun phrases was equally large for all age groups (around 35–40 ms). In the above, we already noted that this effect is larger than usual and is most probably caused by the predictability of the noun given the adjective. It is possible that this kind of predictability levels out potential differences between age groups as well.

Another potential source for the lack of age by preview interactions (interactions that were found in the Häikiö et al., 2009, study) is that the material used in the present study was relatively easy for all age groups. This is different from the Häikiö et al. study, where the text material was relatively difficult for the younger children. The key difference between the studies is that the text materials in the Häikiö et al. study were stories comprising six to eight sentences, whereas the text material in the current study comprised single sentences. It can be assumed that especially for younger children reading and understanding stories of several sentences is more taxing than reading single sentences. Moreover, even though half of the texts in the Häikiö et al. study were aimed at the second-grade level, the other half of the texts in that study were aimed at sixth-grade level, so overall the materials were harder than those in the present study. It is possible that the relative easiness of the text materials in the current study may have allowed the younger readers to widen their attentional span to such an extent that manipulations in the parafovea affected them in the same way as they did older children and adults. In other words, it may also be the case that using text materials suitable for second-graders levels out the existing differences between age groups in the allocation of attention during reading.

In the above, we already noted that this effect is larger than usual and is most probably caused by the predictability of the noun given the adjective. It is possible that this kind of predictability levels out potential differences between age groups as well.

In sum, the present study shows that both elementary school children and adults engage in more extensive parafoveal processing within words than across words. That is, readers of different ages extract more parafoveal information from the second word unit (constituent) within long compounds than from a noun in adjective–noun phrases. The present study also demonstrates that in case of two separate words, processing proceeds serially for adults and elementary school children alike, but that when words are part and parcel of a high-frequency compound, readers of all age groups process properties of these words in parallel. In sum, the present study shows that attentional allocation extends further to the right and is more simultaneous when words are linguistically and spatially unified, providing evidence that attention in text processing is flexible in nature.
REFERENCES


