Author(s): Hautala, Jarkko; Hyönä, Jukka; Aro, Mikko

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Dissociating spatial and letter-based word length effects observed in readers' eye movement patterns

Jarkko Hautala[1], Jukka Hyönä[2], Mikko Aro[1]

[1] University of Jyväskylä, Finland

[2] University of Turku, Finland

Authors' addresses:

Jarkko Hautala, Department of Psychology, Agora, POB 35, FI-40014, University of Jyväskylä, Finland

Mikko Aro, Department of Education, POB 35, FI-40014, University of Jyväskylä, Finland

Jukka Hyönä, Department of Psychology, Assistentinkatu 7, FI-20014, University of Turku, Finland

Abstract

In previous eye movement research on word length effects, spatial width has been confounded with the number of letters. McDonald (2006) unconfounded these factors by rendering all words in sentences in constant spatial width. In the present study, the Arial font with proportional letter spacing was used for varying the number of letters while equating for spatial width, while the Courier font with monospaced letter spacing was used to measure the contribution of spatial width to the observed word length effect. Number of letters in words affected single fixation duration on target words, whereas words' spatial width determined fixation locations in words and the probability of skipping a word. The results support the existence of distinct subsystems for deciding where and when to move eyes in text (Rayner & McConkie, 1976). The number-of-letters effect in fixation duration may be explained by visual acuity, visual crowding, and/or serial letter processing.

Keywords: word length, number of letters, spatial width, eye movements, reading

1. Introduction

In eye movement research on reading, a standard finding is that word length influences both the time spent fixating a word and the amplitude of the saccade entering a word. Longer words are fixated for longer than shorter words (e.g., Calvo & Meseguer, 2002; Hyönä & Olson, 1995; Juhasz, White, Liversedge, & Rayner, 2008; Just & Carpenter, 1980; Kliegl, Grabner, Rolfs, & Engbert, 2004; Rayner, Sereno, & Raney, 1996; Underwood, Binns, & Walker, 2000). The bulk of the effect comes from an increased frequency to refixate a longer word. The increased refixation frequency in turn is likely to reflect constraints of foveal vision. When not all the letters of a word fit in the foveal area, a refixation is needed to compensate for visual acuity limitations (Vergilino-Perez, Collins, & Dòre-Mazars, 2004).

The amplitude of a saccade programmed to a long word is also greater than that to a short word. This is due to the reader targeting the word center (Rayner, 1979): in order to position a fixation around the word center (demonstrated to be the optimal viewing location for word perception, see e.g., Nuthmann, Engbert, & Kliegl, 2005; O'Regan & Levy-Schoen, 1983; Vitu, O´Regan, & Mittau, 1990), a longer saccade is needed than in case of a short word. Despite the lengthening of saccade amplitude as a function of word length, the initial fixation lands closer to the word beginning from the word center for long than short words (e.g., Bertram & Hyönä, 2003; the initial landing position in a word is called the preferred viewing location, Rayner, 1979).

That parafoveal word length information is acquired and utilized in reading is also evidenced by Inhoff, Starr, Liu, and Wang (1998) in a study exploiting the gaze contingent boundary technique, in which the to-be-fixated parafoveal word was manipulated during a saccade towards it. Correct length information (the parafoveal preview and the target word share the same number of letters) provided for the parafoveal word (*barcohqo* -> *movement*, i.e., the preview and the target are both eight letters long) speeded up the target word processing when it was subsequently fixated, compared to incorrect length information (*barc ohqo* -> *movement*; see also Inhoff, Radach, Eiter, & Juhasz, 2003; White, Rayner, & Liversedge, 2005).

Word length is also found to significantly affect the probability of skipping over a word: short words are skipped much more often than longer words (for a review, see Brysbaert, Drieghe, & Vitu, 2005). This finding reflects the fact that short words can be processed parafoveally more efficiently than longer words (Vitu & McConkie, 2000).

In most of these studies (if not all), a monospaced font (Courier) was used in presenting the experimental texts. A relevant feature of monospaced font is that each letter covers the same horizontal width. Thus, the number of letters in a word has a perfectly linear relationship with the word's spatial width. As a result, it is not clear to what extent the previously obtained word length effects reflect processing at the orthographic (an effect due to the number of letters) versus visual (an effect due to spatial width) level. In other words, it is not known whether the effects in refixation probability, saccade amplitude, and skipping probability are due to the number of letters per se, the word's spatial extent, or both.

McDonald (2006) was the first to investigate the independent contributions of number of letters and spatial width in the observed word length effect. In his study all words in the experimental sentences were rendered to cover an equal spatial width. Moreover, a set of 6- and 8-letter target words was selected that were matched for a number of lexical characteristics. In the target word analysis, a number-of-letters effect was observed in gaze duration (i.e., the time spent fixating a word before exiting it) and in the number of fixations. Gaze duration and number of fixations were greater for 8-letter than 6-letter words. However, saccade amplitude was not affected, as both the launch site and the landing position of the saccade entering the target word were unaffected by the number of letters; neither was the skipping probability. Most of these effects were replicated when the data for all words in the experimental sentences were analyzed using a repeated measures multiple regression technique. However, in this analysis the initial landing position (measured in letters rather than in pixels) in words moved rightwards as the number of letters increased. The number-of-letters effect in gaze duration and number of fixations is assumed to reflect orthographic processing, perhaps due to visual crowding (Bouma, 1970, 1973); individual letters of long words are harder to process than those of shorter words. The fact that there was no consistent number-of-letters effect in skipping probability or in initial fixation location suggests that saccades programmed across words are governed by the text's spatial attributes.

As a consequence of the rendering procedure employed by McDonald (2006), each word was written with a different font size. Moreover, as all words occupied exactly the same width on the computer screen, 10-letter words suffered from substantial visual crowding compared to 2-letter words. Finally, the results concerning saccadic programming were somewhat mixed between the two sets of analyses. Thus, more work is needed to dissociate the effects of the number of letters and spatial width from each other.

In the present study, the unconfounding of the effects of number of letters and spatial width was done in a natural way by using differences in fonts. The variability in letter width in proportional fonts enables a comparison of words with a varying number of letters but with an equal spatial width. In a proportional font such as Arial, a large variation exists in letter width (letter *m* is 2.5 times wider than letter *i*). Thus, in Arial the four-letter word 'mama' is wider than the six-letter word 'flight'. A comparison of these types of words provides an opportunity to examine the independent effect of the number of letters from that of the spatial width without the need to scale the font size separately for each word.

We selected short four- and six-letter words as targets for the following reasons. First, as they all fit in the foveal vision (± 1º around the fixation point) when fixated upon, observed effects are unlikely to stem from visual acuity constraints. Second, although six-letter Arial words are visually more crowded than four-letter words, they are less so than the 6- and 8-letter words used by McDonald (2006). Moreover, an effect of visual crowding may have been prevalent in McDonald's study, as his participants were untrained to read texts where each word is written with a different font size. In our study, on the other hand, the participants were free to make use of their natural, highly practiced reading habits developed for reading texts written consistently in the same font, which may additionally reduce crowding effects, as crowding is shown to be reduced by practice (Chung, 2007).

To also examine the extent to which spatial width contributes to word length effect, a spatially controlled number-of-letters effect (studied with Arial, as described above) was compared to a "standard" length effect obtained when reading 4- and 6-letter words written in monospaced font (Courier). The possible unique contribution of spatial width in saccade programming was further evaluated in a post-hoc analysis by comparing eye movements on target words written in proportional font (Arial), for which the spatial extent varied but the number of letters remained constant. Finally, the comparison of proportional and monospaced font both at the word and sentence level should reveal if there are inherent font differences in reading. In what follows, we discuss in more detail the issues addressed in the present study.

As noted above, word length effects frequently emerge in the probability of making a refixation on the word. An additional fixation on a word typically lengthens the gaze duration of this word by 200 ms or more (for a review, see Rayner, 1998). Some refixations are associated with difficulty in word recognition (Rayner et al., 1996; Vergilino-Perez et al., 2004), but most refixations are made to compensate for the acuity limitations of the foveal vision (Vergilino-Perez et al., 2004). Therefore, it is expected that in the present study refixations should be more frequent on monospaced six-letter words than other target words, as they cover more space than the other targets, extending slightly over foveal vision. Moreover, the results of McDonald (2006) suggest that number of letters may affect refixation probability even when the spatial extent is controlled for. If replicable, a difference in refixation probability (and gaze duration) should also emerge between our 4- and 6-letter target words equated for the spatial extent (i.e., written in Arial).

McDonald (2006) also observed a pure number-of-letters effect in the single fixation duration made on the word, suggesting that the number of letters may also influence temporal aspects of eye movement control, not only saccadic programming, as indexed by the effect in refixation probability. Other studies where the spatial extent was not controlled for have also found an effect of word length in first or single fixation durations (Kliegl et al., 2004; Rayner et al., 1996), although it has not been a constant finding (Hawelka, Gagl, & Wimmer, 2010; Joseph, Liversedge, Blythe, White, & Rayner, 2009). A pure number-of-letters effect is especially likely to appear in transparent orthographies (Ziegler, Perry, Jacobs, & Braun, 2001), such as in Finnish, the language used in the present study, in which spelling-to-sound correspondences are based on single graphemes.

It is also of interest to study the independent contributions of spatial width and number of letters in parafoveal word processing in reading. If number of letters affects the probability of skipping over a word, we should then find a difference in skipping rate between 4- and 6-letter words written in Arial. On the other hand, if word skipping is modulated by words' spatial extent, no such effect should emerge, as these target words are of equal width. This is also what McDonald (2006) observed. If so, we should find a difference between 4- and 6-letter Courier words: 4-letter words should be skipped over more frequently than 6-letter words. On the other hand, if both number of letters and spatial width influence skipping rate, an effect would also be present in Arial, accompanied by even a stronger effect in Courier.

Moreover, as noted above, readers extract word length information from parafoveal words that is subsequently used in foveal processing. However, on the basis of the previous evidence, it is not known whether the acquired length information is entirely based on the spatial extent, or whether also the number of letters is extracted from parafoveal words, independently of spatial extent. The findings demonstrating that readers extract orthographic and phonological information of the beginning letters from parafoveal words (see reviews of Hyönä, in press; Rayner, 1998) hints at the possibility that readers may also acquire specific number-of-letter information from parafoveal words.

The above prediction may be tested by examining so called parafovea-on-foveal effects (Kennedy, 1998; Kennedy & Pynte, 2005). They refer to effects where features of the parafoveal word affect the processing of the foveal word. These effects are considered to index parallel processing of two adjacent words. When applied to the present context, an effect of the number of letters of the parafoveal word on the processing of the foveal word would indicate that number-of-letter information of the parafoveal word is processed simultaneously with the processing of the foveal word. In previous studies where number of letters was confounded with spatial extent, a parafoveal-on-foveal word length effect was either not found (Kliegl, Nuthmann, & Engbert, 2006), was inconsistent (Hyönä & Bertram, 2004), or fixation durations were actually shorter on the foveal word when the parafoveal word was longer (an inverse parafoveal word length effect; Drieghe, Brysbaert, & Desmet, 2005; Kennedy, 1998; Kennedy & Pynte, 2005). As these studies used monospaced font, they may underestimate the influence of number of letters as longer words extend farther into the parafovea, thus suffering more from visual degradation. This may lead to a decision to leave the foveal word early, in which case parafoveal processing may be attenuated.

Recently, Miellet, O'Donnell and Sereno (2009) compensated for this degradation by magnifying parafoveal letters in order to increase their spatial resolution to match with the resolution of the foveal letters. The magnification also led to an increase in the spatial width of the parafoveal words. This manipulation did not improve parafoveal word processing. However, the manipulation results in inaccurate parafoveal word length information (in terms of spatial width), which may have downplayed the parafoveal processing benefit.

In the present study, parafoveal processing of the number-of-letters information was examined when the spatial extent was equated for 4- and 6-letter target words. If number-of-letters information is processed for the parafoveal target word in parallel with the processing of the foveal word, the duration of fixation prior to fixating the target word should be affected. If we are to find an inverse parafoveal word length effect (Drieghe et al., 2005; Kennedy, 1998; Kennedy & Pynte, 2005), the greater number of letters in the parafoveal word will lead to a shorter preceding fixation. On the other hand, it is also possible that when the spatial width is controlled, we may find evidence for more effortful parafoveal processing as a function of number of letters. If so, the preceding fixation prior to fixating the parafoveal word will be longer when the parafoveal word is longer.

Finally, visuo-spatial factors may influence how many letters are processed during a fixation. Morrison and Rayner (1981) manipulated the viewing distance to see whether more letters are processed at a closer viewing distance (for visual acuity scales as a function of viewing distance, see Geddes, McLean, McMonnies, & Woodward, 1966). Yet, viewing distance was not found to affect saccade amplitudes in letters, which led to the conclusion that letters are more important than visual angle in determining saccade amplitude. Also font type may exert general effects on saccadic programming as condensed letter spacing of proportional font may allow for more letters to be processed during each fixation relative to monospaced font. Studies using overall reading rate as the dependent measure have found an advantage for monospaced over proportional font in small font sizes, whereas with larger font sizes proportional font has a 5-% advantage over monospaced font (Arditi, Knoblauch, & Grunwald, 1990a; Mansfield, Legge, & Bane, 1996). Arditi, Knoblauch, and Grunwald (1990b) suggest that with larger font sizes the proportional font is read faster, as more letters fit in foveal vision, thus decreasing the number of eye movements required, whereas with small print sizes tight letter spacing produces crowding, which impedes reading. However, in these studies eye movements were not registered, so this conclusion remains somewhat speculative.

Recently, Rayner, Slattery, and Bélanger (2010) studied using the moving window technique to examine whether letter spacing of proportional and monospaced fonts influence saccade amplitude and the perceptual span in reading. Indeed, more fixations per word were made in monospaced than proportional font (i.e., saccades were on average 0.6 letters longer when reading proportional font), but the perceptual span in words was equal between the fonts. On the other hand, fixations were 10 ms longer in the proportional font. Due this trade-off between number of fixations and fixation durations there was no difference between the fonts in overall reading rate. However, there is previous evidence that large differences in the readability of the font do have an influence also on reading speed (Paterson & Tinker, 1947; Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006; Slattery & Rayner, 2010).

In the present study, in addition to target word analyses, we also conducted sentence level analyses of reading monospaced (Courier) and proportional (Arial) font to examine whether font type influences any aspect of readers' eye movements. As both fonts are highly readable (for a review, see Josephson, 2008), no difference in reading speed was expected. The most interesting question in this analysis is whether the mean number of letters travelled during forward saccades differs between fonts, which would indicate a visuo-spatial influence on saccadic programming, and perhaps even on the perceptual span.

2. Materials and Methods

2.1. Participants

All the 35 university students (mean age of 23 years, SD=3 years) participating in the study were native Finnish speakers with no history of reading problems and normal or corrected-to-normal vision. The participants received a movie ticket as a reward for their participation.

2.2. Apparatus

An SMI HiSpeed eye tracker with 500 Hz sampling rate was used to record eye movements of the participants' right eye. The computer screen of 375 x 300 mm with a resolution of 1024 x 768 pixels was located at the distance of 640 mm from the participant's eye. At this viewing distance the center-to-center letter distance of 14 pixels corresponded to a visual angle of 0.459 º per letter (Table 1) equaling 2.17 letters per degree; for Courier New this was the exact value, while in Arial the angle varied depending on the letter – the mean letter width in the Arial sentences was 10.5 pixels equaling 3.05 letters per degree.

2.3. Materials

There were 30 four-letter and 30 six-letter target words in proportional-width Arial 18 pt font and 20 four-letter and 20 six-letter target words in monospaced Courier New 18 pt font[1] (see Appendix for the complete stimulus set). To control for the spatial width, four-letter proportional words were selected among the widest of four-letter words in a 17-

[1] To ensure that the difference in the number of items between the fonts did not explain the findings, we recomputed the analysis by including only the first 20 four-letter and six-letter proportional words in the analysis. The pattern of results turned out to be highly similar.

million word newspaper corpus (Research Institute for the Languages of Finland, 2007). The four-letter words contained many wide letters such as ‘m’. Conversely, the six-letter words were selected from among the narrowest of six-letter words including many narrow letters, such as ‘t, r, i, l’. Matching for the spatial width in such a way is feasible in Finnish, in which narrow-letter word bodies, such as ’iitt’, are relatively frequent. Nonetheless, the pool of suitable words was very limited.

The four groups of target words (four- and six-letter Arial and Courier New words) were matched for surface word-form frequency (see Table 1 for group means). The four- and six-letter Arial and four-letter Courier New words were also matched for pixel width (Table 1), whereas the six-letter Courier New words were wider (81 pixels). All the words were common Finnish nouns appearing in the base form (i.e., non-inflected).

The target words in both fonts were presented in sentences, so that a four-letter Ariel word was paired with a six-letter Ariel word (the same was done with the Courier words), and a sentence frame was created that was identical at least up to the target word (Figure 1). The remainder of the sentence was either identical in each pair or was modified to fit with the earlier part of the sentence. There was no difference between the fonts in the number of letters in words surrounding the target words, either in the preceding (7.7 letters in both fonts) or the subsequent (6.3 letters in proportional and 6.1 letters in monospaced font) word. The mean number of characters per sentence was 47.1 (SD=4.5) and 45.9 (SD=3.7) and the mean number of words was 6.2 (SD=.83) and 5.8 (SD=.97) for the proportional and monospaced font, respectively. The two font conditions were presented in separate blocks; the order of blocks was counterbalanced across participants. The sentences within a block were presented in a fixed, pseudorandom order.

The effect of spatial width when the number of letters was controlled was studied in a post-hoc analysis. The proportional font data allowed us to study this question by dividing the words into wide and narrow based on their spatial width, resulting in a 7-pixel (half a letter) difference, while all the other word properties remained controlled.

Insert Figure 1 about here

Insert Table 1 about here

2.4. Procedure

Participants leaned their head on a forehead and chin rest. After finding a comfortable position a 13-point calibration procedure was run. The calibration was repeated between each block. The instruction for participants was: "Look at a fixation cross and press a mouse button to see a sentence. Read the sentence silently once through. When you have completed reading the sentence, press again a mouse button to see a yes-or-no question related to the sentence. Answer this question either by pressing the left (yes) or the right (no) mouse button". After excluding one ambiguously phrased question, the accuracy in responding to the comprehension questions was very high (98.4 %). There were three practice trials prior to the experimental trials. The participants were instructed not to make head movements during the experiment. The sentences were adjusted on a single line so that the target word always appeared in a center location on the screen.

2.5. Eye movement data processing

Fixations were detected by the saccade-velocity–based algorithm developed by the manufacturer (SMI), using the saccade velocity threshold of 50 º/s and a minimum saccade duration of 15 ms (a saccade reaching an angular velocity of over 50 º/s typically has a duration longer than 15 ms, so this parameter did not restrict the detection of saccades). Fixations shorter than 50 ms (9.0 %) and longer than 1000 ms (0.3 %) were excluded. Two participants with a high proportion of short fixations (15 % and 40 %) were excluded from the analyses.

Three areas of interest were identified: the beginning part of the sentence, the target word including the preceding space, and the sentence end. The fixation was classified as a first-pass fixation only when the reader entered the target word directly from the sentence beginning after having read it for the first time. The dependent variables in the target word analyses included the following first-pass measures: As temporal measures, we used gaze duration, single fixation duration, first fixation duration and the duration of fixation prior to target word fixation. Spatial aspects of eye guidance were measured by the length of the saccade entering the target, the initial landing position on the target (including the preceding space), the probability of skipping the target, and the probability of refixating the target.

In the sentence level analyses the dependent variables included total fixation time and total number of fixations averaged over sentence, word and character, average fixation duration, probability of regression, and average saccade amplitude in pixels and letters (average letter width of 14 pixels for the monospaced font and 10.5 for the proportional font was used; the latter value was determined as the mean letter width in the proportional font sentences).

3. Results

3.1. Effects of the number of letters in the proportional and monospaced font

Table 2 presents the mean values for each eye movement measure for the four- and six-letter target words presented in the proportional and monospaced font. The temporal eye fixation measures showed no interactions between number of letters and font type, Fs < 1, but significant main effects of number of letters and font type. In gaze duration there was a significant main effect of font with Arial yielding a mean of 221 ms and Courier a mean of 205 ms, $F(1,32)=16.72$, $p<.001$, $\eta_p^2=.343$; moreover, the 11 ms effect of number of letters was also significant, $F(1,32)=11.75$, $p = .002$, $\eta_p^2=.269$. The same pattern of results was true for single fixation duration: the 15-ms main effect of font was significant, $F(1,32)=26.00$, $p<.001$, $\eta_p^2=.448$, as was the 8-ms number-of-letters effect, $F(1,32)=5.57$, $p = .025$, $\eta_p^2=.148$; and for first fixation duration: the 17-ms main effect of font, $F(1,32)=24.71$, $p<.001$, $\eta_p^2=.436$, and the 6-ms number-of-letters effect $F(1,32)=7.71$, $p=.009$, $\eta_p^2=.194$ were both reliable. The duration of the previous fixation showed a main effect of font with Arial yielding a mean of 191 ms and Courier a mean of 182 ms, $F(1,32)=15.56$, $p<.001$, $\eta_p^2=.327$, but there was no effect of the number of letters in the target word, $F<1$.

Spatial eye movement variables showed significant interactions between font type and length. For the initial landing position, the main effects of font, $F(1,32)=153.9$, $p<.001$, $\eta_p^2=.828$, and number of letters $F(1,32)=22.17$, $p<.001$, $\eta_p^2=.409$, were qualified by a Font x Number of Letters interaction, $F(1,32)=32.22$, $p<.001$, $\eta_p^2=.502$. The number-of-letters effect (0.6 letters) was significant in the monospaced font, $F(1,32)=34.26$, $p < .001$, $\eta_p^2=.517$, where the increase in the number of letters was accompanied by a corresponding increase in spatial extent, but not in the proportional font, $F(1,32)=1.84$, $p=.185$, $\eta_p^2=.054$, where the spatial extent was identical for the four- and six-letter words.

The amplitude of the entering saccade showed a main effect of font, $F(1,32)=415.7$, $p<.001$, $\eta_p^2=.929$, but not of number of letters, $F(1,32)=1.71$, $p=.199$, $\eta_p^2=.051$, nor a Font x Number-of-Letters interaction, $F<1$. Initial saccades were on average 30 pixels longer in Courier New than in Arial. The font effect disappeared when the mean pixel values were transformed into mean values in letters, $F<1$. Thus, when reading Courier New text, the eyes have to make longer jumps to reach the preferred viewing location in words than when reading Arial text. A more puzzling finding is that the effect of spatial extent seen in the initial landing position in the monospaced font was not present in the initial saccade amplitude. For some reason, the eyes appear to be launched from a somewhat farther distance in the four-letter than six-letter Courier words.

For the skipping probability there was no main effect of font, $F<1$, whereas the main effect of number of letters $F(1,32)=35,14$, $p <.001$, $\eta_p^2=.523$, and the Font x Number of Letters interaction, $F(1,32)=34.40$, $p<.001$, $\eta_p^2=.518$, were highly significant. In the monospaced font, four-letter words were skipped for 21.4 % of the time, whereas six-letter words only for 3.6 % of the time, $F(1,32)=40.20$, $p < .001$, $\eta_p^2=.557$.In the proportional font the average skipping rate was 13.9 % , but there was not even a hint for a length effect, $F<1$. Moreover, four-letter monospaced words were skipped more frequently (21.4 %) than four-letter proportional font words (14.1 %) $F(1,32)=7.34$, $p=.011$, $\eta_p^2=.187$, whereas for the six-letter words the skipping percentage was 3.6 % for monospaced, and 13.6 % for proportional font words, $F(1,32)=24.00$, $p<.001$, $\eta_p^2=.429$.

To examine whether the skipped words were identified and whether the repetition of the sentence frames (the same sentence frame was used twice, once including a four-letter and once including a six-letter target word) influenced skipping (Reichle, Pollatsek, & Rayner, 2006), the trials resulting in target word skipping (439) were categorized into four groups: whether or not a regression was launched to the target word and whether the sentence frame was presented for the first or second time. If the target word skipping is followed by a regression back to it, it may be taken as evidence that the word was skipped without fully identifying it (Vitu & McConkie, 2000). The trials were distributed quite evenly across the four categories: first presentation of sentence frame with no regression, 25 %, second presentation with no regression, 24 %, first presentation with a regression, 23 %, and second presentation with a regression, 28 %. As skipping occurred equally often in sentence frames presented for the first or second time, it is unlikely that readers tried to guess the target words as a result of a familiar sentence beginning. The regression rate was radically increased for skipped (51 %) compared to non-skipped (24 %) target words (see also Vitu & McConkie, 2000). This seems to indicate that some of the words were skipped before fully recognizing them.

Finally, the probability of refixating the target word revealed two marginal effects, a marginal main effect of number of letters $F(1,32)=3.12$, $p=.087$, $\eta_p^2=.089$, and a marginal Font x Number of Letters interaction, $F(1,32)=2.94$, $p=.096$, $\eta_p^2=.084$; the main effect of font was non-significant, $F<1$. These marginal effects reflect the trend of refixating more often six-letter (9.9 %) than four-letter (6.6 %) words in the monospaced font.

Insert Table 2 about here

3.2. The effect of spatial width when the number of letters is controlled

The target word analysis suggests that saccade targeting may be governed almost solely by spatial information. If this is the case, spatial width of words may affect reading independently from the number of letters. The proportional font data allowed us to study this question further by dividing the Arial words into wide and narrow ones based on their spatial width, resulting in a 7 pixel (half a letter) difference. More specifically, the results reported in Section 3.1. suggest that the initial landing position would be adjusted according to spatial width. Moreover, narrower words may be skipped more frequently than wider words, whereas wider words may be refixated more frequently than narrower words. Table 3 presents the means and significance levels of the analyses of variance for the spatial measures involving spatial width as a within-participants factor.

The spatial measures were consistently affected by spatial width. Narrow words were fixated two pixels closer towards the word beginning than wide words, $F(1,32)=6.71$, $p=.014$, $\eta_p^2=.173$, which corresponds to 0.16 letters when number of letters was used as the measure, $F(1,32)=4.61$ $p=.040$, $\eta_p^2=.126$. The initial saccade amplitude was 3 pixels shorter for saccades executed into narrow than wide words, $F(1,32)=4.79$ $p=.036$, $\eta_p^2=.130$, which was not significant when measured in number of letters, $F=1.88$. The strongest effect was observed in skipping rate, which indicated that narrow words were more frequently skipped

(17.2 %) than wide words (10.6 %), $F(1,32)=20.80$, $p<.001$, $\eta_p^2=.394$. Thus, it is the spatial width, not the number of letters that governs the decision of whether or not to skip a word. Finally, differences between the words were apparently too short to produce a width effect in refixation probability, $F<1$.

Insert Table 3 about here

3.3. Sentence level analyses

Table 4 presents the means of sentence-level eye movement measures for reading proportional and monospaced font. Average fixation time per sentence, $F(1,32)=3.02$, $p=.092$, $\eta_p^2=.086$, per character, $F(1,32)=.564$, $p=.458$, $\eta_p^2=.017$, and per word, $F(1,32)=1.29$, $p=.263$, $\eta_p^2=.039$, showed no overall font difference; neither did number of fixations per sentence, $F(1,32)=1.52$, $p=.676$, $\eta_p^2=.006$, or per character, $F<1$, whereas more fixations per word were made in reading monospaced (1.74) than proportional font (1.63), $F(1,32)=10.98$, $p=.002$, $\eta_p^2=.256$. Out of all fixations, 25 % were regressions, but there was no difference between the fonts in the percentage of regressions, $F(1,32)=2.16$, $p=.151$, $\eta_p^2=.063$. However, consistently with the target word analysis, average fixation duration was 8 ms shorter in reading monospaced than proportional font, $F(1,32)=16.80$, $p<.001$, $\eta_p^2=.344$. Finally, average forward saccade amplitude was larger in monospaced than in proportional (111 vs. 82 pixels) font when measured in pixels, $F(1,32)=944$, $p<.001$,

η_p^2 =.967, but not when measured in mean number of letters, F(1,32)=1.190, p = .283, η_p^2 =.036, as on average 7.87 letters was progressed during a saccade in both fonts.

Insert Table 4 about here

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4. Discussion

The present study provides important new insight about the word length effect standardly observed in readers' eye movements, by dissociating from each other the effect of the number of letters and that of spatial width. This was achieved by taking advantage of variation in letter width in proportional font, enabling a comparison of four- and six-letter words with equal spatial width. The spatially controlled word length effect was then contrasted with the "standard" word length effect obtained with monospaced font, where an increase in the number of letters coincides with a corresponding increase in spatial extent. Effects of the number of letters and word's spatial extent were examined both in spatial and temporal eye movements parameters.

Similarly to McDonald (2006), saccade programming, as indexed by the amplitude of the saccade entering the target word and its landing position, was determined by spatial width but was not affected by the number of letters. Also the probability of skipping over four- and six-letter words was determined by their spatial width, but not by the number of letters. Effects of spatial width in saccade programming were also observed in an analysis comparing these eye movement measures for wide and narrow four-letter proportional-font words. Finally, there was a marginal trend to refixate more often six- than four-letter monospaced words; in addition, the sentence-level analysis revealed that more fixations per word were made in monospaced than proportional font. These findings are in line with the view that the text's spatial attributes are the primary force in saccade programming during reading. Number-of-letter information appears to be play no role, at least when targeting saccades to shorter words. This pattern of results provides novel support for the view that the decisions of where and when to move the eyes are being made independently from each other, as originally suggested by Rayner and McConkie (1976).

As noted above, skipping probability was governed by spatial width and not affected by the number of letters (see also McDonald, 2006). The percentage of skipped six-letter monospaced words was only 3.6 %, while that of four-letter monospaced words was 21.4%. In the comparison of wide and narrow Arial words, the skipping probability was found to increase by one percent per pixel. Such a dependency on mere spatial width but not on the number of letters is likely to be related to visual acuity constraints of the foveal vision. The further into the parafovea a word extends, the less likely it is that letter identity information necessary for word identification may be gleaned from the outmost letters. The supplementary analysis of skipping trials provided evidence for the view that some skipped words were not fully identified prior to skipping (see also Vitu & McConkie, 2000), as more regressions were being launched to skipped than non-skipped words. Word skipping is likely to result partially from oculomotor error leading to saccadic overshoot and possibly lead to its subsequent correction by a regression targeted to the skipped word.

There was also a font difference in skipping probability, as four-letter monospaced words were skipped more often than four letter proportional words (14.1% and 21.4 % of trials, respectively). This is surprising as these words had equal spatial width. This finding may at least partially be explained by the presence of horizontal Serifs (semi-structural details at the ends of strokes) in the monospaced Courier New font. When the outer Serifs are removed, the average pixel width drops by five pixels equaling the width of narrow Arial words, and also the skipping probabilities are more alike (21.4 % for four-letter Courier and 17.2 % for four-letter narrow Arial words). Nevertheless, the four-percent difference suggests that also some other visual factors than mere spatial width may contribute to skipping probability at small visual angles. One potential explanation is a crowding effect between words, as spaces between words in proportional font are narrower than in monospaced font. Wider word spaces have been found to have beneficial effects on reading with small print sizes (Arditi et al., 1990a, 1990b; Drieghe et al., 2005; Rayner, Fischer, & Pollatsek, 1998). Specifically, visually well distinguishable, short parafoveal words in monospaced font may be easier to recognize, which would show up in increased skipping rate. Finally, it should be noted that monospaced four-letter words were slightly more frequent than four-letter proportional font words, which may also contribute to the observed difference (for a review of word skipping, see Brysbaert et al., 2005).

With respect to general font effects, our results are largely in line with those of Rayner et al. (2010): There was no overall font difference in reading time, average fixation duration was longer for proportional font, and more fixations per word were made in monospaced font. In contrast to Rayner et al. (2010), however, it was not found that more letters would be traversed during each saccade when reading monospaced than proportional font. This discrepancy may be due to a methodological difference, as we did not measure how many letters was traversed during each saccade, but average saccade length in pixels was divided by average letter width - a procedure which may have underestimated local text influences on saccade programming. Our finding of no effect of letter spacing on saccade amplitude in letters, a small effect found by Rayner et al. (2010), and the findings that parafoveal processing is not affected by letter spacing (Rayner et al., 2010) or spatial frequency of the parafoveal letters (Miellet et al., 2009) all support the view that the perceptual span is mainly attentionally (Morrison & Rayner, 1981) rather than visuo-spatially (Arditi et al., 1990b) limited. Font effects in fixation durations may be accounted for by a slightly increased visual processing load during reading of proportional font. The Arial and Courier New fonts differ from each other not only in letter spacing, but also in stroke width and presence of Serifs, so no strong conclusions about the exact source of this font difference can be made (Mansfield et al., 1996).

In contrast to saccade targeting, fixation time measures were influenced by the number of letters. In gaze duration, first fixation duration and single fixation duration there was a genuine word length effect not modulated by font type, which supports the view that number of letters is an important factor in governing the fixation time on foveally inspected words, at least in transparent orthographies (Ziegler et al., 2001) such as Finnish, the language studied in the present experiment. The lack of a parafoveal-on-foveal effect (i.e., target word length did not influence the duration of the preceding fixation) suggests that the number-of-letters effect was restricted to fixated words, which is consistent with the view that attention is allocated serially between words in reading (Reichle, Pollatsek, Fisher, & Rayner, 1998).

As regards temporal measures of eye movements, we obtained a small but reliable number-of-letters effect in gaze duration (11 ms), in first fixation duration (6 ms) and in single fixation duration (7 ms). The small effect size may be explained by the fact that these differences were observed between short, four- and six-letter words. The effect size is smaller than that obtained by McDonald (2006) for six- and eight-letter target words (a difference of 20 ms in gaze duration and a linear increase of 6 ms per letter in single fixation duration). The effect in gaze duration is in line with previous studies, in which the effect is caused by more frequent refixations on longer words (e.g., Hawelka et al., 2009; Joseph et al., 2009: Rayner et al., 1996). The length effect in single fixation duration appears to be somewhat at odds with previous studies conducted in monospaced font. Hawelka et al. (2010) did not find a word length effect among three- to seven-letter words in single fixation duration. Neither did Joseph et al. (2009) find a length effect in first fixation duration between four- and eight-letter words, nor did Hyönä and Olson (1995) for words ranging from 5 to 11 letters. The absence of a number-of-letters effect in first fixation duration may be due to the fact that the first fixation is often followed by a refixation on the word, resulting in a reliable word length effect in gaze duration.

In the two most prominent eye guidance models (E-Z Reader, Reichle et al., 1998, 2006; SWIFT, Engbert, Nuthmann, Richter, & Kliegl, 2005) a word length effect in fixation duration and refixation rate stems from the effort required for letter encoding dependent on the eccentricity of the letters from the center of the fovea. The further away a letter is, the more difficult it is to recognize. If the letters are too far to be encoded, a refixation is made. The temporal length effects in monospaced font may be explained by this visual acuity account. The spatial extent of six letter monospaced words exceeded slightly the span of foveal vision, so letter encoding of the outmost letters may have required extra time, thus producing the effect in single fixation duration. Also, a refixation was sometimes required, presumably for visual acuity reasons (Vergilino-Perez et al., 2004).

However, an explanation based on visual acuity cannot account for the number-of-letters effect obtained for spatially controlled proportional font words. We propose two alternative accounts for this effect, one based on visual crowding and another based on serial letter processing. McDonald (2006) suggests that visual crowding (Bouma, 1970, 1973) may be responsible for the spatially controlled word length effect obtained in single fixation duration. He scaled words horizontally to an equal spatial width of 2 visual degrees, so that the longest words (a maximum length of 10 letters) were compressed, thus suffering from noticeable crowding, while the shortest words (a minimum of 2 letters) were expanded in size, which was likely to reduce an effect of crowding to a minimum. However, crowding was much less dramatic in the present study than in the McDonald study, as words were presented in their natural appearance (i.e., no scaling was carried out).

According to Levi, Klein, and Hariharan (2002), foveal crowding occurs only at the edge-to-edge distance of shorter than 1/6 of the center-to-center distance of adjacent letters, which corresponds to 2.3 pixels with the typical 14-pixel center-to-center letter distance in both fonts used in the current experiment. The closest-edge letter spacing in both fonts was typically 2-3 pixels. For many letters (e,u,o,p,a,s,m) there is not a big difference in letter spacing between the fonts used in the present study (i.e., Arial: euopasm, Courier New: euopasm). However, for some letters in the Courier New font (itlj) the closest-edge distance is much greater than in Arial, where these letters have a closest edge distance of only 1 pixel (itlj). The last set of letters were frequent in our six-letter Arial and four-letter Courier words, so it is fair to say that inter-letter spacing was sparser in the monospaced font. Moreover, according to Liu and Arditi (2000), narrow letter spacing may produce letter confusion between some letters: The point-of-spread function imitates the actual visual image of the retina, which is somewhat blurred. When inter-letter spacing decreases, some letters tend to merge together in this blurred picture. With very short inter-letter spacing, for example the letter string 'JJ' may be sometimes recognized as 'JU'. Taken together, foveal crowding provides a reasonable explanation for spatially controlled number-of-letters effect in single fixation duration observed in the present study.

Another explanation for the number-of-letters effect is offered by the dual-route model of word recognition (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). In this model word recognition is seen as a net result of the workings of the sublexical and lexical routes. The sublexical route operates by converting graphemes to phonemes working serially from left to right, thus producing a number-of-letters effect. On the other hand, the lexical route processes all letters in parallel and maps the letter cluster onto an orthographic word representation; thus, no length effect is produced by this route.

In transparent orthographies, such as Finnish, the correspondence between graphemes and phonemes is regular, so the grapheme-phoneme conversion (GPC) route can always provide a correct pronunciation. Accordingly, phonological influences on word recognition (Katz & Frost, 1992) as well as the word length effect (Ziegler et al., 2001; Ziegler, Perry, Ma-Wyatt, Ladner, & Schulte-Körne, 2003b) are pronounced in transparent orthographies (but see Hawelka et al., 2010). Computational simulations of the dual route model suggest that a transparent orthography may lead to faster working of the GPC route, thus allowing the serial process to contribute more to word recognition (Ziegler, Perry, & Coltheart, 2003a). The number-of-letters effect in fixation time may be explained by this view, as we obtained a persistent number-of-letters effect in a completely transparent orthography (Finnish), even when the words were so short that their processing was not constrained by the limitations of the foveal area.

The above view is also advocated by Wydell, Vuorinen, Helenius, and Salmelin (2003), who detected a word length effect between four- and eight-letter words in a functional neuroimaging study conducted with Finnish-speaking participants. Wydell et al. suggested that the serial letter-to-phoneme conversion may be a permanent part of reading orthographically transparent languages such as Finnish (however, see Adelman, Marquis, & Sabatos-DeVito, 2010, for recent evidence for parallel processing of letters in English).

It was also of interest to examine whether the word length effect is present during parafoveal processing of target words. However, no such effect was detected, as the duration of fixation prior to fixating the target word was practically equal between four- and six-letter proportional font words. This result appears to be at odds with the findings of an inverse effect of parafoveal word length (i.e., the fixation prior to fixating a long word is shorter) obtained in monospaced font (Drieghe et al., 2005; Kennedy, 1998; Kennedy & Pynte, 2005). The length manipulation in these studies was more robust than in the present study, so it seems possible that the inverse parafoveal word length effect may reflect an effect of spatial width rather than an effect of the number of letters.

In conclusion, by comparing word length effects in reading text in proportional font (where an increase in the number of letters may not necessarily widen the word's spatial extent) and monospaced font (number of letters and spatial extent co-vary) we found that in the transparent Finnish orthography saccades are programmed solely on the basis of words' spatial width, whereas fixation durations are affected by the number of letters. The number-of-letters effect obtained in fixation duration may be explained by visual acuity, visual crowding, serial letter processing, or a joint influence of all three factors.

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Appendix (Target Words)

The sequence of target words with corresponding English translations in the parentheses:

Proportional font: karkki (sweet), pupu (bunny), tontti (slot), mato (worm), pultti (bolt), kortti (card), ansa (trap), tulkki (interpreter), muru (bit), muta (mud), leikki (play), maja (hut), pesä (nest), turkki (fur), kana (chicken), home (mould), keitto (soup), mopo (moped), tankki (tank), maha (belly), torttu (tart), maku (taste), teltta (tent), nuha (flu), viitta (cape), meno (plan), muna (egg), kyltti (sign), aamu (morning), loitsu (spell), romu (scrap), pomo (boss), kaisla (reed), mono (ski boot), reitti (route), hymy (smile), kuitti (receipt), niitty (field), saha (saw), veitsi (knife), silkki (silk), namu (candy), leivos (cake), mehu (juice), laitos (facility), vintti (attic), hana (tap), nenä (nose), voitto (victory), hame (skirt), kontti (container), liekki (flame), ahma (wolverine), kioski (kiosk), vilkku (blinker), räme (marsh), sumu (mist), piikki (spike), puhe (speech), linkki (link)

Monospaced font: ilta (night), hammas (tooth), juna (train), kala, (fish), kaivos (mine), kauppa (shop), kesä (summer), kerros (floor), kynä (pen), kiekko (puck), kirkko (church), lasi (glass), latu (trail), koukku (hook), kurkku (cucumber), lelu (toy), lamppu (lamp), meri (sea), lautta (ferry), mainos (advertisement), myrsky (storm), mäki (hill), naru (rope), palo (fire), pipo (cap), patsas (statue), poro (reindeer), raja (border), rapu (crab), piippu (chimney), sade (rain), sora (gravel), puisto (park), rengas (tire), suihku (shower), susi (wolf), taivas (sky), vene (boat), vanhus (oldie), verkko (net)

Figure caption

Figure 1. A sample sentence in the two fonts. The Arial sentence translates literally into English as follows: ‘Prepared from its own ingredients a *juice* / *soup* has the best taste’, with the words in italics corresponding to the Finnish word ‘mehu’ and ‘keitto’, respectively. The Courier New sentence translates literally into English as follows: ‘Dropped to the floor the *glass* / *lamp* broke down loudly’.

Table 1

Table 1. Descriptive Statistics of Target Words Including the Mean Values for Word Frequency (Per Million Words), and Width in Pixels and in Visual Angle, with Standard Deviations in the Parentheses.

	Monospaced Courier New		Proportional Arial			
	Four	Six	Four	Six	Narrow	Wide
Word freq[1].	15.2	15.4	7.1	8.0	6.7	8.3
	(12.9)	(26.7)	(9.4)	(16.8)	(12.2)	(14.8)
Width (pixels)	53*	81	52.8	51.3	48.7	55.4
			(3.4)	(4.5)	(2.2)	(2.1)
Visual angle (degrees)	1.73	2.65	1.73	1.68	1.59	1.81

*=48.05 (2.45) when outer serifs are removed.

[1] Words were common Finnish words. Due to hundreds of inflected word forms of the same base word, surface word frequencies are typically lower in Finnish than in English. The frequency of monospaced words were slightly higher, which may explain why font main effects in fixation times tended to be larger in target word analysis compared to sentence level analysis.

Table 2

Table 2. Mean Values for First-Pass Eye Movement Measures for the Number of Letters Effect in the Proportional and Monospaced Font, Standard Deviations in the Parentheses.

	Proportional Arial		Monospaced Courier New	
Measure	Four-letter	Six-letter	Four-letter	Six-letter
Gaze duration	216 (28)	225 (34)	199 (29)	212 (39)
Single fixation duration	205 (24)	214 (34)	192 (28)	198 (35)
First fixation duration	206 (23)	212 (32)	189 (28)	195 (34)
Previous fixation duration	190 (24)	192 (30)	182 (27)	181 (31)
Skipping probability	.141 (.144)	.136 (.140)	.214 (.195)	.036 (.062)
Refixation probability	.080 (.065)	.076 (.045)	.066 (.060)	.099 (.088)
Initial landing position, in pixels	35 (5.1)	34 (5.4)	43 (7.2)	52 (9.3)
Initial landing position, in letters	3.35 (.48)	3.24 (.51)	3.09 (.52)	3.71 (.66)
Initial saccade amplitude, in pixels	90 (16)	91 (24)	119 (24)	121 (16)
Initial saccade amplitude, in letters	8.57 (1.53)	8.70 (1.85)	8.47 (1.70)	8.65 (1.17)

Table 3

Table 3. Mean Values and Level of Significance of First-Pass Eye Movement Measures for the Effect of Spatial Width When Number of Letters was Controlled by Using a Proportional Font; Standard Deviations Are Presented in the Parentheses.

Measure	Narrow	Wide
Skipping probability	.172 (.171)	.106 (.112) **
Refixation probability	.076 (.066)	.079 (.055)
Initial landing position, in pixels	33.7 (5.66)	35.5 (4.46) *
Initial landing position, in letters	3.22 (.54)	3.38 (.43) *
Initial saccade amplitude, in pixels	88.7 (14.7)	92.4 (20.1) *
Initial saccade amplitude, in letters	8.52 (1.46)	8.76 (1.94)

* = $p < .05$; ** = $p < .001$.

Table 4

Table 4. Mean Values and Significance Levels for the Sentence-Level Eye Movement Measures in Reading Proportional and Monospaced Font; Standard Deviations Are in the Parentheses.

Font type	Proportional Arial	Monospaced Courier New
Fixation time per sentence	2028 (366)	1940 (359)
Fixation time per word	332 (61)	343 (63)
Fixation time per character	43.3 (7.9)	42.5 (7.9)
Number of fixations per sentence	9.90 (1.7)	9.85 (1.5)
Number of fixations per word	1.63 (.28)	1.74 (.25)*
Number of fixations per character	.21 (.04)	.22 (.03)
Regression percentage	24.6 (6.7)	25.5 (7.0)
Forward saccade amplitude in letters	7.84 (1.18)	7.91 (1.09)
Forward saccade amplitude in pixels	82.3 (12.3)	110.7 (15.3) **
Average fixation duration	205 (23)	197 (24) **

* = $p < .05$; ** = $p < .001$.

Kotimaisista aineksista valmistettu mehu maistuu parhaimmalta.
Kotimaisista aineksista valmistettu keitto maistuu parhaimmalta.

Lattialle tippunut lasi hajosi äänekkäästi.
Lattialle tippunut lamppu hajosi äänekkäästi.