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The development of whole-word representations in compound word processing: Evidence from eye fixation patterns of elementary school children

Tuomo Häikiö, Raymond Bertram & Jukka Hyönä

University of Turku

Finland

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Address all correspondence to:

Tuomo Häikiö

Department of Psychology

University of Turku

FIN-20014 Turku

Finland

Tel: +358-2-3338501

Fax: +358-2-3335060

E-mail: tuilha@utu.fi

Abstract

The role of morphology in reading development was examined by measuring participants' eye movements while they read sentences containing either a hyphenated (e.g., *ulko-ovi* 'front door') or concatenated (e.g., *autopeli* 'racing game') compound. The participants were Finnish 2nd, 4th, and 6th graders (aged 8, 10, and 12 years, respectively). Fast 2nd graders and all 4th and 6th graders read concatenated compounds faster than hyphenated compounds. This suggests that they resort to slower morpheme-based processing for hyphenated compounds but prefer to process concatenated compounds via whole-word representations. In contrast, slow 2nd graders' fixation durations were shorter for hyphenated than concatenated compounds. This implies that they process all compounds via constituent morphemes and that hyphenation comes to aid in this process.

Keywords: Morphology, reading development, eye movements, Finnish

It has been established that both adults and children make use of morphological constituents (e.g., *joukkue* ‘team’ and *henki* ‘spirit’) when processing morphologically complex words (e.g., *joukkuehenki* ‘team spirit’). For both groups evidence for the role of morphology in processing complex words has been found across tasks, languages, and readers of different ability (e.g., Bertram, Laine, & Virkkala, 2000; Bertram & Hyönä, 2003; Burani, Marcolini, De Luca, & Zoccolotti, 2008; Carlisle, 2000; Frost, Deutsch, & Forster, 2000; Giraudo & Grainger, 2001). For 3rd grade and 6th grade elementary school children for instance, Bertram et al. (2000) found that low-frequency derived words are easier to define than their monomorphemic counterparts. Burani et al. (2008) reported that both adults and dyslexic and normal children were better in reading pseudowords aloud when they contained morphological constituents than when they did not. Colé, Royer, Hilton, Marec, and Gombert (2005) demonstrated that morphologically complex target words are read faster by good 1st grade-readers when preceded by morphologically related primes in comparison to orthographic or unrelated controls. All in all, it seems that elementary school children from the 1st grade onwards can make use of morphemes when processing morphologically complex words. For adults, a wealth of evidence suggests that readers make use of morphemes when processing morphologically complex words. For instance, several priming studies show that processing such complex words is facilitated when preceded by a morphologically related prime and that processing morphemes is facilitated when preceded by a morphologically related complex word (Rastle, Davis, & New, 2004; Meunier & Longtin, 2007). Similarly, Bertram and Hyönä (2003) showed in a sentence reading study that adults process long Finnish compounds words like *joukkuehenki* ‘ team spirit’ much faster when the first constituent (*joukkue*) is of high frequency than when that constituent is of low frequency, an indication that the first constituent is a functional processing unit in processing compounds (see also Hyönä & Pollatsek, 1998, and Pollatsek, Hyönä, & Bertram, 2000, for similar evidence with respect to the second constituent).

On the other hand, it has been argued that as reading skill improves children as well as adults may develop whole-word representations which contribute to or dominate the access of morphologically complex words. For instance, Burani et al. (2008) observed that skilled 6th grade and adult readers were equally fast in reading aloud familiar morphologically complex and monomorphemic words, which was taken as evidence for whole-word access for both types of words. Moreover, Bertram and Hyönä (2003) demonstrated that for adults processing time of short 7-8-letter compounds is a function of the frequency of the whole word rather than of the frequency of the first constituent. Also other studies with adults showed that reaction/reading times on morphologically complex words decrease as whole-word frequency increases (Bertram, Baayen, & Schreuder, 2000; Vannest, Järvikivi, Bertram, & Niemi, 2002; Andrews, Miller, & Rayner, 2004), which has been taken as evidence that whole-word representations are used in recognizing such words.

To capture these results pointing to the contribution of both morphological and whole-word units in complex word processing, several processing architectures have been proposed. For instance, Taft and Forster (1976) proposed a model of compound word processing in which the first constituent is thought to be the access unit through which the whole compound word is retrieved. Full decomposition models claim that morphological constituent activation precedes whole-word activation (e.g., Longtin & Meunier, 2005; Rastle et al., 2004; Taft & Ardasinski, 2006). The supralexical model of Giraudo and Grainger (2001) proposes that a complex word is accessed as a whole, after which the morphemic units are activated. Finally, more dynamic models such as the dual-route model of Baayen and Schreuder (1999) as well as the multiple source model PROMISE of Kuperman, Bertram and Baayen (2008) allow for simultaneous activation of both whole-word and morpheme-based representations in combination with the assumption that different factors like frequency and word length modulate the contribution of whole-word and morpheme-based information during complex word processing.

In the current study, we examined whether the use of whole-word units in short compound processing increases with development of reading skill. In order to do so, we tested children from the 2nd, 4th, and 6th grade by having them read sentences containing relatively short 7-9-letter compound words while their eye movements were recorded. Our working hypothesis was that children in the early stages of reading development may have to rely mostly on morphemic units in processing short compounds, while whole-word units may come to aid when reading becomes more fluent. This hypothesis in line with the findings mentioned above (e.g., Burani et al., 2008; Colé et al., 2005) and ties in with the idea that the development of stable whole-word representations takes time and repetitive exposure to morphologically complex words.

We investigated the role of morphology in reading short compounds by pitting hyphenated compounds against concatenated compounds. In Finnish, when the first constituent of a compound ends with the same vowel as the second constituent begins, it is mandatory to insert a hyphen between the constituents (e.g., *ulko-ovi* ‘front door’) in order to prevent giving a misleading phonological cue (*ulkoovi* is phonologically quite different from *ulko-ovi*). We hypothesized that hyphenation may enhance morpheme-based processing and disrupt whole-word processing, since a) the hyphen provides an excellent cue as to where the constituent boundary is and with that it may come to aid in identifying the constituents, and b) the hyphen divides a compound into two visual units (or “blobs”), which is likely to affect the way visual attention is allocated in the words. That is, when processing hyphenated compounds attentional focus is initially likely to be on the first constituent (i.e., on a visually distinct object), while it is more likely to stretch out over the whole word in case of concatenated compounds. In case a reader tries to make contact with the whole-word representation of a hyphenated compound, be it immediately or via the access of the first constituent, the initial focus on the first constituent would delay its retrieval in comparison to the retrieval of the whole-word representation of a concatenated compound. Thus, we predicted that less-developed readers benefit from hyphenation, since they are more likely identify compounds via their constituent morphemes rather than via the whole-word representation. If this would indeed be the case, one would expect to find benefits in the eye movement record for hyphenated compound processing in an early measure such as first fixation duration as well as in a later measure like second fixation duration. For more skillful readers, on the other hand, hyphenation may be detrimental for the retrieval of the whole-word representation and hence we may expect that concatenated compound words are processed faster than hyphenated ones.

The issues discussed above lead to the following predictions. We expect that 2nd graders process relatively short compounds (7-9 letters) via morphemes. Consequently, we expect the presence of a hyphen at the morpheme boundary signaling morphological structure to benefit 2nd graders, which would be in line with earlier research showing that 2nd graders make use of and benefit from morphological units when processing complex words (e.g., Burani et al., 2008; Colé et al., in press). Because a) 6th graders resemble adults in the size of their perceptual span in reading (Rayner, 1986; Häikiö, Bertram, Hyönä, & Niemi, 2009), b) 6th graders seem to make use of whole-word representations in processing complex words (Burani et al., 2008), and c) adults are disrupted by hyphenation in short compounds (Bertram & Hyönä, submitted), we expect that 6th graders will be disrupted by hyphenation in short compounds. Finally, it may be hypothesized that 4th graders are in a transition period, so that perhaps no effect of hyphenation is observed. On the other hand, Seymour, Aro and Erskine (2003) have shown that due to the shallow orthography of Finnish, Finnish children learn to read quickly. Therefore, it is possible that detrimental effects of hyphenation may be observed at an earlier stage than suggested above. However, also in Finnish there is considerable variation in reading development within each age group. In order to investigate whether individual differences in reading proficiency affect the role of hyphenation and the way compound words are processed, we included a measure of reading proficiency (as assessed by reading speed) as an additional factor in the analyses.

Method

Participants

A total of 71 children (34 second graders [14 boys and 20 girls], 17 fourth graders [7 boys and 10 girls], and 19 sixth graders [11 boys and 8 girls]) were included in the analyses. The participants were elementary school children recruited from two schools in Turku and Lieto (South-West of Finland). The 2nd graders were on average 8;7 years old, the 4th graders were on average 10;10 years old, and the 6th graders were on average 12;10 years old. Half of the 2nd graders were tested in the spring and the other half in the fall. At the time of testing (April 2008 and October 2008), the 2nd graders had received approx. 1 year 8 months, and 1 year 2 months of reading instruction, respectively.[1] The children received candy as reward for their participation. None of the participants had participated in an eye movement experiment before. All participants had normal or corrected-to-normal vision. Permission from the participants' parents was acquired prior to the test.

Prior to the experiment proper, the children's reading skill was tested to screen out the weakest readers of each age group. The 2nd graders were tested with a sentence comprehension task of ALLU (Lindeman, 1998), a standardized reading test in Finnish for elementary-school aged children, and the 4th and 6th graders were tested with a word chain task of ALLU (Lindeman, 1998). In the sentence comprehension task, children saw a picture (e.g., people sailing) and had to choose which of the four sentences (e.g., "They swim", "They dive", "They sail", and "They dance") corresponded to the picture. There was a time limit of 120 seconds, and 1 point was awarded for each correctly chosen sentence. In the word chain test, children had to separate out words from a string of letters (e.g., catcomputerprincessstone) by drawing a vertical line at word boundaries (cat|computer|princess|stone) as quickly as possible. There was a time limit of 210 seconds, and 1 point was awarded for each correctly placed vertical line. For each grade, the weakest readers (according to the test norms) were excluded from the experiment. For 2nd graders, this was done in order to assure that the task was not too hard for the participants and prevent that some participants would lose their motivation while participating in the experiment.[2] For the other grades the weakest readers were screened out in order to obtain comparable groups to the 2nd grade participants.

Apparatus

Eye movements were recorded with an EyeLink 1000 eyetracker manufactured by SR Research Ltd. (Mississauga, Ontario, Canada). The eyetracker is an infrared video-based tracking system combined with hyperacuity image processing with a spatial resolution of 0.4

degrees. A remote table-mounted model was used, and the recording was monocular. An infrared illuminator for illuminating the eye is placed next to the eye movement camera. The camera samples pupil location, pupil size and corneal reflection at the rate of 1000 Hz. Recording is performed by placing the camera and the infrared light source approximately 50 cm away from the eye. A chin-and-forehead rest was used to minimize head movements. The texts were presented on a 20-inch ViewSonic G225f computer screen with a refresh rate of 150 Hz.

Materials

Nineteen adult members of the University of Turku community rated the age of acquisition (AoA) of a list of potential target compounds on a 7-point scale (1 = 0-2 years, 2 = 3-4 years, 3 = 5-6 years, 4 = 7-8 years, 5 = 9-10 years, 6 = 11-12 years, 7 > 12 years). On the basis of these ratings, we selected 13 hyphenated[3] and 13 concatenated compounds for the experiment proper (average AoA-rating 3.45). Eighteen compounds were rated by at least half of the raters with 4 or lower and had on average a rating below 4 (i.e., acquired before 7 years of age). However, eight compounds had on average a slightly higher AoA-rating than 8 years (maximum 5.68), but our estimation was that this was due to these words having become popular only relatively recently (e.g., *autopeli* ‘racing game’). Hence, six 8-year-old children who did not take part in the actual experiment were asked to define the eight potential target compounds alongside filler compounds that were to our estimation unknown to 2nd graders and that were rated to be acquired relatively late (average AoA-rating 6.0). Whereas the latter compounds were indeed largely unknown to the children, at least 5 out of 6 children could give a proper definition for the eight potential target compounds and hence we included them in the experiment proper.

The 13 hyphenated compound words were matched with the 13 concatenated compounds (see Table 1) on word length, left and right lexeme length, whole-word frequency, 1st lexeme and 2nd lexeme frequency, average bigram frequency, initial trigram frequency, final trigram frequency and left lexeme family size (i.e., the number of derived and compound words starting with the same left lexeme as the target words). All values were extracted from a newspaper corpus containing 22.7 million word forms (Laine & Virtanen, 1999). The items are presented in the Appendix. One may claim that hyphenated compounds are orthographically somewhat peculiar, since in adult texts hyphens only appear within compounds with two identical vowels spanning the constituent boundary. Also, or perhaps consequently, bigram and trigrams including a hyphen are not all that frequent. However, beginning Finnish readers are exposed in the 1st grade to words that are hyphenated at the syllable level (e.g., *ta-lo* 'house', *ka-me-li* 'camel'). The hyphens are then gradually removed from the ABC books and textbooks, but they are preserved in long and difficult words to some extent until the end of the 2nd grade. In other words, children are used to be exposed to hyphenated words. Second, we took great care that, apart from the hyphen, the orthographic structure of the hyphenated compounds is similar to that of concatenated compounds. This is evident from the fact that average bigram frequency, initial trigram frequency and final trigram frequency did not differ between the compound types.

The target compounds were embedded in sentence frames. Each hyphenated compound word was paired with a concatenated compound word, and a sentence that was identical up to word N+1was constructed for each pair. The target word never appeared in the beginning or end of the sentence. The context in which the sentences were presented differed between the two testing periods due to material from other experiments appearing as fillers. In the first period (April), each participant (half of the 2nd graders, all 4th and 6th graders) read a total of 160 sentences. In the second period (October), each participant (the other half of the 2nd graders) read a total of 102 sentences. The sentences were divided in two blocks, and the block order was counterbalanced across participants. The order of sentences was pseudo-randomized. A typical sentence pair can be seen in the example below. The target word is in bold; a literal and free English translation is presented between parentheses.

Hyphenated: Isän ostama **vara-auto** oli väriltään punainen.

(Literal: Father's bought **extra car** was colored red; Free: The **extra car** father bought was red.)

Concatenated: Isän ostama **autopeli** oli oikein hauska.

(Literal: Father's bought **car game** was very enjoyable; Free: The **racing game** father bought was very enjoyable.)

The sentences were presented in Courier font so that each character position was of equal width. With a viewing distance of about 60 cm, three character spaces subtended approximately 1 degree of visual angle. With respect to the vertical axis, sentences were always presented halfway between the top and the middle of the screen. Sentences were all single-line sentences with a maximum of 79 characters on a line.

(Insert Table 1 about here.)

Procedure

Prior to the experiment proper, the eyetracker was calibrated using a three-point horizontal calibration grid that extended over the entire computer screen. Before each sentence the participant had to fixate on a calibration point at the left side between the top and the middle of the screen. When the participant was fixating the calibration point, the experimenter pushed a button, which caused the sentence to appear on the screen starting at the same position as where the calibration point was presented.

Participants were instructed to read the texts silently for comprehension at their own pace, as they would read a magazine or a book. They were further told that after varying intervals they would be presented with a statement about the last sentence, to which they had to answer yes/no by pressing a corresponding button on a game-pad. There were 20 or 16 statements in total, for the first and second testing period, respectively. A practice session containing six sentences preceded the first experimental block.

Results

Only participants whose success rate on responding to the yes/no statements was equal to or higher than 75% were included in the analyses. The 75% cutoff point was used to ensure that the participants had a good understanding of what they were reading. For participants with lower comprehension scores it is hard to make straightforward interpretations as to what the eye movement measures reflect. For the remaining participants, trials in which the target word was initially skipped were excluded from the analyses (0.2%, 0.2%, and 1.0% of trials for the 2nd, 4th, and 6th grade, respectively). Furthermore, for all measures values more than two standard deviations above the grand participant mean were excluded, apart from the number of fixations, where three standard deviations was used as the cut-off point in order not to exclude too many cells. To render the estimates of the condition means normally distributed and standard deviations more comparable with each other, a logarithmic transformation was computed for each duration measure. In cases where the Mauchly's sphericity test became significant, MANOVAs and Greenhouse-Geisser corrected ANOVAs were also conducted. However, the effects were the same as in the uncorrected ANOVAs, which are reported below.

The ANOVAs included three factors, compound type (concatenated vs. hyphenated), grade (2nd vs. 4th vs. 6th), and reading speed (slow vs. fast). A median split based on overall reading speed observed in the experiment was conducted separately for each grade to form reading speed groups. For grade level and reading speed, we were not interested in the main effects (which were obviously present in practically all measures), but in interactions with compound type. However, the main effects of grade and reading speed as well as Grade x Reading speed interactions are presented in Table 2.[4] If an interaction involving compound type and grade was significant, we computed separate analyses for each grade, including pairwise t-tests for each reader group. The means for each measure broken down by the three factors can be found in Table 3 (non-transformed means are presented).

The following measures were used as dependent variables: gaze duration, number of fixations for the first pass reading, first fixation duration, and second fixation duration. Gaze duration indexes the overall processing time of the word, whereas the other fixation duration measures index the relative time course of processing so that first fixation duration indexes an early effect, while second fixation duration reflects a relatively more delayed effect. The ANOVAs were performed by treating both participants (F_1) and items (F_2) as the random factor, except for second fixation duration, for which there were too many empty cells for an item analysis apart from the 2nd grade.

(Insert Tables 2 and 3 about here.)

Gaze duration. The main effect of compound type was significant in the participant analysis, $F_1(1,64) = 6.41$; $p = .01$; $\eta_p^2 = .09$, but only marginal in the item analysis, $F_2(1,12) = 3.52$; $p = .09$; $\eta_p^2 = .23$. Gaze duration was shorter in concatenated than hyphenated compounds. The Compound Type x Grade interaction was marginal in the item analysis, $F_2(2,24) = 2.73$; $p = .09$; $\eta_p^2 = .19$, but not in the participant analysis, $F_1(2,64) = 1.67$; $p = .20$; $\eta_p^2 = .05$. The Compound Type x Reading Speed interaction was not significant, both *p*s > .15, but the Compound Type x Reading Speed x Grade interaction was significant, $F_1(2,64) = 4.26$; $p = .02$; $\eta_p^2 = .12$, $F_2(2,24) = 6.24$; $p < .01$; $\eta_p^2 = .34$. We illustrate the nature of this interaction in Figure 1. To assess the significant interactions in more detail, we performed separate analyses for each grade. For the 2nd grade, there was a significant Compound Type x Reading Speed interaction, $F_1(1,32) = 7.01$; $p = .01$; $\eta_p^2 = .18$, $F_2(1,12) = 9.88$; $p < .01$; $\eta_p^2 = .45$. The fast children had longer gaze durations in hyphenated than concatenated compounds, $p_1 = .03$, $p_2 = .06$. For slow 2nd graders, the pattern was numerically reversed. However, it was not significant, $p_1 = .15$, $p_2 = .16$. For the 4th grade, there was a tendency for a main effect of compound type, $F_1(1,15) = 2.98$; $p = .11$; $\eta_p^2 = .17$, $F_2(1,12) = 4.25$; $p = .06$; $\eta_p^2 = .26$, hinting at longer gaze durations in hyphenated than concatenated compounds. For the 6th grade, there was no Compound Type x Reading Speed interaction, *F*s < 1. The main effect of compound type, $p_1 = .03$, $p_2 = .02$, reflects the fact that gaze duration was shorter in concatenated than hyphenated compounds.

(Insert Figure 1 about here.)

Number of fixations for the first pass reading. The main effect of compound type was significant, $F_1(1,64) = 12.39$; $p = .001$; $\eta_p^2 = .16$, $F_2(1,12) = 10.18$; $p < .01$; $\eta_p^2 = .46$. Readers made more fixations on hyphenated than concatenated compounds. Separate analyses for each grade showed that for 2nd grade there was a significant Compound Type x Reading Speed interaction in the item analysis, $F_1(1,32) = 1.80$; $p = .19$; $\eta_p^2 = .05$, $F_2(1,12) = 6.44$; $p = .03$; $\eta_p^2 = .35$. This reflects the fact that for fast 2nd graders there were more fixations in hyphenated than concatenated compounds, $p_1 = .01$, $p_2 = .04$, whereas for slow 2nd graders there was no difference between compound types, both *p*s > .5. For both 4th and 6th graders there were no Compound Type x Reading Speed interactions, all *F*s < 1. There were significantly more fixations in hyphenated than concatenated compounds for both 4th and 6th graders, all *p*s < .04.

First fixation duration. There was a significant main effect of compound type, $F_1(1,64) = 10.34$; $p < .01$; $\eta_p^2 = .14$, $F_2(1,12) = 16.68$; $p < .01$; $\eta_p^2 = .58$. First fixation duration was shorter in hyphenated than concatenated compounds. The Compound Type x Grade interaction was marginal in the participant analysis, $F_1(2,64) = 2.54$; $p = .09$; $\eta_p^2 = .07$, and significant in the item analysis, $F_2(2,24) = 5.12$; $p = .01$; $\eta_p^2 = .30$. There were no other interactions involving compound type, all *p*s > .15. The main effect of compound type was significant for the 2nd graders, $F_1(1,32) = 6.48$; $p = .02$; $\eta_p^2 = .17$, $F_2(1,12) = 4.26$; $p = .06$; $\eta_p^2 = .26$, as well as for the 4th graders, $F_1(1,15) = 8.59$; $p = .01$; $\eta_p^2 = .36$, $F_2(1,12) = 29.56$; $p < .001$; $\eta_p^2 = .71$. First fixation duration was longer in concatenated than hyphenated compounds for both grades. For the 6th graders, there was no main effect of compound type, *F*s < 1.[5]

Second fixation duration. The main effect of compound type was not significant, $F_1 < 1$. The Compound Type x Reading Speed interaction was significant, $F_1\ (1,46) = 4.86$; $p = .03$; $\eta_p^2 = .10$, as was the Compound Type x Grade interaction, $F_1\ (2,46) = 7.89$; $p = .001$; $\eta_p^2 = .26$.

There were no other significant interactions, all *F*s < 1. For the 2nd grade, there was no difference between concatenated and hyphenated compounds for the fast readers, $p_1 > .2$, $p_2 = .07$. For the slow 2nd graders, second fixation in hyphenated compounds was shorter than in concatenated compounds, $p_1 < .005$, $p_2 = .01$. This trend could also be observed in a Compound Type x Reading Speed interaction which was marginal in the participant analysis, $F_1(1,27) = 2.98$; $p = .10$; $\eta_p^2 = .10$, but not in the item analysis, $F_2 < 1$. For the 4th grade, there was a significant Compound Type x Reading Speed interaction, $F_1\ (1,12) = 5.14$; $p = .04$; $\eta_p^2 = .04$. Second fixation duration of the fast readers was shorter in concatenated than hyphenated compounds, $p_1 = .05$. For the slow 4th graders there was no difference between compound types, $p_1 > .3$. For the 6th graders, there was no Compound Type x Reading Speed interaction, $F_1 < 1$. The main effect of compound type, $p_1 = .06$, was due to the 6th graders making longer second fixations in hyphenated than concatenated compounds.

Discussion

To summarize the results (see also Table 4), we found that for the fast 2nd graders, all 4th graders, and all 6th graders hyphenated compounds elicited longer gaze durations than concatenated compounds. For the slow 2nd graders we found an opposite pattern: Gaze durations for hyphenated compounds were shorter than for concatenated compounds even though this difference failed to reach significance. However, significant main effects of compound type were found for slow 2nd graders in both first fixation duration and second fixation duration. That is, first and second fixation durations were shorter in hyphenated compounds than concatenated compounds. Also for fast 2nd graders and all 4th graders first fixation durations were shorter in hyphenated than concatenated compounds, whereas for 6th graders there was no difference between compound types. In contrast to the results obtained for slow 2nd graders, concatenated compounds elicited either equally fast (fast 2nd graders and slow 4th graders) or faster (fast 4th graders and all 6th graders) second fixation durations than hyphenated compounds. Finally, for slow 2nd graders there was no difference in the number of fixations between concatenated and hyphenated compounds, whereas for all the other groups there were fewer fixations in concatenated than hyphenated compounds.

(Insert Table 4 about here.)

Taken together, the pattern of results distinguishes the slow 2nd graders from all other participant groups. More precisely, for slow 2nd graders all measures indicate that hyphenation is not disruptive to compound reading. In fact, individual fixation durations indicate that for them it is easier to process hyphenated compounds than concatenated ones. For all other participant groups there is at least one measure that indicates that hyphenation disrupts compound processing. Most importantly, for all groups but slow 2nd graders gaze durations for concatenated compounds were shorter than for hyphenated compounds. How can this different pattern of results for slow 2nd graders in comparison to the other participant groups be explained?

We think that slow 2nd graders do not make use of whole-word representations but instead rely solely on morphemes in processing compound words. Since morphological structure is explicitly signalled in hyphenated compounds but not in concatenated compounds, the former type of compounds is easier to process. More precisely, since the constituent boundary is not explicitly marked in concatenated compounds, extra processing effort is needed to decide where the first constituent ends and the second begins. This extra processing effort is reflected in significantly longer first and second fixation durations. The type of morpheme-based processing slow 2nd graders resort to is not hampered by hyphenation, or to put it differently, by the role a hyphen may play in initially restricting attention to the first constituent. That is, for a reader who reads a compound via its morphological constituents, initial focus on the first constituent should enhance rather than hamper the ease of processing.

All other participant groups read faster concatenated than hyphenated compounds implying that it is unlikely that both types of compounds are processed solely via morphemes. It is possible that there is a qualitative difference in processing the different types of compounds with hyphenated compounds being processed via morphemes and concatenated ones via whole-word representations. If this is the case, processing concatenated compounds would be faster, because decomposed access as such is likely to be slower than direct access via whole-word representations due to the fact that one has to go through more processing stages in the former case. That is, one needs to access two representations instead of one and also to assemble the decomposed parts together, which requires additional processing time. Another possibility is that whole-word representations are directly accessed in case of concatenated compounds, but that they are involved in processing hyphenated compounds only after activation of the first constituent. The idea of whole-word representations being activated via the first constituent was introduced by Taft and Forster (1976) for all compounds but is perhaps most likely for compounds where the first constituent is visually distinct as is the case for hyphenated compounds. If this is indeed the case, it would mean that there is an additional processing stage for hyphenated compounds in comparison to concatenated compounds which would manifest in longer processing times for the former type of compounds. In sum, the finding that gaze durations are faster for concatenated than hyphenated compounds is in line with either hyphenated compounds being processed solely via morphemes or by activating the whole-word representation via the first constituent morpheme, while concatenated compounds are directly accessed via whole-word representations.

One question that remains still is why in the initial stages, indexed by first fixation duration, hyphenated compounds are either processed equally fast or even faster than concatenated ones even though in the end they are processed slower by five out of six participant groups. Again, we would like to argue that the presence of hyphen affects the allocation of attention within a compound; more precisely, a hyphen causes the reader to restrict his/her attention to the first constituent. In case of concatenated compounds it is not clear from the beginning where the first constituent ends or even whether the word in question is a compound or not, and therefore attention is likely to stretch over the whole word. Because the attentional focus is restricted to a smaller (and also more frequent) lexical unit in the former situation, initial processing is more favorable for hyphenated compounds than concatenated compounds.

Our hypothesis was that hyphenation would only disrupt compound reading for the 6th graders, but to our surprise, hyphenation was already disruptive in the early elementary school years. In the Introduction we noted that Finnish elementary school children develop reading skills very quickly. This is partly due to the shallow orthography of written Finnish, which enables beginning Finnish readers to perform tasks such as reading familiar words and nonwords with better accuracy and speed than beginning readers of many other languages (Seymour et al., 2003). We think that this quick development of reading skill may have led to the situation that already at the 2nd grade many Finnish children are able to identify at least relatively short familiar compound words (7-9 letters) via whole-word representations. It needs to be noted that the fact that we screened out the weakest readers prior to the experiment may have shifted the balance of the results somewhat. Especially for the 2nd grade the inclusion of weaker readers could have led to a positive main effect of hyphenation. However, this is not to deny that for a substantial number of 2nd graders hyphenation is disruptive rather than facilitative. Only the slower (i.e., less proficient) 2nd grade readers make use of and benefit from hyphenation. It is likely that explicitly signalling morphological structure by means of a hyphen is beneficial for other less proficient readers as well, for instance for 1st graders or for dyslexic readers. The study of Harley and O'Mara (2006) supports this claim. They found that their phonological dyslexic patient JD read aloud morphologically complex words like *needless* and *paranormal* very well (85% correct) once hyphens were included at the morpheme boundary (*need-less, para-normal*). On the other hand, JD was not able to read any of the 20 concatenated complex words aloud when they were written in concatenated format.

So far, we have discussed the use of morphological and whole-word information with respect to reading skill. However, recent studies have indicated that several other factors such as constituent frequency, whole-word frequency, family size of the left constituent and word length affect the extent to which different sources of information are used in processing morphologically complex words. We should also note that these kinds of factors may interact with each other (Bertram & Hyönä, 2003; Kuperman et al., 2008; Kuperman, Bertram, Schreuder, & Baayen, in press; Niswander-Klement & Pollatsek, 2006). For example, Bertram and Hyönä (2003) and Niswander-Klement and Pollatsek (2006) demonstrated that adults make more use of morphological information in case of long words. The authors argued that this finding is caused by degraded visibility of the letters in the end of long words. Accordingly, Bertram and Hyönä proposed the visual acuity hypothesis, which holds that readers initially process the first constituent morpheme of a complex word if they do not perceive enough of the latter part of that word. In line with this hypothesis, Bertram and Hyönä (submitted) found that adult readers benefit from hyphenation when reading long (12-14 letters) hyphenated compounds, but are disrupted by hyphenation when reading short (7-9 letters) hyphenated compounds. Bertram and Hyönä argue that when a word is long, hyphenation facilitates reading because the reader will initially access the first constituent in long compounds anyway and a hyphen visually marks the lexeme boundary thus enhancing the identification of this constituent. However, in case of short and familiar compounds, practically all letters fall within the foveal span on the first fixation, enhancing direct whole-word access. In this case, hyphenation is detrimental, because it enforces initial focus on the first constituent which either encourages the reader to use decomposition or leads to delayed access of the whole-word representation.

We may argue that for slow 2^{nd} graders the 7-9-letter compounds used in this study are still relatively long and thus would encourage morpheme-based processing, whereas for fast 2^{nd} graders and older children they are sufficiently short so that these readers rely on access via whole-word representations. This ties in with the findings of Häikiö et al. (2009), who observed that the letter identity span of fast 2^{nd} graders and older children is at least 7 letters to the right of fixation. This means that in the present study, the entire word (7-9 letters) usually falls within their letter identity span, even if the initial fixation is in the very beginning of the word (for the fast 2^{nd} graders, the initial fixation falls on average on the third letter of the word). However, for slow 2^{nd} graders, Häikiö et al. (2009) found that the letter identity span is only 5 letters to the right of fixation. This implies that for the target compounds of this study, the letter identity span of slow 2^{nd} graders fairly often does not cover the whole compound (for the slow 2^{nd} graders, the initial fixation falls on the second letter of the word on average). Taken together, the results imply that the visual acuity hypothesis of Bertram and Hyönä (2003) may explain the results obtained for slow 2nd grade readers.

One thing we would still like to point out is that we do not want to claim that Finnish children only make use of morphological structure relatively early in reading development or when morphologically complex words are of considerable length. After all, the explosive vocabulary growth that takes place during elementary school years is largely morphologically driven (Anglin, 1993). Besides, as mentioned above, Finnish is morphologically very productive and consequently a Finnish speaker or reader is daily confronted with several new morphological formations – also shorter ones. Related to this, one may consider the fact that in Finnish, a verb may appear in approximately 13,000 inflectional forms and a noun or adjective can combine with inflectional suffixes, so that about 2,000 different inflectional variants of the same noun could be realized (Karlsson & Koskenniemi, 1985). In addition, derivation and compounding is very productive in Finnish, so that the family size of a given word – the number of derivational and compound descendants of a given word – outnumbers to a great extent the family size in other languages like Dutch for instance (see Moscoso del Prado Martin et al., 2004). In other words, throughout the elementary school years (and throughout his/her entire life) a Finnish reader will have to resort to morpheme-based processing, if it were only to deal with the uncountable new morphologically complex words.

Our results add to the growing body of evidence that morphological models should be flexible, allowing for different sources of information to contribute to complex word processing depending on the circumstances (Bertram & Hyönä, 2003; Kuperman et al., 2008). Here we found that reading proficiency is one factor that modulates the contribution of morphological information during complex word processing. Models like the supralexical model of Giraudo and

Grainger (2001) claiming that whole words are activated before morphological constituents, or decomposition models proposing that morphological constituent activation precedes whole-word activation (e.g., Longtin & Meunier, 2005; Rastle et al., 2004; Taft & Ardasinski, 2006) lack this kind of flexibility. In contrast, more flexibility is incorporated in dual-route models (Baayen & Schreuder, 1999) as well as in the multiple source model PROMISE of Kuperman et al. (2008), which allow for simultaneous activation of both whole-word and morpheme-based representations in combination with the assumption that different factors like frequency and word length modulate the contribution of whole-word and morpheme-based information during complex word processing.

In sum, the current study suggests that slow 2nd graders process both concatenated and hyphenated 7-9-letter compound words via morphemes without making use of whole-word representations. Hyphenation comes to aid in signalling the morphological structure of compound words, hence the faster fixation durations on hyphenated than concatenated compounds. To put it differently, the results imply that slow 2nd graders prefer to process short 7-9-letter compound words via units that are easily digestible given their reading skill. For fast 2nd graders as well as for all 4th and 6th graders the results imply that concatenated compounds are accessed via whole-word representations, whereas hyphenated compounds are accessed morpheme by morpheme or via whole-word representations activated by the first constituent. It seems to us that this type of decomposition or delayed access of the whole-word representations is linked to the role of hyphen, causing initial attentional focus to be mainly on the first constituent.

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Appendix

List of items used in the experiment.

Concatenated	*Hyphenated*
autopeli (racing game)	vara-auto (extra car)
pihapuu (garden tree)	peli-ilo (game pleasure)
lasiovi (glass door)	kuu-ukko (moon man)
kiviaita (stone wall)	rauta-aita (iron wall)
talviuni (hibernation)	uima-asu (swimming suit)
kevätsää (spring weather)	juhla-asu (party clothes)
pikatie (highway)	pika-apu (instant help)
lumisota (snow fight)	lava-auto (pickup truck)
junarata (railway)	aamu-uinti (morning swim)
kotipiha (home yard)	koti-ilta (home evening)
iltasatu (bedtime story)	peli-ilta (game night)
yöpaita (nightgown)	ajo-ohje (driving instruction)
ulkovalo (outer light)	ulko-ovi (front door)

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Footnotes

1. We expected to obtain slightly different results for the early than for the late 2nd graders, but the results of these groups did not differ from each other in any measure. Hence we treated them as one group in all the analyses.

2. In other studies we tested the weakest readers of the 2nd grade, and noticed that they experienced the experiment as very difficult resulting in a decrease in motivation

3. In Finnish, a hyphen is always inserted between the lexemes of a compound when the first lexeme ends with the same vowel as the second lexeme begins.

4. In some of the measures, there was a significant Reading Speed x Grade interaction. All of these reflected the fact that the difference between the slow and fast readers was bigger for the 2nd grade than for the other grades, i.e., readers become more homogeneous with age.

5. We also conducted an analysis for single fixation duration, for which the results were similar to first fixation duration for the 4th and 6th grade; single fixation duration was longer in concatenated than hyphenated compounds for the 4th grade, whereas for the 6th grade there was no significant effect of compound type. For the 2nd grade, there were not enough observations for a reliable analysis.

Table 1. Lexical statistics of the two compound type conditions used in the experiment.

	Concatenated	Hyphenated	*P* Value of T Test
1st lexeme frequency*	172	174	0.97
1st lexeme length**	4.00	4.00	1.00
1st lexeme bigram frequency***	6.31	6.86	0.58
2nd lexeme frequency*	176	191	0.77
2nd lexeme length**	3.69	3.69	1.00
2nd lexeme bigram frequency***	8.18	7.03	0.46
Whole word frequency*	1.16	0.91	0.59
Whole word length**	7.69	7.69	1.00
Whole word bigram frequency***	7.10	6.99	0.91
Initial trigram frequency***	0.46	0.53	0.63
Final trigram frequency***	0.82	0.82	0.99
Family size	447	499	0.66

* = Per million; ** = in characters; *** = per thousand

Table 2. Main effects of grade and reading speed and Grade x Reading Speed interactions for each measure.

	Grade			Reading speed			Grade x Reading Speed		
By participants									
	F (2,64)	*p*	η_p^2	*F* (1,64)	*p*	η_p^2	*F* (2,64)	*p*	η_p^2
Gaze	38.71	< .001	.55	23.05	< .001	.27	2.28	.11	.07
FFD	8.50	.001	.21	2.23	.14	.03	< 1	-	-
SFD	22.81*	< .001	.50	14.16**	< .001	.24	< 1*	-	-
NFix	26.31	< .001	.45	16.41	< .001	.20	3.19	.05	.09
By items									
	F (2,24)	*p*	η_p^2	*F* (1,12)	*p*	η_p^2	*F* (2,24)	*p*	η_p^2
Gaze	222.28	< .001	.95	240.74	< .001	.95	13.08	< .001	.52
FFD	30.59	< .001	.72	3.67	.08	.23	2.54	.10	.18
SFD	-	-	-	-	-	-	-	-	-
NFix	118.30	< .001	.91	213.35	< .001	.95	28.13	< .001	.70

* (2,46) degrees of freedom

** (1,46) degrees of freedom

FFD = First Fixation Duration; SFD = Second Fixation Duration; NFix = Number of fixations

Table 3. Means for each eye movement measure as a function of grade, reading speed, and compound type (standard deviations in parentheses).

	2nd grade						4th grade						6th grade					
	Slow		Fast		**Overall**		Slow		Fast		**Overall**		Slow		Fast		**Overall**	
	Conc	Hyph	Conc	Hyph	**Conc**	**Hyph**	Conc	Hyph	Conc	Hyph	**Conc**	**Hyph**	Conc	Hyph	Conc	Hyph	**Conc**	**Hyph**
Gaze	1075	996	545	594	**810**	**795**	491	539	352	373	**417**	**451**	369	410	296	326	**331**	**366**
	(402)	(308)	(225)	(194)	**(419)**	**(326)**	(144)	(79)	(45)	(58)	**(123)**	**(108)**	(85)	(88)	(36)	(61)	**(73)**	**(84)**
FFD	300	277	266	251	**283**	**264**	264	253	259	223	**261**	**237**	226	225	227	225	**227**	**225**
	(40)	(40)	(52)	(50)	**(49)**	**(46)**	(39)	(44)	(32)	(37)	**(34)**	**(42)**	(31)	(18)	(37)	(23)	**(33)**	**(20)**
SFD	331	285	258	253	**298**	**271**	249	231	188	208	**223**	**221**	199	221	159	178	**186**	**207**
	(71)	(58)	(43)	(60)	**(70)**	**(60)**	(43)	(33)	(26)	(22)	**(47)**	**(31)**	(24)	(27)	(19)	(3)	**(30)**	**(31)**
NFix	3.39	3.44	2.12	2.47	**2.76**	**2.96**	1.92	2.30	1.50	1.75	**1.70**	**2.00**	1.72	1.86	1.37	1.55	**1.53**	**1.70**
	(1.05)	(0.81)	(0.87)	(0.65)	**(1.13)**	**(0.88)**	(0.34)	(0.32)	(0.17)	(0.31)	**(0.33)**	**(0.41)**	(0.48)	(0.45)	(0.25)	(0.32)	**(0.40)**	**(0.40)**

Conc = Concatenated; Hyph = Hyphenated; FFD = First Fixation Duration; SFD = Second Fixation Duration; NFix = Number of fixations

Table 4. The effect of hyphenation for each reader group.

	First fixation duration	Second fixation duration	Gaze duration	Number of fixations
Slow 2nd graders	--	--	0	0
Fast 2nd graders	--	0	++	++
Slow 4th graders	--	0	+	++
Fast 4th graders	--	++	+	++
Slow 6th graders	0	+	++	++
Fast 6th graders	0	+	++	++

- = Hyphenated compounds read faster than concatenated compounds/more fixations in concatenated than hyphenated compounds;

0 = No difference between hyphenated and concatenated compounds;

+ = Concatenated compounds read faster than hyphenated compounds/more fixations in hyphenated than concatenated compounds;

--/++ = significant effect; -/+ = marginal effect

Figure caption

Figure 1. The size of the hyphenation effect (gaze duration on hyphenated compounds minus gaze duration on concatenated compounds).

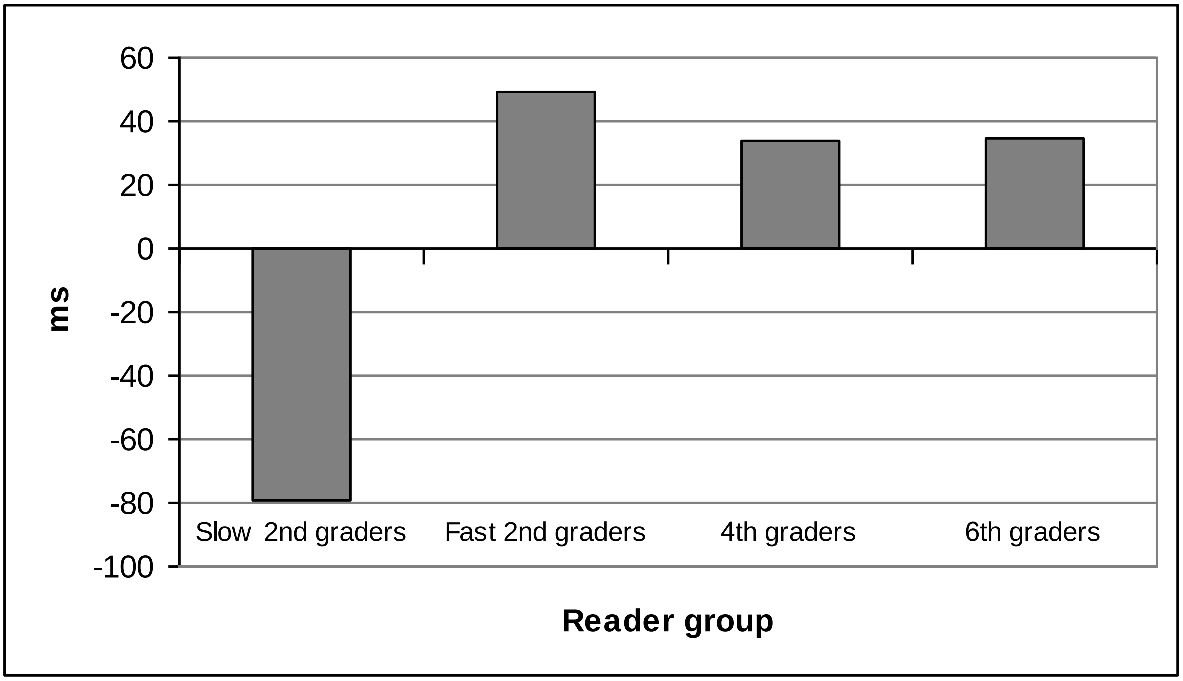
60
40
20
0
-20
-40
-60
-80
-100
ms
Slow 2nd graders
Fast 2nd graders
4th graders
6th graders
Reader group

Figure 1.