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Development of the letter identity span in reading: Evidence from the eye movement moving window paradigm

Tuomo Häikiö *, Raymond Bertram, Jukka Hyönä, Pekka Niemi

Department of Psychology, University of Turku, FIN-20014 Turku, Finland

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ABSTRACT

By means of the moving window paradigm, we examined how many letters can be identified during a single eye fixation and whether this letter identity span changes as a function of reading skill. The results revealed that 8-year-old Finnish readers identify approximately 5 characters, 10-year-old readers identify approximately 7 characters, and 12-year-old and adult readers identify approximately 9 characters to the right of fixation. Comparison with earlier studies revealed that the letter identity span is smaller than the span for identifying letter features and that it is as wide in Finnish as in English. Furthermore, the letter identity span of faster readers of each age group was larger than that of slower readers, indicating that slower readers, unlike faster readers, allocate most of their processing resources to foveally fixated words. Finally, slower second graders were largely not disrupted by smaller windows, suggesting that their word decoding skill is not yet fully automatized.

Introduction

The amount of information that can be extracted during a single eye fixation in reading is intimately linked to the development of reading skill. In support of this claim, Rayner (1986) found that when reading skill improves, the amount of information that can be extracted during a single fixation increases as well. In particular, he found that increased reading skill goes hand in hand with the ability to extract more information about the length and the letters of words to the right of fixation. The main goal of the current study was to examine the number of letters readers can identify during a fixation.

* Corresponding author. Fax: +358 2 3335060.
E-mail address: tuilha@utu.fi (T. Häikiö).

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More specifically, we examined how far to the right of fixation readers extract letter identity information and how this skill develops across elementary school years toward adulthood.

Studies with adult readers (for a summary, see Rayner, 1998) have established that the global perceptual span—the area from which useful information is extracted during a fixation in reading—extends from the beginning of the currently fixated word to approximately 14 or 15 characters to the right of fixation. The global perceptual span comprises an area of high visual acuity, the foveal area, and an area where acuity is not as good, the parafoveal area. Under normal reading conditions (with respect to font size and reading distance), the foveal area extends approximately 6 to 8 characters around the fixation point and the parafoveal area functionally extends up to 15 characters to the right of fixation (when reading from left to right). The remainder of the visual field is the periphery, from which no information relevant to reading is extracted. Even though the global perceptual span is physiologically symmetric, in languages such as English and Finnish that are read from left to right, the span of effective vision is asymmetric to the right, that is, toward new text information (Rayner, 1998).

The global perceptual span can be divided into three different regions based on the type of information obtained around an eye fixation: information about word lengths, letter features, and letter identities. It has become clear that word length information is extracted farthest away from the fixation with the help of spaces between words (e.g., McConkie & Rayner, 1975; Rayner, 1986). This information is used to program saccades to upcoming words. Consistent with this, the majority of saccades land near the center of words (e.g., McConkie, Kerr, Reddix, & Zola, 1988; Rayner, 1979; Vitu, McConkie, Kerr, & O'Regan, 2001) and rarely on the spaces between words (e.g., Abrams & Zuber, 1972). The area from which word length information is extracted is referred to here as the *word length span*. Whereas letter identity information refers to identities of specific letters, letter features refer to more global letter shapes. For example, *o* and *c* share the same basic shape of roundness, whereas *b* and *h* both are ascenders. Here we refer to the area from which letter feature information is extracted as the *letter feature span* and the area from which letter identity information is extracted as the *letter identity span*. Naturally, identifying a letter means that one has also identified the global visual features of that letter. On the other hand, readers may extract letter shape information without obtaining access to letter identity information. This is likely to happen for letters appearing farther away from the current fixation. With specific textual manipulations combined with the moving window technique (McConkie & Rayner, 1975), the letter feature and letter identity spans can be assessed separately, as explained in more detail below.

The moving window technique

By using the moving window technique developed by McConkie and Rayner (1975), the different components of the global perceptual span can be assessed accurately and reliably. In this technique, reading performance associated with the nonmanipulated text (baseline condition) is compared with reading performance of a text with an experimenter-defined window around the current fixation point (window condition). The text outside the experimenter-defined window is mutilated, whereas the text inside the window is shown intact. The window moves in synchrony with the eye movements so that readers always see a fixed amount of original text. Each time readers move their eyes, a new region of the original text is shown around the fixation and the remaining text area becomes mutilated (see Fig. 1). Readers are able to make eye movements as usual, but the amount of useful information available on each fixation is varied depending on the window size. The underlying idea is that when the window becomes smaller than the global perceptual span or any component of it, reading will be disrupted in comparison with reading in the baseline condition. (A special case of the moving window technique is the eye movement contingent display change paradigm of Rayner, 1975, where only one word in the parafovea is manipulated prior to fixating it and is subsequently changed into the correct form during the saccade entering it.)

Different types of manipulations are needed to examine the different components of the global perceptual span (see Fig. 2). For instance, to examine the letter identity span, as is done in the current study, one needs a condition in which letter identity information outside predefined windows is withheld and then compared with the baseline condition in which no text information is withheld. Moreover, this window condition should preserve letter feature information outside the window so as to be

```
Baseline condition on fixation N:   “during a saccade because the eyes are moving”
                                                         *
Baseline condition on fixation N+1: “during a saccade because the eyes are moving”
                                                                   *
Window condition on fixation N:     “xxxxxx x xxxcade because the xxxx xxx xxxxxx”
                                                         *
Window condition on fixation N+1:   “xxxxxx x xxxxxxx xxxxxse the eyes are mxxxxx”
                                                                   *
```

Fig. 1. An example of a baseline and a 17-character window using the moving window paradigm on two consecutive fixations.

	WL	LF	LI	11 character window
Control condition	X	X	X	`Here is a preview showing eleven letters.`
Current study	X	X	-	`Kono la a preview sbcmluy aiaxau isffsna.`
Rayner Experiment 2 and 3	X	-	-	`XXXX XX a preview sXXXXXX XXXXXX XXXXXXX.`
Rayner Experiment 1	-	-	-	`XXXXXXXXa preview sXXXXXXXXXXXXXXXXXXXXX.`

Fig. 2. The type of information intact outside of a symmetric text window in the current study and in Rayner (1986) when fixating *v* in the word *preview*. WL, word length information; LF, letter feature information; LI, letter identity information.

able to attribute differences in performance solely to the withheld letter identity information and not to a combination of letter feature and letter identity information. Consequently, in our experiment, in the different window conditions, we replaced the correct letters with letters that were visually similar in shape (e.g., *o* with *c*). We reasoned that if, for instance, a window of 11 correct letters (with 5 letters to the right and left of fixation) with visually similar letters outside the window disrupts reading, this implies that readers normally identify letters outside this window. If they normally would just extract letter features but not identify letters outside this window, reading performance should be similar to that in the baseline condition. Thus, if in our example (see Fig. 2, current study) a reader is fixating on the *v* in *preview* and has a letter identity span of 5, he or she will not be disrupted by the fact that letter identity information (but not letter shape information) is withheld outside the window. However, if a reader has a letter identity span of 7, he or she will be disrupted when the 6th and 7th characters are not *h* and *o* but rather visually similar letters like *b* and *c*. In general, a difference between the window and baseline conditions must be due to withheld letter identity information. Hence, this type of manipulation can be used to assess the letter identity span.[1]

Next, we compare our manipulation with the manipulations used in the first three experiments of Rayner (1986), the seminal (and also the only) study on the development of the global perceptual span. In the window conditions of Experiments 2 and 3 in Rayner's study, the replaced letters were visually dissimilar (all Xs) to the correct ones. In other words, in comparison with the unchanged base-

[1] It should be noted that the word identity span is incorporated into the letter identity span. The word identity span refers to the area of text around the fixation in which words can be identified. Because the letters of the to-be-identified word need to be recognized, the word identity span is smaller than or equal in size to the letter identity span. Importantly in the current context, Rayner, Well, Pollatsek, and Bertera (1982) showed that the letter identity span does not depend on whether a currently fixated word or an upcoming word is fully or only partly visible (i.e., a subset of letters fall outside of the text window).

line condition, both letter feature information and letter identity information were withheld. Hence, any difference between reading performance in the baseline and window conditions may be attributed to withholding both letter feature information and letter identity information. To highlight the difference between our manipulation and Rayner's manipulations, consider our example discussed above (see Fig. 2). If a reader is fixating on the *v* in *preview* and has a letter identity span of 5 and a letter feature span of 7, he or she will not be disrupted in the visually similar condition that we used because the correct letters (*h* and *o*) that should be there share the global shapes with *b* and *c* that are initially there. However, the reader would be disrupted by the visually dissimilar conditions used by Rayner (see current Fig. 2; Experiments 2 and 3 in Rayner, 1986) because the correct letters are initially replaced by Xs and these Xs do not share visual features with the correct letters (*h* and *o*). In general, we assume that letter features may be extracted either farther from the parafovea than letter identities or equally as far. Thus, according to this logic, the type of manipulation employed in Rayner's study can be used to assess the letter feature span. Note further that a comparison of the current study with Rayner's Experiments 2 and 3 may answer the question of whether the letter feature span is identical to or larger than the letter identity span.

Finally, word length span may be assessed (not done in the current study) by filling in the spaces between words outside the window and comparing it with a condition in which spacing is preserved, as was done in Experiment 1 of Rayner (1986; see also the example sentence from Rayner's Experiment 1 as depicted in Fig. 2 of the current study). This type of manipulation disrupts reading farther away in the parafovea than withholding letter feature and letter identity information (see below).

Development of components of global perceptual span

As explained above, Rayner (1986) used the moving window technique to investigate the word length and letter feature spans among readers of different ages. In Experiment 1, Rayner found that after 1 year of reading instruction the word length span is asymmetrical to the right of fixation. For the second graders, the word length span extends from the beginning of the currently fixated word (3 or 4 characters to the left of fixation) to approximately 11 characters to the right of fixation. The same holds true for fourth graders, whereas the word length span of sixth graders is as wide as that of the adults, that is, approximately 14 characters to the right of fixation. Even though the word length span does not develop after the sixth grade, readers still become more fluent in reading at a later stage, as witnessed by fewer forward fixations, fewer regressions, and longer and fewer saccades (Lefton, Nagle, Johnson, & Fisher, 1979; Rayner, 1998). Although the word length span of beginning readers is relatively large, it is evident that beginning readers devote most of their processing capacity to the currently fixated word; Rayner (1986) found that the smallest window size was least disrupting for the youngest readers.

As argued above, Experiments 2 and 3 of the Rayner (1986) study assessed the letter feature span. It was found that reading performance of second graders was not affected beyond the condition where one could see the currently fixated word and the next word (altogether, approximately 7 characters to the right of fixation) and that fourth graders extract information about letter features approximately 11 characters to the right of fixation. This is approximately the upper limit given that it was the same as what was found for sixth graders and adults. In sum, word length information can be extracted from farther to the right than can letter feature information. Moreover, maximum performance for extracting letter features is reached at the fourth grade, and maximum performance for extracting word length information is reached at the sixth grade.

Since the seminal study of Rayner (1986), the question about the development of readers' perceptual span has been left virtually untouched. To fill in the lack in our knowledge, in the current study we examined by means of the moving window technique the development of letter identity span that was not directly assessed in Rayner's study (see the reasoning above). To that end, letters outside the predefined window were replaced with visually similar letters (e.g., *o* was replaced by *c*, *h* was replaced by *b*). Thus, text outside the window comprised nonwords. We wanted to know how large a window must be for readers of different age groups to read text with the same speed as when there is no window (i.e., when text was displayed normally). To examine this, we used as the dependent measure the overall reading speed expressed as the number of words a participant was able to read within 1 min.

When comparing reading performance of different age groups, one problem is to choose appropriate texts. One possibility is to choose exactly the same texts for all age groups so that one can compare age effects independent of text features. Alternatively, one may present each age group with a different (age-appropriate) text so that readers are not confronted with texts above or below their reading (or cognitive) level. In the current study, we combined these two approaches. We selected second- and sixth-grade texts that were read by all age groups so that we could compare performance of all age groups on exactly the same texts, while at the same time we compared the second graders with the sixth graders when both groups read age-appropriate texts. The former setup also allowed us to examine whether letter identity span is modulated by text difficulty, a finding that would be in line with Rayner (1986), who showed that fourth graders' letter feature span was modulated by text difficulty.

Another aspect that adds to the novelty of this study is that it was conducted in Finnish. Most studies examining components of the global perceptual span have been conducted in English, and it may well be that the size of specific components of the perceptual span are language specific (Rayner, 1998). One crucial difference between English and Finnish pertains to grapheme–phoneme correspondence. Finnish has a shallow orthography (i.e., it has consistent grapheme–phoneme correspondences), whereas English has a deep orthography. It has been established that, due to this difference, Finnish children reach fluency in reading much sooner than do English-speaking children (Seymour, Aro, & Erskine, 2003). Furthermore, words are on average longer in Finnish than in English. This may result in more information being extracted from the parafoveal area when reading Finnish than when reading English. Therefore, it is not implausible to assume that the development of the letter identity span differs between English and Finnish.

Not only does reading skill vary as a function of age, but also there is enormous variability in reading skill within each age level. In the current study, we examined possible effects of within-group variability by dividing each age group into two subgroups: the slower readers and the faster readers. We were interested in whether faster readers have a larger letter identity span than do slower readers. This is not necessarily the case given that the letter identity span may be equally wide for faster and slower readers and the difference in reading speed could be due purely to faster readers' more effective extraction of letter identity information within a given span.

Method

Participants

A total of 80 participants (16 second graders [5 boys and 11 girls], 22 fourth graders [11 boys and 11 girls], 18 sixth graders [7 boys and 11 girls], and 24 adults [6 men and 18 women]) were included in the analyses. The second graders were on average 8 years old, the fourth graders were on average 10 years old, and the sixth graders were on average 12 years old. At the time of testing, second graders had received from 1 year to 1 year 4 months of reading instruction. The child participants received candy as a reward for participation. The adult participants were university students who either took part in the experiment as part of a course requirement or received a small amount of money.

Prior to the experiment proper, the child participants were tested with the Word Chain test of Nevala and Lyytinen (2000). This test was performed to screen out the weakest readers of each age group. In the Word Chain test, one must recognize and separate words in a string of letters (e.g., catcomputerprincessstoneheavy) by drawing a vertical line at word boundaries (cat|computer|princess|stone|heavy) as quickly as possible. There is a time limit (85, 65, and 60 s for second, fourth, and sixth graders, respectively), and the test is scored by giving 1 point for each correctly placed vertical line. Children who were assessed to be "very weak" or "weak" in their reading skill (according to the test norms) were not included in the experiment.

Some of the adult participants had participated in an earlier eye movement experiment, but none of them had participated in a moving window experiment. None of the child participants had participated in an eye movement experiment before. All participants had normal or corrected to normal vision. Permission from the child participants' parents was acquired prior to the test.

Apparatus

Eye movements were recorded with an EyeLink II eye tracker manufactured by SR Research (Mississauga, ON, Canada). The eye tracker is an infrared video-based tracking system combined with hyperacuity image processing with a spatial resolution of 0.75°. The eye movement cameras are mounted on a headband (one camera for each eye), but the recording was monocular. Two infrared 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 a rate of 500 Hz. Recording is performed by placing the camera and the two infrared light sources 4 to 6 cm away from the eye. Head position with respect to the computer screen is tracked with the help of a head-tracking camera mounted on the center 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. Furthermore, a chin rest was used to minimize head movements. The texts were presented on a 21-inch ViewSonic P225f computer screen that has a refresh rate of 150 Hz.

Materials

The experimental material consisted of 10 stories about animals in Finnish, all of which were presented on three consecutive text screens. Each text screen consisted of a maximum of four lines of text that extended horizontally up to 67 characters in length. The space between the text lines was approximately 5.5 cm (i.e., 6 spaces between lines). Each text screen ended with a line stating "The story continues, press a button." or "The story ends, press a button." In addition to instructing the participants on what they were supposed to do, this line also attracted the eyes away from the final text line and so avoided excessively long fixations on the final text line while the participants pressed the button. The stories consisted of 80 to 87 words. Five of the stories were at the second-grade level, and another five stories were at the sixth-grade level. The stories were divided into two blocks: one consisting of all the second-grade-level (easy) stories and the other one consisting of all the sixth-grade-level (difficult) stories. The stories were matched for average length (82.6 words for difficult texts and 84.2 words for easy texts). The words in the easy texts were somewhat more frequent (average log frequency of 2.3 per million) than the words in the difficult texts (average log frequency of 2.1 per million). The frequency values were extracted from a newspaper corpus containing 22.7 million word forms (Laine & Virtanen, 1999). Average word length was shorter for easy texts than for difficult texts (7.2 characters for difficult texts and 6.7 characters for easy texts). The second-grade-level texts were modified versions of texts that are used to assess reading comprehension of first graders (Vauras, Mäki, Dufva, & Hämäläinen, 1995) and second graders (Kajamies, Poskiparta, Annevirta, Dufva, & Vauras, 2003). The sixth-grade-level texts were modified versions of school textbook texts (Hietakangas, Hirvenoja, & Järvinen, 1980; Hietakangas, Hirvenoja, Järvinen, & Kiiskinen, 1987; Mattila, Nyberg, & Vestelin, 1985, 1986) or modified versions of texts similar to school textbooks (Laurila, Halkka, Karlsson, Lappalainen, & Parkkari, 1998).

The moving window technique introduced by McConkie and Rayner (1975) was used. As the participants' eyes moved over the text, a text window of predefined size moved along. In this way, readers always saw readable text around the fixation point, whereas the text outside the predefined window was replaced with visually similar letters. Letters were considered visually similar when they shared the same basic shape (i.e., descenders were replaced with descenders [*q* replaced *p*], round letters were replaced with round letters [*o* replaced *e*], and ascenders were replaced with ascenders [*t* replaced *l*]). This means that letter feature information, but not letter identity information, was preserved outside the window. The spaces between words were left intact. Windows never included lines below or above the fixated line. It took 9 ms on average to refresh the screen during a saccade. Because vision is greatly reduced during saccades (due to saccadic suppression), it is highly unlikely that the participants saw the actual changes taking place.

The participants read all 10 stories. The second- and sixth-grade texts were blocked; within both blocks, the texts appeared in one of the four window conditions (7, 11, 15, and 19 characters, abbreviated WS7, WS11, WS15, and WS19, respectively) and in the full line condition (FL, the control condition). All of the text windows were symmetrical. For example, in WS11 the participants saw 5 characters to the left of fixation, the currently fixated character, and 5 characters to the right of fixation. In the FL condition, the lines above and beneath the currently fixated line were mutilated, but due to the large space between the lines, the participants did not notice this.

The order of the stories was randomized within a block, as was the order of the window conditions. Block order was counterbalanced across participants; half of the participants read the second-grade texts first, and half of the participants read the sixth-grade texts first. The sentences were presented in Courier font so that each character position was of equal width. With a viewing distance of approximately 60 cm, one character space subtended approximately 0.5° of visual angle. It should be noted that the font size used was somewhat larger than what is typical in many eye movement experiments (e.g., Rayner, 1986).

Procedure

Prior to the experiment proper, the eye tracker was calibrated using a nine-point calibration grid that extended over the entire computer screen. Before each text page, the participants needed to fixate a calibration point in the upper left corner of the screen. When the participants were fixating the calibration point, the experimenter pushed a button, causing a text page to appear on the screen. The system also used the calibration point to adjust for minor inaccuracies in calibration.

The participants were instructed to read the texts silently for comprehension at their own pace in the same way as they would read a magazine or a book. The participants were encouraged to read each story only once unless they did not understand parts of it. They were further told that after each story they would be asked five yes/no comprehension questions presented on the screen to make sure that they attended to what they read. The participants answered the comprehension questions by pushing a button on a game pad. A practice session containing one story without a moving text window preceded each experimental block. Between the two experimental blocks, the participants were allowed to take a short break. However, with second graders the experiment was conducted in two separate sessions to avoid overburdening them.

Results

There were some inaccuracies in the data due to calibration problems, leading to the exclusion of approximately 5% of the trials (i.e., text screens: 8% for second graders, 8% for fourth graders, 3% for sixth graders, and 3% for adults). Furthermore, clause-final words were excluded from the analyses to avoid data being influenced by clause wrap-up processes (for wrap-up effects, see Rayner, Kambe, & Duffy, 2000; Rayner, Sereno, Morris, Schmauder, & Clifton, 1989). Because the variances and distributions of the condition means varied quite considerably among age groups, data transformations were made to render the estimates of the condition means normally distributed and standard deviations more comparable to each other. To this end, a square root transformation was conducted for overall reading rate (Tabachnik & Fidell, 2001). A series of 4 (Age) × 5 (Window Size) × 2 (Text Difficulty) repeated measures analyses of variance (ANOVAs) were conducted for the transformed data. The results of Greenhouse–Geisser corrected ANOVAs are reported below. Means and standard errors of the means are given in Fig. 3 (nontransformed estimates are presented). Alongside reading rate, we also performed analyses for more specific eye movement measures, the results of which are presented in Appendix A.

To further examine significant Window Size × Age interactions, pairwise contrasts between the FL condition and each of the four window sizes are reported separately for each age group to determine the point at which each age group reached asymptote (i.e., when reading performance did not significantly differ from the FL condition).

Main analyses

Reading rate was calculated by dividing the number of words by the total reading time and was transformed to a words per minute (WPM) scale. There was a significant main effect of window size,

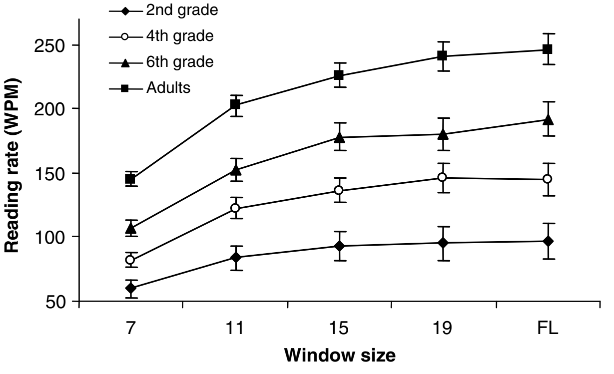

Fig. 3. Reading rate (words per minute) for each age group as a function of window size. Error bars indicate the standard errors of the means. WPM, words per minute; FL, full line.

$F(4, 304) = 200.36$, $p < .001$, $\eta_p^2 = .73$, age, $F(3, 76) = 37.09$, $p < .001$, $\eta_p^2 = .59$, and text difficulty, $F(1, 76) = 50.65$, $p < .001$, $\eta_p^2 = .40$. As expected, the smallest window slowed down reading considerably more than did larger windows, reading speed increased with age, and reading was faster with easy text than with difficult text. There was also a significant interaction between window size and age, $F(12, 304) = 3.28$, $p = .002$, $\eta_p^2 = .12$. However, we did not find evidence of letter identity span being modulated by text difficulty, both *F*s < 2, both *p*s > .10.

The Window Size × Age interaction was further examined with tests of within-participants contrasts for each age group separately. For second graders, only WS7 differed significantly from FL, $F(1, 15) = 18.81$, $p = .001$, $\eta_p^2 = .56$; there was no significant difference between WS11 and FL, $F(1, 15) = 1.53$, $p > .20$, $\eta_p^2 = .09$. This suggests that second graders reached asymptote at WS11. For fourth graders, the difference between WS11 and FL was significant, $F(1, 21) = 17.06$, $p < .001$, $\eta_p^2 = .45$, and the difference between WS15 and FL approached significance, $F(1, 21) = 3.58$, $p = .07$, $\eta_p^2 = .15$. However, there was no difference between WS19 and FL, $F < 1$. Therefore, fourth graders reached asymptote at either WS15 or WS19. For sixth graders, the pattern was not as clear-cut; the difference between WS11 and FL was significant, $F(1, 17) = 44.73$, $p < .001$, $\eta_p^2 = .73$, and the differences between WS15 and FL and between WS19 and FL were close to significant, $F(1, 17) = 3.74$, $p = .07$, $\eta_p^2 = .18$, and $F(1, 17) = 4.36$, $p = .052$, $\eta_p^2 = .20$, respectively. On the basis of two follow-up analyses of reading rate (see below), we conclude that sixth graders reached asymptote at WS19. For adults, the difference between WS15 and FL was significant, $F(1, 23) = 5.18$, $p = .03$, $\eta_p^2 = .18$, but there was no significant difference between WS19 and FL, $F < 1$. Therefore, we conclude that the adults reached asymptote at WS19.

Second and sixth graders reading age-appropriate texts

It is possible that some of the results reported above may be compromised by the youngest children reading materials at or above their level and the oldest children reading materials at or below their level. To rule out this possibility, we analyzed the WPM data of second and sixth graders reading age-appropriate material (i.e., second graders reading second-grade texts and sixth graders reading sixth-grade texts). Means and standard deviations are presented in Table 1. Similarly to the main analysis, a significant Window Size × Age interaction was found, $F(4, 128) = 6.26$, $p = .002$, $\eta_p^2 = .16$, as was a significant main effect of window size, $F(4, 128) = 47.24$, $p < .001$, $\eta_p^2 = .60$, and age, $F(1, 32) = 22.74$, $p < .001$, $\eta_p^2 = .42$. The interaction indicates that the second and sixth graders reached asymptote at different points. For the second graders the difference between WS7 and FL was significant, $F(1, 15) = 7.44$, $p = .016$, $\eta_p^2 = .33$, but the difference between WS11 and FL was no longer significant, $F < 1$, whereas for the sixth graders the difference between WS15 and FL was still significant, $F(1, 17) = 4.67$, $p = .045$, $\eta_p^2 = .22$, but the difference between WS19 and FL was only marginally significant,

Table 1
Means and standard deviations of reading rate for second and sixth graders reading age-appropriate texts

Group	WS7		WS11		WS15		WS19		FL	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Second graders	63	21	91	36	101	47	102	51	100	67
Sixth graders	96	38	140	34	166	41	174	49	185	44

Note. WS, window size; FL, full line.

$F(1, 17) = 3.20$, $p = .09$, $\eta_p^2 = .16$. Hence, we conclude that the second graders reached asymptote at WS11, whereas the sixth graders reached asymptote at WS19. These asymptotes are approximately the same as in the main analysis of reading rates of second and sixth graders. All in all, we argue that the developmental trends observed in the letter identity span were not confounded by text difficulty.

Differences between faster and slower readers

To examine whether individual differences in reading speed are related to letter identity span, we used a median split procedure to categorize the readers of each age level into two subgroups, faster and slower readers, based on their reading speed of both texts in the FL condition. ANOVAs for the transformed WPM data were conducted for each age group separately. There were significant Window Size × Reading Speed interactions for second graders, $F(4, 56) = 8.30$, $p < .001$, $\eta_p^2 = .37$, fourth graders, $F(4, 80) = 8.58$, $p < .001$, $\eta_p^2 = .30$, and adults, $F(4, 88) = 4.07$, $p = .011$, $\eta_p^2 = .16$, and a tendency for an interaction for sixth graders, $F(4, 64) = 2.42$, $p = .078$, $\eta_p^2 = .13$. Means and standard deviations for the subgroups are presented in Table 2.

The interactions were further assessed by tests of within-participants contrasts. For second graders, different asymptotic profiles emerged for faster and slower readers. For slower second-grade readers, the difference between WS7 and FL was significant, $F(1, 7) = 8.11$, $p = .025$, $\eta_p^2 = .54$; after WS11, there was no increase in WPM. Note that the difference between WS11 and FL was significant, $F(1, 7) = 16.94$, $p = .004$, $\eta_p^2 = .71$, but the effect was in the opposite direction (WS11 better than FL). The fact that there was no increase in reading rate after WS11 was also evident in the contrast between WS11 and WS19 being nonsignificant, $F < 1$. Therefore, we conclude that the slower second-grade readers reached asymptote at WS11. For faster second-grade readers, the difference between WS11 and FL was significant, $F(1, 7) = 5.89$, $p = .046$, $\eta_p^2 = .46$, but the difference between WS15 and FL was not, $F(1, 7) = 1.20$, $p > .30$, $\eta_p^2 = .15$. Therefore, we conclude that they reached asymptote at WS15.

Table 2
Means and standard deviations of reading rate separately for slower and faster readers of each age group

Group	Reading speed	Asymptote	WS7		WS11		WS15		WS19		FL	
			M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Second graders												
	Faster	15	73	21	108	29	128	38	128	38	139	60
	Slower	11	42	8	57	11	56	13	58	11	51	13
Fourth graders												
	Faster	19	90	16	141	26	160	25	178	31	178	34
	Slower	11	70	13	100	16	108	20	112	29	108	21
Sixth graders												
	Faster	19	125	46	177	35	205	40	216	44	234	29
	Slower	15	84	13	125	19	148	27	143	15	148	17
Adults												
	Faster	19	159	27	230	40	259	53	284	72	291	60
	Slower	15	127	25	170	33	190	34	193	36	194	18

Note. WS, window size; FL, full line.

For slower fourth-grade readers, there was a significant difference between WS7 and FL, $F(1, 10) = 63.01$, $p < .001$, $\eta_p^2 = .86$, but not between WS11 and FL, $F(1, 10) = 2.02$, $p > .15$, $\eta_p^2 = .17$. Therefore, they reached asymptote at WS11. For faster fourth-grade readers, the difference between WS15 and FL was significant, $F(1, 10) = 6.28$, $p = .03$, $\eta_p^2 = .39$, but the difference between WS19 and FL was not, $F < 1$. Therefore, they reached asymptote at WS19.

For slower sixth-grade readers, the difference between WS11 and FL was significant, $F(1, 8) = 31.28$, $p = .001$, $\eta_p^2 = .80$, but the difference between WS15 and FL was not, $F < 1$. Therefore, they reached asymptote at WS15. For faster sixth-grade readers, there was a significant difference between WS15 and FL, $F(1, 8) = 6.90$, $p = .03$, $\eta_p^2 = .46$, but not between WS19 and FL, $F(1, 8) = 2.67$, $p = .14$, $\eta_p^2 = .25$. Therefore, they reached asymptote at WS19.

For slower adult readers, the difference between WS11 and FL was significant, $F(1, 11) = 6.81$, $p = .024$, $\eta_p^2 = .38$, but the difference between WS15 and FL was not, $F < 1$. For faster adult readers, the difference between WS15 and FL was significant, $F(1, 11) = 10.26$, $p < .01$, $\eta_p^2 = .48$, but the difference between WS19 and FL was not, $F < 1$. Therefore, we conclude that slower adult readers reached asymptote at WS15 and that faster adult readers reached asymptote at WS19.

Discussion

The purpose of the current study was to examine whether the letter identity span in reading varies as a function of age. To this end, second, fourth, and sixth graders were tested alongside a group of adults with the moving window technique (McConkie & Rayner, 1975). In Table 3, the development of the letter identity span in Finnish is compared with that of other components of the global perceptual span in English (Rayner, 1986). To obtain an estimate of the actual letter identity span to the right of fixation, the width of the text window (minus the middle character) was divided by two. To sum up, second graders' letter identity span is estimated to be approximately 5 characters to the right of fixation and, hence, smaller than that of older readers. However, this implies that even for second graders who have received 1 year of reading instruction, the letter identity span extends in most cases at least to the end of the currently fixated word and sometimes (i.e., when fixating a short word) to the beginning letters of the following word. For fourth graders, the letter identity span extends approximately 7 characters to the right of fixation, whereas sixth graders and adults resemble each other in that their letter identity span is approximately 9 characters to the right of fixation.

Table 4 shows that the reading rate in the current study for WS15 is close to 95% of the reading rate for the FL condition in all age groups. In contrast, in Experiment 1 of Rayner's (1986) study, the reading rate for WS17 was less than 90% of the full line reading rate for all age groups. In fact, the percentage reading rates for WS11 in the current study are comparable to those for WS17 in Rayner's Experiment 1. We believe that this difference derives from the fact that the current study withheld only letter identity information, whereas in Rayner's Experiment 1 neither word length or letter feature information nor letter identity information was preserved. This implies that even though readers make use of letter identity information in the parafovea, the impact of parafoveal word length and letter feature information is greater.

In the Introduction, we raised the question of whether the letter identity span in Finnish is different from that in English. We argued that due to differences in orthographic depth and average word length, the letter identity span in Finnish may be larger than that in English. However, this appeared not to be the case. A span of 7 or 8 characters typically found for English readers (e.g. Henderson &

Table 3
Type of information obtained to the right of fixation in the current study and Rayner (1986)

	Second grade	Fourth grade	Sixth grade	Adults
Letter identity (current study)	5	7	9	9
Letter feature (Rayner Experiments 2 and 3)	7	11–12	11–12	11–12
Word length (Rayner Experiment 1)	11	11	14	14-15

Table 4
Percentages of reading rates in comparison with the full line condition separately for age groups in the current study and in Experiment 1 of Rayner (1986)

	WS7	WS11	WS15	WS19	FL
Current study					
Second graders	61	87	97	98	100
Fourth graders	56	84	94	100	100
Sixth graders	55	79	93	94	100
Adults	59	83	93	98	100

	WS5	WS11	WS17	WS23	WS29	FL
Rayner (1986)						
Second graders	62	82	88	100	100	100
Fourth graders	40	74	88	100	100	100
Sixth graders	44	84	86	96	100	100
Adults	34	62	75	89	99	100

Note. WS, window size; FL, full line.

Ferreira, 1990; Pollatsek, Lesch, Morris, & Rayner, 1992; Rayner et al., 1982) is quite comparable to the 9 characters observed in the current study from the sixth grade onward.

Another question we raised was whether the letter identity span is smaller than the letter feature span (e.g., Henderson & Ferreira, 1990; Pollatsek et al., 1992; Rayner et al., 1982) or whether both spans are approximately similar (McConkie & Rayner, 1975). In our study, the maximum letter identity span (for sixth graders and adults) was approximately 9 characters, and that is smaller than the 11- or 12-character letter feature span observed from the fourth grade onward (Rayner, 1986; see also Table 3). This suggests that indeed the letter identity span is smaller than the letter feature span; that is, letter feature information is extracted farther from the parafovea than is letter identity information.

The final question we raised pertained to the variability in reading skill at each age level. We asked whether faster readers extract letter identity information more effectively from the same area as do slower readers or whether the letter identity span of faster readers is wider than that of slower readers. Even when the weakest readers of the age group were excluded (as was done in the current study), the letter identity span of the faster readers was observed to be wider than that of the slower readers for each age group. Therefore, it is evident that the amount of reading instruction is not sufficient to predict the letter identity span and that the letter identity span varies not only across age groups but also within age-matched subgroups. One explanation is that slower readers allocate most of their processing resources to the foveally fixated word, and their attention does not shift as efficiently and as far into the parafovea as is the case with faster readers, who process foveal words with greater ease and speed. This would in turn lead to both a slower reading rate and a smaller letter identity span for slower readers. This explanation is generally in line with the so-called foveal load hypothesis of Henderson and Ferreira (1990; see also Kennison and Clifton, 1995; White, Rayner, and Liversedge, 2005), which posits that when foveal load increases, the resources left for processing parafoveal information decrease.

One issue concerning the differential effects of window size on slower and faster readers is that the slower second-grade readers are hardly affected at all by the small window size (see Table 5). This indicates that slower second-grade readers have not yet fully automatized word decoding; that is, they do not obtain automatic access to a word's orthographic and/or phonological code but rather acquire access in a piecemeal fashion. Because they have not acquired automaticity of word identification, reading with the smallest window where the majority of words are not fully visible is not as disruptive as is the case with faster readers, for whom automaticity is more developed. For most children, automaticity of word decoding is acquired during the first grade (e.g., Guttentag & Haith, 1978, 1980; Stanovich, Cunningham, & Feeman, 1984), but for some children it is delayed, as is probably the case for the slower second graders in our sample.

It should be noted that in the current study, the slow readers in each age group were actually not the weakest ones given that the weakest child readers were screened out prior to the actual experi-

Table 5
Percentages of reading rates (words per minute) for subgroups in comparison with the full line condition

Group	WS7	WS11	WS15	WS19
Second graders				
Faster	53	78	92	93
Slower	82	100	100	100
Fourth graders				
Faster	51	79	90	100
Slower	65	93	100	100
Sixth graders				
Faster	53	76	88	92
Slower	57	84	100	97
Adults				
Faster	55	79	89	98
Slower	65	88	98	99

Note. WS, window size.

ment. Also, the slower adult readers in our study may be relatively fast readers given that all of the adults were university students. This suggests that ultimately the differences in letter identity span between stronger and weaker readers may be even more pronounced than was observed in the current study. It is also evident that the letter identity span is fully developed at a younger age for faster readers than for slower readers, as indicated by faster readers reaching the upper limit of the letter identity span already at fourth grade, whereas for slower readers this happens at sixth grade. However, this is to some extent speculative because the current study was not longitudinal. Finally, it is interesting to note that for faster fourth-grade readers the letter identity span was approximately as large as that for faster adult readers and larger than that for slower adult readers. This indicates that the letter identity span is fully matured for the faster fourth-grade readers and that the differences in the letter identity span between faster and slower readers are not likely to disappear with time. However, it is worth noting that even though the slower adult readers had a smaller letter identity span than the faster fourth-grade readers, they still had a faster reading rate than the faster fourth-grade readers. This suggests that an individual with a smaller letter identity span can compensate by using the information within this span more effectively.

To sum up, in the current study development of letter identity span was examined among Finnish elementary school children and adults. The key findings are as follows. First, significant development in letter identity span takes place throughout the elementary school years. By the sixth grade, the letter identity span has reached the adult level even for slower readers. Second, faster readers at each age level have a larger letter identity span than do their slower reading peers. Interestingly, the letter identity span of faster fourth-grade readers is as wide as that of faster adult readers. Third, the letter identity span in Finnish appears to be comparable to that observed in English.

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Appendix A

Overall reading rate is a composite measure that depends on the average fixation duration and the number of fixations made. The latter measure itself is related to how long the average saccade is and how many words are skipped. This dissection into these more specific measures reflects the fact that readers need to make "when" and "where" decisions during reading—decisions that are assumed to be made independent of each other (Findlay & Walker, 1999; Rayner & McConkie, 1976; Rayner & Pollatsek, 1981). It is possible that a composite measure such as reading rate obscures some important trends in these more specific "when" and "where" measures. Hence, below we present data on average fixation duration, average forward saccade length, and probability of word skipping and discuss the extent to which they differ from the patterns found for reading rate.

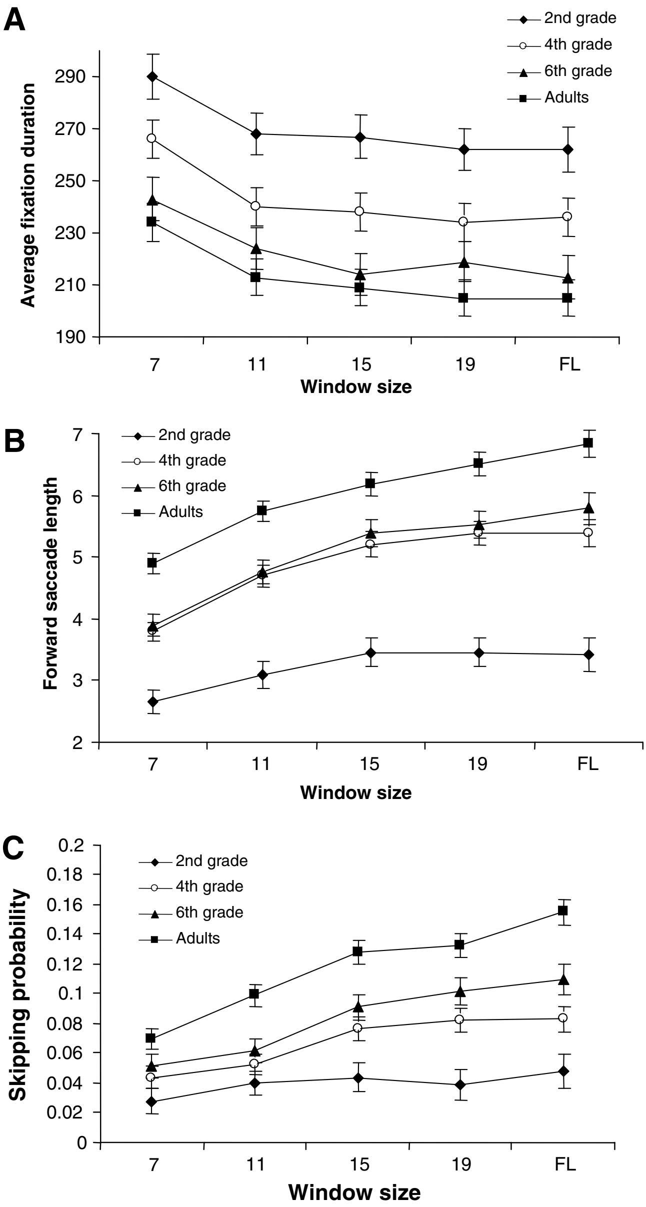

Fig. A1. Average fixation duration (in ms) (A), forward saccade length (in character spaces) (B), and probability of word skipping for each age group (C) as a function of window size. Error bars indicate the standard errors of the means.

As for overall reading rate, transformations were conducted for each measure (Tabachnik & Fidell, 2001) to normalize the distributions and make them more comparable across age groups. For forward saccade length, a square root transformation was conducted. For skipping rate and average fixation duration, an inversion transformation was conducted. Means and standard errors of means are given in Fig. A1 (nontransformed estimates are presented).

For the most part, the patterns in the eye movement measures reflected the pattern seen in the overall reading rate. For each measure, a significant main effect of window size and age emerged, all *F*s > 7.90, all *p*s < .001. Increased age or window size elicited longer saccades, shorter average fixation durations, and more skips. There was also a significant interaction between window size and age for forward saccade length, $F(12, 304) = 4.84$, $p < .001$, $\eta_p^2 = .16$, and skipping probability, $F(12, 304) = 4.26$, $p < .001$, $\eta_p^2 = .14$. For average fixation duration, there was a slight tendency for an interaction between window size and age, $F(12, 304) = 1.53$, $p = .11$, $\eta_p^2 = .06$. These interactions were further examined with tests of within-participants contrasts for each age group separately. In Table A1, asymptotes are presented for the age groups and measures. The *p* values for contrasts are presented in Table A2.

The most notable aspect of these post hoc analyses was that the "when" measure (average fixation duration) was less affected by smaller window sizes than were the "where" measures (forward saccade length and skipping probability). Apparently, saccadic programming (comprising saccade target selection and fine-tuning of the saccadic amplitude [Radach & McConkie, 1998]) benefits more from larger text windows than from making the decision of when to move on in the text.

Table A1
Window sizes where age groups reached asymptote, as estimated by reading rate and three eye movement measures

	Second graders	Fourth graders	Sixth graders	Adults
Reading rate	WS11	WS15/19	WS19[a]	WS19
Average fixation duration	WS11	WS11	WS15	WS15
Forward saccade length	WS15	WS15	FL[b]	FL[b]
Skipping probability	WS11	WS15	WS19	FL[b]

Note. WS, window size; FL, full line.
[a] Asymptote based on the main and subgroup analysis and that with age-appropriate texts.
[b] Asymptote was not reached at WS19.

Table A2
p Values of contrasts for average fixation duration, forward saccade length, and probability of word skipping separately for each age group

	WS7 vs. FL	WS11 vs. FL	WS15 vs. FL	WS19 vs. FL
Average fixation duration				
Second graders	<.001	>.10	>.10	>.10
Fourth graders	<.001	>.10	>.10	>.10
Sixth graders	<.001	<.001	>.10	.063
Adults	<.001	<.01	>.10	>.10
Forward saccade length				
Second graders	<.001	.013	>.10	>.10
Fourth graders	<.001	<.001	>.10	>.10
Sixth graders	<.001	<.001	.001	.001
Adults	<.001	<.001	<.001	.022
Probability of word skipping				
Second graders	.062	>.10	>.10	>.10
Fourth graders	<.001	<.001	>.10	>.10
Sixth graders	<.001	<.001	.054	>.10
Adults	<.001	<.001	.004	.006

Note. WS, window size; FL, full line.

References

Abrams, S. G., & Zuber, B. L. (1972). Some temporal characteristics of information processing during reading. *Reading Research Quarterly, 12*, 41–51.

Findlay, J. M., & Walker, R. (1999). A model of saccade generation based on parallel processing and competitive inhibition. *Behavioral and Brain Sciences, 22*, 661–721.

Guttentag, R. E., & Haith, M. M. (1978). Automatic processing as a function of age and reading ability. *Child Development, 49*, 707–716.

Guttentag, R. E., & Haith, M. M. (1980). A longitudinal study of word processing by first-grade children. *Journal of Educational Psychology, 72*, 701–705.

Henderson, J. M., & Ferreira, F. (1990). Effects of foveal processing difficulty on the perceptual span in reading: Implications for attention and eye movement control. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 16*, 417–429.

Hietakangas, H., Hirvenoja, T., & Järvinen, R. (1980). *Opi biologiaa 5 [Learn biology 5]*. Porvoo, Finland: WSOY.

Hietakangas, H., Hirvenoja, T., Järvinen, R., & Kiiskinen, P. (1987). *Opi biologiaa 6 [Learn biology 6]*. Porvoo, Finland: WSOY.

Kajamies, A., Poskiparta, E., Annevirta, T., Dufva, M., & Vauras, M. (2003). *YTTE: Luetun ja kuullun ymmärtämisen ja lukemisen sujuvuuden arviointi [YTTE: Assessment of reading and listening comprehension and reading fluency]*. Turku, Finland: Oppimistutkimuksen keskus [Center for Learning Research].

Kennison, S. M., & Clifton, C. (1995). Determinants of parafoveal preview benefit in high and low working memory capacity readers: Implications for eye movement control. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 21*, 68–81.

Laine, M., & Virtanen, P. (1999). *WordMill lexical search program*. Turku, Finland: University of Turku, Center for Cognitive Neuroscience.

Laurila, J., Halkka, A., Karlsson, A., Lappalainen, M., & Parkkari, A. (Eds.). (1998). *Löytöretkiä lähiluontoon [Exploratory expeditions to the neighboring nature]*. Forssa, Finland: Suomen luonnonsuojelun tuki Oy [Support for Finnish Conservation].

Lefton, L. A., Nagle, R. J., Johnson, G., & Fisher, D. F. (1979). Eye movement dynamics of good and poor readers: Then and now. *Journal of Reading Behavior, 11*, 319–328.

Mattila, R., Nyberg, T., & Vestelin, O. (1985). *Koulun biologia 7 [School biology 7]*. Keuruu, Finland: Otava.

Mattila, R., Nyberg, T., & Vestelin, O. (1986). *Koulun biologia 5 [School biology 5]*. Keuruu, Finland: Otava.

McConkie, G. W., Kerr, P. W., Reddix, M. D., & Zola, D. (1988). Eye movement control during reading: I. The location of initial eye fixations on words. *Vision Research, 28*, 1107–1118.

McConkie, G. W., & Rayner, K. (1975). The span of the effective stimulus during a fixation in reading. *Perception & Psychophysics, 17*, 578–586.

Nevala, J., & Lyytinen, H. (2000). *Sanaketjutesti [Word Chain test]*. Jyväskylä, Finland: Niilo Mäki Instituutti ja Jyväskylän yliopiston lapsitutkimuskeskus [Niilo Mäki Institute and Child Research Center of University of Jyväskylä].

Pollatsek, A., Lesch, M., Morris, R. K., & Rayner, K. (1992). Phonological codes are used in integrating information across saccades in word identification and reading. *Journal of Experimental Psychology: Human Perception and Performance, 18*, 148–162.

Radach, R., & McConkie, G. W. (1998). Determinants of fixation positions in words during reading. In G. Underwood (Ed.), *Eye guidance in reading and scene perception* (pp. 77–100). Oxford, UK: Elsevier.

Rayner, K. (1975). The perceptual span and peripheral cues in reading. *Cognitive Psychology, 7*, 65–81.

Rayner, K. (1979). Eye guidance in reading: Fixation locations within words. *Perception, 8*, 21–30.

Rayner, K. (1986). Eye movements and the perceptual span in beginning and skilled readers. *Journal of Experimental Child Psychology, 41*, 211–236.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin, 124*, 372–422.

Rayner, K., Kambe, G., & Duffy, S. A. (2000). The effect of clause wrap-up on eye movements during reading. *Quarterly Journal of Experimental Psychology A, 53*, 1061–1080.

Rayner, K., & McConkie, G. W. (1976). What guides a reader's eye movements? *Vision Research, 16*, 829–837.

Rayner, K., & Pollatsek, A. (1981). Eye movement control during reading: Evidence for direct control. *Quarterly Journal of Experimental Psychology A: Human Experimental Psychology, 33*, 351–373.

Rayner, K., Sereno, S. C., Morris, R. K., Schmauder, A. R., & Clifton, C. (1989). Eye movements and on-line language comprehension processes. *Language and Cognitive Processes, 4*, 21–49.

Rayner, K., Well, A. D., Pollatsek, A., & Bertera, J. H. (1982). The availability of useful information to the right of fixation in reading. *Perception & Psychophysics, 31*, 537–550.

Seymour, P. H. K., Aro, M., & Erskine, J. M. (2003). Foundation literacy acquisition in European orthographies. *British Journal of Psychology, 94*, 143–174.

Stanovich, K. E., Cunningham, A. E., & Feeman, D. J. (1984). Relation between early reading acquisition and word decoding with and without context: A longitudinal study of first-grade children. *Journal of Educational Psychology, 76*, 668–677.

Tabachnik, B. G., & Fidell, L. S. (2001). *Using multivariate statistics*. Boston: Allyn & Bacon.

Vauras, M., Mäki, H., Dufva, M., & Hämäläinen, S. (1995). *Diagnostiset testit 2: Kuullun ja luetun ymmärtäminen [Diagnostic tests 2: Listening and reading comprehension]*. Turku, Finland: Oppimistutkimuksen keskus [Center for Learning Research].

Vitu, F., McConkie, G. W., Kerr, P., & O'Regan, J. K. (2001). Fixation location effects on fixation durations during reading: An inverted optimal viewing position effect. *Vision Research, 41*, 3513–3533.

White, S. J., Rayner, K., & Liversedge, S. P. (2005). Eye movements and the modulation of parafoveal processing by foveal processing difficulty: A reexamination. *Psychonomic Bulletin & Review, 12*, 891–896.