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

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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 7 characters, and 12-year-old and adult readers 9 characters to the right of fixation. Comparison with earlier studies reveals 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 - unlike faster readers - slower readers allocate most of their processing resources to foveally fixated words. Finally, slower 2nd graders were practically not disrupted by smaller windows suggesting that their word decoding skill is not yet fully automatized.

Keywords: reading development, parafovea, perceptual span, moving window, eye movements, children, Finnish

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 present study is to examine the amount of letters readers can *identify* during a fixation. 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 towards adulthood.

Studies with adult readers (see Rayner, 1998, for a summary) have established that the global perceptual span, that is, the area from which useful information is extracted during a fixation in reading, extends from the beginning of the currently fixated word to approximately 14-15 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 to about 6-8 characters around the fixation point and the parafoveal area extends up to 15 characters to the right of fixation. The remainder of the visual field is called 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.

The global perceptual span can be divided into three different regions based on the type of information obtained around an eye fixation, namely information about word lengths, letter features, and letter identities. It has become clear that word length information is extracted furthest 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 lands near the center of words (e.g., McConkie, Kerr, Reddix, & Zola, 1988; 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 will be referred to as the "word length span." While 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, while *b* and *h* are both ascenders. We will refer to the area from which letter feature information is extracted as the "letter feature span" and to 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, the reader may extract letter shape information without obtaining access to letter identity information. This is likely to happen for letters appearing further away from the current fixation. With specific textual manipulations combined with the moving window technique (McConkie & Rayner, 1975), the letter feature and letter identity span 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 accurately and reliably assessed. In this technique, reading performance associated with the non-manipulated text (baseline condition) is compared to reading performance of a text with an experimenter-defined (but physically invisible) window around the current fixation point (window condition). The text outside the experimenter-defined window is mutilated, while inside the window text is shown intact. The window moves in synchrony with the eye movements so that a reader always sees a fixed amount of original text. Each time the reader moves her/his eyes, a new region of the original text is shown around the fixation and the remaining text area becomes mutilated (see Figure 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 to 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 subsequently changed into the correct form during the saccade entering it.)

Insert Figure 1 about here

Different types of manipulations are needed to examine the different components of the global perceptual span (see Figure 2). For instance, to examine the letter identity span, as done in the present study, a condition is needed in which letter identity information outside predefined windows is withheld and then compared to the baseline condition in which no text information is withheld. Moreover, this window condition should preserve letter feature information outside the window in order to be 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 we replaced in the different window conditions 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, it 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 Figure 2, present study) a reader is fixating on the 'v' in 'preview' and has a letter identity span of 5, (s)he 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, (s)he will be disrupted when the 6th and 7th character are not 'h' and 'o', but visually similar letters of 'b' and 'c'. In general, a difference between the window and the baseline condition must be due to withheld letter identity information. Hence, this type of manipulation can be used to assess the letter identity span.[1]

Insert Figure 2 about here

Next, we compare our manipulation with those 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 Experiment 2 and 3 in Rayner's study the replaced letters were visually dissimilar (all Xs) to the correct ones. In other words, in comparison to the unchanged baseline condition, both letter feature and letter identity information were withheld. Hence any difference between reading performance in the baseline and in the window conditions may be attributed to withholding both letter feature and letter identity information. To highlight the difference between our and Rayner's manipulations, consider our example discussed above (see Figure 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, (s)he 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 shape with 'b' and 'c' that are initially there. However, (s)he would be disrupted by the visually dissimilar conditions used by Rayner (see

Figure 2, Rayner, 1986, Experiment 2 and 3), 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 further from the parafovea than letter identities or equally 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 present study with Experiments 2 and 3 of Rayner (1986) may answer the question 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 present study) by filling in the spaces between words outside the window and comparing it to a condition where spacing is preserved, as was done in Experiment 1 of Rayner (1986; see Figure 2, Rayner Exp. 1). This type of manipulation disrupts reading further away in the parafovea than withholding letter feature and letter identity information (see below).

Development of the Components of the Global Perceptual Span

As explained above, Rayner (1986) used the moving window technique to investigate the word length and letter feature span among readers of different ages. In Experiment 1, Rayner found that after one year of reading instruction the word length span is asymmetrical to the right of fixation. For the 2nd graders the word length span extends from the beginning of the currently fixated word (3-4 characters to the left of fixation) to approximately 11 characters to the right of fixation. The same holds true for 4th graders while the word length span of 6th 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 6th grade, readers still become more fluent in reading at a later stage as witnessed by fewer forward fixations, fewer regressions, as well as 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 2nd 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 4th graders extract information about letter features approximately 11 characters to the right of fixation. This is about the upper limit, since it was the same as what was found for 6th graders and adults. In sum, word length information can be extracted from further to the right than letter feature information. Moreover, maximum performance for extracting letter features is reached at the 4th grade, and for extracting word length information at the 6th 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 an apparent lack in our knowledge, in the present study we examined by means of the moving window technique the development of letter identity span that was not directly touched upon 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* and *h* by *b*). Thus, text outside the window comprised non-words. We wanted to know how large a window has to 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 one minute.

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 a different – age-appropriate – text so that readers are not confronted with texts above or below their reading (or cognitive) level. In the present study, we combined these two approaches. We selected 2nd grade and 6th 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 2nd graders with the 6th graders when both groups read age-appropriate texts. The former set-up 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 4th 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, that is, it has a consistent grapheme-phoneme correspondence, while English has a deep orthography. It has been established that due to this difference, Finnish children reach fluency in reading much sooner than 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 English. Therefore, it is not implausible to assume that the development of the letter identity span differs between English and Finnish.

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

Method

Participants

Eighty participants (16 2nd graders, 5 males, 11 females; 22 4th graders, 11 males, 11 females; 18 6th graders, 7 males, 11 females; and 24 adults, 6 males, 18 females) were included in the analyses. The mean age of the 2nd grade children was approximately 8 years, the 4th grade children on average 10 years, and the 6th grade children were on average 12 years. At the time of testing, 2nd graders had received from 1 year to 1 year 4 months of reading instruction. Child participants received candy as a reward for participation. The adult participants were university students who took part in the experiment either 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 s, 65 s, and 60 s for 2nd, 4th, and 6th grade, respectively); the test is scored by giving 1 point for each correctly placed vertical line. Children who were – according to the test norms – assessed to be "very weak" or "weak" in their reading skill 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 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 0.75 degrees. 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 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. 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 on-line from the eye position records. Furthermore, a chinrest was used to minimize head movements. The texts were presented on a 21-inch ViewSonic P225f computer screen, which 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, which extended horizontally up to 67 characters in length. The space between the text lines was approximately 5.5 cm (i.e., line spacing of 6). 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 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 80-87 words. Five of the stories were at 2nd grade level and another five at 6th grade level. The stories were divided into two blocks. One block consisted of all the 2nd grade level (easy) stories and the other block contained all the 6th 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) than the words in difficult texts (average log frequency of 2.1). 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 2nd grade level texts were modified versions of texts that are used to assess reading comprehension of 1st graders (Vauras, Mäki, Dufva, & Hämäläinen, 1995), and 2nd graders (Kajamies, Poskiparta, Annevirta, Dufva, & Vauras, 2003). The 6th grade level texts were modified versions of school textbook texts (Hietakangas, Hirvenoja, & Järvinen, 1980; Hietakangas, Hirvenoja, Järvinen, & Kiiskinen, 1987; Mattila, Nyberg, & Vestelin, 1985; Mattila, Nyberg, & Vestelin, 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 participant's eyes moved over the text, a text window of predefined size moved along. In this way the reader 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 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 approximately 9 ms on average to refresh the screen during a saccade. As vision is greatly reduced during saccades (due to saccadic suppression), it is highly unlikely that the participant saw the actual changes taking place.

Each participant read all 10 stories. The 2nd grade and 6th 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 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 2nd grade texts first and half of the participants read the 6th grade texts first. The sentences were presented in Courier font so that each character position was of equal width. With a viewing distance of about 60 cm, one character space subtended approximately 0.5 degrees of visual angle. It should be noted that the font size used is somewhat larger than what is typical in many eye movement experiments (e.g., Rayner, 1986).

Procedure

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

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. 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 2nd graders the experiment was conducted in two separate sessions in order to avoid overburdening them.

Results

There were some inaccuracies in the data due to calibration problems, which led to the exclusion of approximately 5% of the trials (i.e., text screens; 8% for 2nd graders, 8%

for 4th graders, 3% for 6th 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, Sereno, Morris, Schmauder, & Clifton, 1989; Rayner, Kambe, & Duffy, 2000). Because the variances and distributions of the condition means varied quite considerably between age groups, data transformations were made to render the estimates of the condition means normally distributed and standard deviations more comparable with each other. To this end, a square root transformation was conducted for overall reading rate (Tabachnick & Fidell, 2001). A series of 4 (Age) x 5 (Window Size) x 2 (Text Difficulty) repeated measures analysis of variance was conducted for the transformed data. The results of Greenhouse-Geisser corrected ANOVAs are reported below. Means and standard errors of mean are given in Figure 3 (non-transformed estimates are presented). Alongside reading rate, we also performed analyses for more specific eye movement measures, results of which are presented in the Appendix.

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

Insert Figure 3 about here

Main analyses

Reading rate was calculated by dividing the number of words by the total reading time and transformed to a words per minute (WPM) scale. There was a significant main effect of window size, $F(4,304) = 200.36$; $p < .001$; $\eta_p^2 = .73$, 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 larger windows, reading speed increased with age, and reading was faster with easy than 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 for letter identity span being modulated by text difficulty (both Fs < 2, both ps > .1).

The Window Size X Age interaction was further examined with tests of within-subjects contrasts for each age group separately. For 2nd 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, $F(1,15) = 1.53$; $p > .2$; $\eta_p^2 = .09$. This suggests that 2nd graders reached asymptote at WS11. For 4th 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, 4th graders reached asymptote either at WS15 or WS19. For 6th 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 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 6th 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.

2nd and 6th 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 2nd and 6th graders reading age-appropriate material (i.e., 2nd graders reading 2nd grade texts and 6th graders reading 6th grade texts). Means and standard deviations are presented in Table 1. Similarly to the main analysis, a significant Window Size x Age interaction was found, $F(4,128) = 6.26$; $p = .002$; $\eta_p^2 = .16$, as well as 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 2nd graders and 6th graders reached asymptote at a different point. For the 2nd 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, $F < 1$, while for the 6th 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, $F(1,17) = 3.20$; $p = .09$; $\eta_p^2 = .16$. Hence, we conclude that the 2nd graders reached asymptote at WS11, while for the 6th graders asymptote was reached at WS19. These asymptotes are approximately the same as in the main analysis of reading rate of 2nd and 6th graders. All in all, we argue that the developmental trends observed in the letter identity span were not confounded by text difficulty.

Insert Table 1 about here

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 x Reading Speed interactions for 2nd graders, 4th graders and adults, $F(4,56) = 8.30$; $p < .001$; $\eta_p^2 = .37$, $F(4,80) = 8.58$; $p < .001$; $\eta_p^2 = .30$, and $F(4,88) = 4.07$; $p = .011$; $\eta_p^2 = .16$, respectively, and a tendency for an interaction for 6th graders, $F(4,64) = 2.42$; $p = .078$; $\eta_p^2 = .13$. Means and standard deviations for each subgroup are presented in Table 2.

Insert Table 2 about here

The interactions were further assessed by tests of within-subjects contrasts. For 2nd graders, a different asymptotic profile emerged for faster than slower readers. For slower 2nd graders 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 non-significant, $F < 1$. Therefore, we conclude that the slower 2nd graders reached asymptote at WS11. For faster 2nd graders 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, $F(1,7) = 1.20$; $p > .3$; $\eta_p^2 = .15$. Therefore, we conclude that they reached asymptote at WS15.

For slower 4th graders 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, $F(1,10) = 2.02$; $p > .15$; $\eta_p^2 = .17$; thus, they reached asymptote at WS11. For faster 4th graders the difference between WS15 and FL was significant, $F(1,10) = 6.28$; $p = .03$; $\eta_p^2 = .39$, but not between WS19 and FL, $F < 1$; thus, they reached asymptote at WS19.

For slower 6th grade readers the difference between WS11 and FL was significant, $F(1,8) = 31.28$; $p = .001$; $\eta_p^2 = .80$, but not between WS15 and FL, $F < 1$. Hence, their asymptote was at WS15. For faster 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, $F(1,8) = 2.67$; $p = .14$; $\eta_p^2 = .25$. Hence, faster 6th grade readers 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 not between WS15 and FL, $F < 1$. For faster adult readers the difference between WS15 and FL was significant, $F(1,11) = 10.26$; $p < .01$; $\eta_p^2 = .48$, but this was not the case between WS 19 and FL, $F < 1$. Therefore, we conclude that slower adult readers reached asymptote at WS15 and faster adult readers at WS19.

Discussion

The purpose of the present study was to examine whether the letter identity span in reading varies as a function of age. To this end, 2nd grade, 4th grade, and 6th grade children 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 to 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, 2nd 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 2nd graders who have received one 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 4th graders the letter identity span extends approximately 7 characters to the right of fixation, while 6th graders and adults resemble each other, as their letter identity span is approximately 9 characters to the right of fixation.

Table 4 shows that the reading rate in the present study for WS15 is close to 95% of the reading rate for the FL-condition for all age groups. In contrast, in Rayner's (1986) Experiment 1 the reading rate for WS17 was less than 90% of the full-line reading rate for all age groups. In fact, the percent-wise reading rates for WS11 in the present study are comparable to those for WS17 in Rayner's Experiment 1. We believe that this difference derives from the fact that the present study only withheld letter identity information, whereas in Rayner's Experiment 1 neither word length or letter feature information nor letter identity information were 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.

Insert Table 3 and 4 about here

In the Introduction we raised the question whether the letter identity span in Finnish is different from that in English. We argued that due to difference in orthographic depth and average word length the letter identity span in Finnish may be larger than in English. However, this appeared not to be the case. A span of 7-8 characters typically found for English readers is quite comparable to the 9 characters observed in the present study from the 6th grade onwards.

Another question we raised was whether the letter identity span is smaller than the letter feature span (e.g., Henderson & Ferreira, 1990; Pollatsek, Lesch, Morris, & Rayner, 1992, Rayner et al., 1982) or whether both spans are approximately similar (McConkie & Rayner, 1975). In our study, the maximum letter identity span (for 6th graders and adults) was about 9 characters and that is smaller than the 11-12 -character letter feature span observed from the 4th grade onwards (Rayner, 1986, see Table 3). This suggests that indeed the letter identity span is smaller than the letter feature span, that is, letter feature information is extracted further from the parafovea than letter identity information.

The final question we raised pertained to the variability in reading skill within each age level. We asked whether faster readers extract letter identity information more effectively from the same area as slower readers, or if 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 done in the present study), the letter identity span of the faster readers was observed to be wider than that of 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 to the parafovea as is the case with faster readers who process foveal words with greater ease and speed. This would in turn lead both to slower reading rate and 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 & Clifton, 1995; White, Rayner, & 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 2nd grade readers are hardly affected at all by the small window size (see Table 5). This indicates that slower 2nd 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 acquire access in a piecemeal fashion. Since 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 for 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 2nd graders in our sample.

Insert Table 5 about here

It should be noted that in the current study the slow readers in each age group were actually not the weakest ones, as the weakest child readers were screened out prior to the actual experiment. Also the slower adult readers in our study may be relatively fast readers, since all the adults were university students. This suggests that ultimately the differences in letter identity span between better and weaker readers may be even more pronounced than observed in the present study. It is also evident that for faster readers the letter identity span is fully developed at a younger age than for slower readers, as indicated by faster readers reaching the upper limit of the letter identity span already at 4th grade while for slower readers this happens at 6th grade. However, this is to some extent speculative because the present study was not longitudinal. Finally, it is interesting to note that for faster 4th grade readers the letter identity span was about as large as for faster adult readers and larger than for slower adult readers. This indicates that the letter identity span is fully matured for the faster 4th graders 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 faster 4th graders, this did not manifest in differences in reading rate. This suggests that an individual with a smaller letter identity span can compensate it by using the information within this span more effectively.

To sum up, in the present study development of letter identity span was examined among Finnish elementary school children and adults. The key findings are: (1) Significant development in letter identity span takes place throughout the elementary school years. By the 6th grade the letter identity span has reached the adult level even for the slower readers. (2) Faster readers of each age level have a larger letter identity span than their slower reading peers. Interestingly, the letter identity span of faster 4th graders is as wide as that of faster adult readers. (3) Letter identity span in Finnish appears to be comparable to that observed in English.

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Appendix

Overall reading rate is a composite measure, which depends on the average fixation duration and the number of fixations made. The latter measure itself depends on how long the average saccade length 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 independently from each other (Findlay & Walker, 1999; Rayner & McConkie, 1976; Rayner & Pollatsek, 1981). It is possible that a composite measure like 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 to what extent they differ from the patterns found for reading rate.

As for overall reading rate, transformations were conducted for each measure (Tabachnick & 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 mean are given in Figure A1 (non-transformed estimates are presented).

Insert Figure A1 about here

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 Fs > 7.90, all ps < .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-subject contrasts for each age group separately. In Table A1, asymptotes are presented for each age group and each measure. The *p* values for contrasts are presented in Table A2.

Insert Table A1 and A2 about here

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 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 making the decision of when to move on in the text.

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Footnote

1. It should be noted that word identity span is incorporated in letter identity span. The word identity span refers to the area of text around the fixation in which words can be identified. As the letters of the to-be-identified word need to be recognized, the word identity span is smaller than or equal in size with the letter identity span. Importantly in the present 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 (i.e., a subset of letters fall outside the text window) visible.

Table 1.

Means (M) and Standard Deviations (SD) of Reading Rate for 2nd Graders and 6th Graders Reading Age-Appropriate Texts.

Window size	WS7		WS11		WS15		WS19		FL	
Group	M	SD	M	SD	M	SD	M	SD	M	SD
2nd graders	63	21	91	36	101	47	102	51	100	67
6th graders	96	38	140	34	166	41	174	49	185	44

Table 2.

Means (M) and Standard Deviations (SD) of Reading Rate Separately for Slower and Faster Readers of Each Age Group.

Window size		WS7		WS11		WS15		WS19		FL	
Group	Reading speed	M	SD	M	SD	M	SD	M	SD	M	SD
2nd graders											
	Faster	73	21	108	29	128	38	128	38	139	60
	Slower	42	8	57	11	56	13	58	11	51	13
4th graders											
	Faster	90	16	141	26	160	25	178	31	178	34
	Slower	70	13	100	16	108	20	112	29	108	21
6th graders											
	Faster	125	46	177	35	205	40	216	44	234	29
	Slower	84	13	125	19	148	27	143	15	148	17
Adults											
	Faster	159	27	230	40	259	53	284	72	291	60
	Slower	127	25	170	33	190	34	193	36	194	18

Table 3.

<u>Type of Information Obtained to the Right of Fixation in the Present Study and That of Rayner (1986)</u>.

	2nd grade	4th grade	6th grade	Adults
Letter identity (Present study)	5	7	9	9
Letter feature (Rayner, Exp. 2&3)	7	11-12	11-12	11-12
Word length (Rayner, Exp. 1)	11	11	14	14-15

Table 4.

Percentage of Reading Rate in Comparison to the Full Line Condition (FL) Separately for Each Age Group in the Present Study and in Experiment 1 of Rayner (1986).

Present study

	WS7	WS11	WS15	WS19	FL
2nd graders	61	87	97	98	100
4th graders	56	84	94	100	100
6th graders	55	79	93	94	100
Adults	59	83	93	98	100

Rayner (1986)

	WS5	WS11	WS17	WS23	WS29	FL
2nd graders	62	82	88	100	100	100
4th graders	40	74	88	100	100	100
6th graders	44	84	86	96	100	100
Adults	34	62	75	89	99	100

Table 5.

Percentage of Reading Rates (Words Per Minute) for Each Subgroup in Comparison to the Full Line Condition.

Window size		WS7	WS11	WS15	WS19
Group					
2nd grade					
	Faster	53	78	92	93
	Slower	82	100	100	100
4th grade					
	Faster	51	79	90	100
	Slower	65	93	100	100
6th grade					
	Faster	53	76	88	92
	Slower	57	84	100	97
Adults					
	Faster	55	79	89	98
	Slower	65	88	98	99

Table A1.

Window Size Where Each Age Group Reached Asymptote, As Estimated by Reading Rate and Three Eye Movement Measures.

	2nd graders	4th graders	6th graders	Adults
Reading rate	WS11	WS15/19	WS19*	WS19
Average fixation duration	WS11	WS11	WS15	WS15
Forward saccade length	WS15	WS15	FL**	FL**
Skipping probability	WS11	WS15	WS19	FL**

* Asymptote based on the main and subgroup analysis, and that with age-appropriate texts.

** 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				
2nd graders	< .001	> .1	> .1	> .1
4th graders	< .001	> .1	> .1	> .1
6th graders	< .001	< .001	> .1	.063
Adults	< .001	< .01	> .1	> .1
Forward saccade length				
2nd graders	< .001	.013	> .1	> .1
4th graders	< .001	< .001	> .1	> .1
6th graders	< .001	< .001	.001	.001
Adults	< .001	< .001	< .001	.022
Probability of word skipping				
2nd graders	.062	> .1	> .1	> .1
4th graders	< .001	< .001	> .1	> .1
6th graders	< .001	< .001	.054	> .1
Adults	< .001	< .001	.004	.006

Figure captions

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

Figure 2. The type of information intact outside of a symmetric text window in the present study and that of Rayner (1986) when fixating ‘v’ in word ‘preview’.

Figure 3. Reading rate (words per minute) for each age group, as a function of window size. Error bars indicate the standard error of the means.

Figure A1. a) Average fixation duration (ms), b) forward saccade length (in character spaces), and c) probability of word skipping for each age group, as a function of window size. Error bars indicate the standard error of the means.

```
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"
                                                                        *
```

Figure 1.

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

WL = Word length information, LF = Letter feature information, LI = Letter identity information

Figure 2.

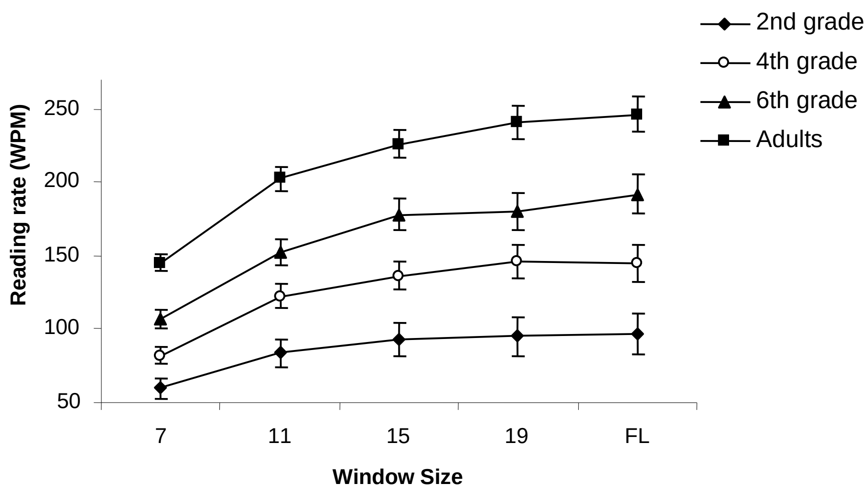
2nd grade
4th grade
6th grade
Adults
Reading rate (WPM)
250
200
150
100
50
7
11
15
19
FL
Window Size

Figure 3.

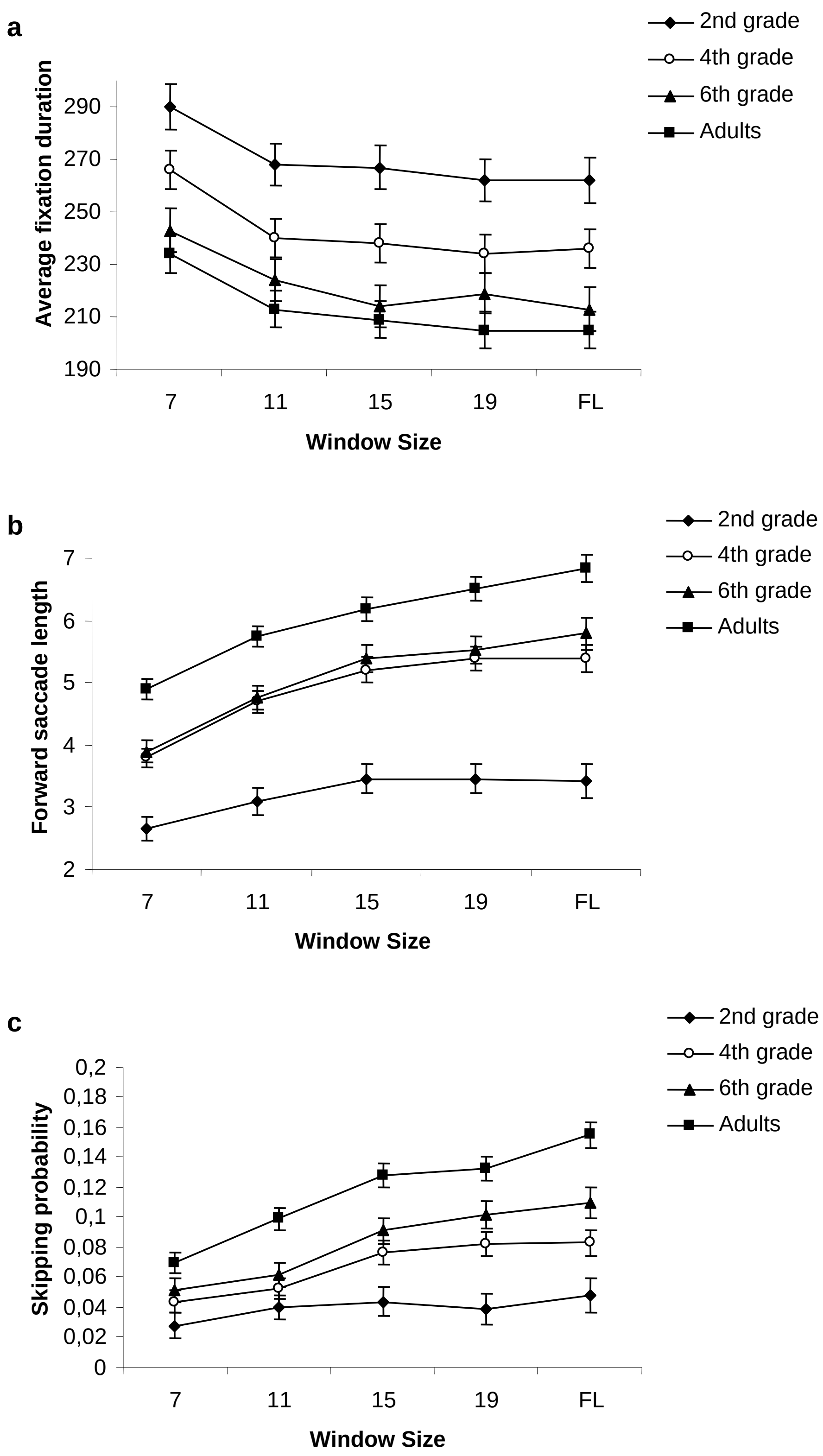
a
Average fixation duration
190
210
230
250
270
290
7
11
15
19
FL
Window Size
2nd grade
4th grade
6th grade
Adults
b
Forward saccade length
2
3
4
5
6
7
7
11
15
19
FL
Window Size
2nd grade
4th grade
6th grade
Adults
c
Skipping probability
0
0,02
0,04
0,06
0,08
0,1
0,12
0,14
0,16
0,18
0,2
7
11
15
19
FL
Window Size
2nd grade
4th grade
6th grade
Adults

Figure A1.