Reading Finnish Compound Words: Eye Fixations Are Affected by Component Morphemes

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The role of morphemic processing in reading was investigated in 2 experiments in which participants read sentences as their eye movements were monitored. The target words were 2-morpheme Finnish compound words. In Experiment 1, the length of the component morphemes was varied and word length was held constant, and in Experiment 2, the uniqueness of the initial morpheme was varied and the rated familiarity and length of the word were held constant. The length of the initial morpheme influenced the location of the second fixation on the target word and the pattern of fixation durations (although it had a negligible influence on the gaze duration of the word). The frequency of the initial morpheme influenced the duration of the first fixation on the target word, had a substantial effect on the gaze duration, and also influenced the location of the first and second fixations on the target word. Subsidiary analyses indicated that these effects were unlikely to stem from orthographic factors such as bigram frequency.

It is now well established that people are quite sensitive to various properties of words when they silently read text. In particular, they are quite sensitive to both the length (i.e., the number of letters) of a word and the word's frequency in the language. These variables have been shown to affect both where a reader's eyes land and the duration of fixations. In particular, both the length of a word and its frequency in the language have been shown to affect the gaze duration on a word (the total fixation time on a word before the reader moves forward in the text) and the probability that the word is skipped. Moreover, the frequency of a word has been shown to affect the duration of the initial fixation on a word, whereas the length of a word has been shown to affect the location of the initial fixation on a word. Data also indicate that these two aspects of eye guidance during reading—guiding where the eye moves and guiding when the eye moves—are, to some extent, independent. (We review some of these data below; see Rayner & Pollatsek, 1989, for a more thorough review and Rayner & Raney, 1996, for an update.) In the present study we used Finnish compound words to examine whether these where and when decisions are similarly influenced by the component morphemes of compound words.

In Finnish, compound words are extremely common, and word compounding is a productive way to construct novel words. (This is also true in German.) Typically, two or more nouns are simply attached to each other to form a compound word (e.g., lumi = snow, lumipallo = snowball, lumi-pallosota = snowball fight, lumipaltosotatenere = snowball fight field). In the two experiments reported here, we studied the processing of two-noun compound words by recording readers' eye fixations on these words when they were embedded in sentences. We were interested in assessing whether the morphological structure of compound words has an effect on where in the word readers fixate and for how long they stay fixating on a specific word location. In the following paragraphs, we delineate alternative models of eye guidance separately for the mechanisms governing these where and when decisions.

With respect to where decisions, there is now ample evidence indicating that low-level visual features, such as word length (indicated by the spaces between words), are important factors in governing where the reader fixates on a word. It has been shown for several languages that readers land initially near the word center on the basis of word length and spacing information obtained from the parafoveal vision (Hyöniä, Niemi, & Underwood, 1989; Kliegl, Olson, & Davidson, 1983; McConkie, Kerr, Reddix, & Zola, 1988; O'Regan, 1981; Radach & Kempe, 1993; Rayner, 1979; Underwood, Clews, & Everatt, 1990; Vitu, O'Regan, & Mittau, 1990). We refer to this location as the preferred landing position (Rayner, 1979), which is somewhat to the left of the center of a word.

Whether information other than word length is used in deciding where to fixate on a word is more controversial, however. Underwood, Clews, and Everatt (1990), and Inhoff, Briühl, and Schwartz (1996) provided evidence consistent with the view that lexical-semantic features may...
influence where readers initially fixate in words. Hyönnä et al. (1989) and Underwood, Clews, and Everatt (1990) showed that the initial fixation goes farther into a word when the word has an informative as opposed to a redundant ending. A word ending was defined as informative when the identity of the word could be guessed correctly given the last six letters and as redundant when the word-final letters did not adequately constrain the identity of the word. (All the words with informative endings in the Hyönnä et al. study were compound words, and most of the words with redundant endings were derived words.) Similarly, Inhoff et al. (1996) found the initial fixation to be more toward the word’s center for compound words than for derived (or monomorphemic) words. The first two findings were challenged by Rayner and Morris (1992), who could not replicate the Underwood, Clews, and Everatt (1990) study. Moreover, Hyönnä (1995) did not find any effects on the initial landing position as a function of the type of word ending: The initial landing position in a word was similar for derived words and compound words that had identical beginnings but different endings. However, Hyönnä (1995) observed an effect of orthographic regularity of the word beginning: For highly irregular word beginnings, the initial landing position was more toward the word beginning.

It thus appears that where the reader fixates on a word is affected by factors other than word length, but it is not clear whether lexical-semantic factors such as morphemes—as opposed to orthographic features—are relevant. Most of the studies discussed above used a variety of multimorphemic words: compound words and affixed words. This makes it particularly hard to diagnose whether the effects were due to morphemic or orthographic differences between the words. In order to have a better chance of isolating morphemic factors, in the present research we used only one type of multimorphemic word—compound words. Our major focus in Experiment 1 was to assess whether the length of the component morphemes in fact had an influence on the locations of fixations in words. We used two types of noun–noun compound words: compounds with a long initial morpheme and a short second morpheme (e.g., maailman/ sota = world war) and compounds with a short initial morpheme and a long second morpheme (e.g., ydin/ reaktori = nuclear reactor). The target words were 12–14 characters long, which means that they were typically read with two fixations (see Hyönnä et al., 1989). Thus, we were able to examine morphological effects on the location of both initial and second fixations on the words.

According to a pure visual guidance model (i.e., one in which eye movement control is merely guided by word length information), neither the initial nor second fixation location would be influenced by the compound word structure. In contrast, according to a morpheme guidance model, fixation locations in short+long compounds would differ from those in long+short compounds. For compound words, a plausible way in which morphological structure could have direct control over fixation locations is as follows: A compound word is decomposed into its constituent morphemes, with the individual morphemes playing a role in guiding the eyes. One possibility is that the eyes might be guided to the center of the first morpheme on the initial fixation on a word and to the center of the second morpheme on the second fixation. If the morphemes were actually processed as separate words, one might expect the initial fixation on a compound word to be a little to the left of the middle of the first morpheme and the second fixation to be a little to the left of the middle of the second morpheme. It is not likely, however, that fixation locations for morphemes of compound words would be the same as if they were delimited by spaces because there is no salient low-level information indicating where morphemes begin and end. Nevertheless, if the morpheme guidance model is correct, there should be a difference in landing positions for the two types of compound words, with both the initial and second fixations being farther into a word, the longer the initial morpheme.

Because a saccade into a word is programmed when the eyes are fixating on a preceding word, the location of initial fixation is determined while the reader is still processing a word located to the left of the target. The prediction that the morphological structure of a compound word influences the location of the initial fixation on the word presupposes the existence of parafoveal morphological preprocessing, for which no empirical evidence has yet been reported (see Inhoff, 1989; Lima, 1987). However, it is now widely accepted that readers do indeed perform some sort of parafoveal processing of the word to the right of the currently fixated word. It is quite generally accepted that (a) abstract letter codes for at least the first 3–4 letters are activated parafoveally (Rayner, McConkie, & Zola, 1980) and (b) the saccade trajectory into the following word is determined on the basis of word length information acquired parafoveally (Morris, Rayner, & Pollatsek, 1990; Pollatsek & Rayner, 1982). Seeing the letters of the subsequent word parafoveally facilitates its subsequent foveal processing—this phenomenon is called parafoveal preview benefit. However, neither Lima (1987) nor Inhoff (1989) were able to show that the parafoveal preview benefit was larger when the initial letters of a word formed a separate morpheme (e.g., reread or cowboy). Similarly, Underwood, Petley, and Clews (1990) were unable to obtain a priming effect for noun–noun compound constituents by priming either the first or the second morpheme of a compound word by a word earlier in the sentence. Thus, to date, there is no reported evidence supporting the existence of parafoveal morphological decomposition. Hence, if we were to observe an effect of morphological structure on the initial fixation location, it would be the first clear evidence for the existence of parafoveal morphological preprocessing. (However, the initial fixation location effect demonstrated by Hyönnä et al., 1989. Inhoff et al., 1996, and Underwood, Petley, & Clews, 1990, can potentially be interpreted as a morphological effect.)

Alternatively, an apparent morphemic effect could be due to lower level orthographic factors. For example, morpheme boundaries in compound words may comprise an irregular bigram (e.g., wb in cowboy in English), which might attract a fixation close to it. If so, then a purely orthographic model could predict that fixations will be further into a word, the
longer the initial morpheme. It should be noted, however, that an effect of orthographic irregularity on fixation location has so far been shown only for word-initial letters and with highly irregular letter clusters (see Beavillain, Doré, & Baudouin, 1996; Hyyrä, 1995). We used regression analyses to test the plausibility of such an alternative explanation for fixation location differences.

In regard to the when decisions, two basic types of models can also be entertained: a visual guidance model and a processing guidance model. According to the visual guidance model (also called the oculomotor control model) put forth by O'Regan (1992), the location of a fixation within a word is the primary determinant of fixation duration. If the fixation lands far away from the optimal viewing location (i.e., around the center of the word), a short fixation ensues and the eyes are sent toward the other end of the word. Lexical or any higher order processing is not assumed to determine durations of these "inconveniently" positioned fixations. Fixations landing close to the optimal viewing position are of longer duration, and they might show some sensitivity to lexical processes (for a recent criticism of O'Regan's model, see Rayner, Sereno, & Raney, 1996).

Processing guidance models posit that fixation durations are governed by ongoing cognitive processes. For instance, a word that is difficult to identify or integrate into the preceding context receives a longer fixation time than does an easily processed word (see Rayner & Pollatsek, 1989, and Pollatsek & Rayner, 1990, for reviews). Processing guidance models can be categorized into two types: those that allow morphological features to have a significant role in eye guidance and those that do not (i.e., models that consider only properties of the whole word to be relevant). One possible way in which the morphological structure of compound words could be relevant to eye movement guidance would be if morphemes had the same status as words. Such a model would predict that a low-frequency morpheme as the first part of a compound word would receive a longer fixation than would a high-frequency morpheme, just as there are longer fixation times on low-frequency words than on high-frequency words (Henderson & Ferreira, 1990; Hyyrä & Olson, 1995; Inhoff, 1984; Inhoff & Rayner, 1986; Just & Carpenter, 1980; Raney & Rayner, 1995; Rayner & Duffy, 1986).

We tested these latter predictions in Experiment 2 with two-noun compound words in which we manipulated the frequency of the first morpheme. We compared the durations of fixations on compound words that had a frequent first morpheme (i.e., a morpheme that started many compound words) with those on another set of compound words that had a unique initial morpheme (i.e., a morpheme that started at most one other compound word), with the familiarity of the two sets of compound words equated. The frequency of the initial morpheme could also have an influence on where the eye lands on a word (especially the second fixation). If the initial morpheme is difficult to process, more re fixesations might be programmed on the initial morpheme, and thus the second fixation on a word may be, on average, less far into a word for less-frequent initial morphemes.

Experiment 1

Method

Participants. Twenty-five students from the introductory psychology course at the University of Turku, all of whom were native speakers of Finnish, participated in the experiment as part of the course requirement.

Apparatus. Eye movements were collected with an EYELINK eyetracker (SR Research Ltd., Canada). The eyetracker combines an infrared video-based tracking system with hyperacuity image processing. There are two cameras mounted on a headband (one for each eye), including two infrared LEDs for illuminating each eye. The headband weighs 450 g. The cameras sample pupil location and pupil size at the rate of 250 Hz. Registration is monocular and is performed for the selected eye by placing the camera and the two infrared light sources 4–6 cm away from the eye. The resolution of eye position (i.e., differential accuracy) is 15" of arc, and the absolute spatial accuracy is approximately 0.5". Head position with respect to the computer screen is tracked with the help of a head-tracking camera mounted on the center of the headband at the level of the forehead. Four LEDs are attached to the corners of the computer screen and are viewed by the head-tracking camera once the participant sits directly facing the screen. Possible head motion is detected as movements of the four LEDs and is compensated for on-line from the eye position records. The system allows free head motion within a 100-cm² cube. The compensation is better than 1° over the acceptable range of head motion.

Materials and design. Two sets of two-noun compound words (12–14 characters long) were used as target items: one set with a short initial morpheme and a long second morpheme and another set with a long initial morpheme and a short second morpheme. When short, the morpheme was 3–5 letters long; when long, it was 8–11 letters long. There were 51 words of each kind. The average length of the target words was matched between the two compound word types (the average length was 12.4 characters for both word types), and so was the word frequency; the average frequencies were 14.8 per million and 11.0 per million for the short and long beginning compounds, respectively (based on the frequency dictionary of Säkkinen, Haipus, Niemikorpi, & Sulkala, 1979). The average bigram frequency of the morphemic boundary was 30/10,000 for compounds with a short initial morpheme and 39/10,000 for compounds with a long first morpheme (based on the work of Mikkonen, 1972).

The target words were embedded in sentences; they appeared toward the sentence beginning, but not in the initial position. One word from each compound word type was paired with one word from the other compound word type, and they were embedded in matched (but not identical) sentence frames: (a) The matched sentence frames were identical up to the target word; (b) the words immediately following the target word (word N + 1) were either identical or of the same length; however, (c) the sentence frames differed considerably after word N + 1. (See Table 1 for an example of a sentence pair.) The target words almost always appeared in the nominative case (three of the nominatives were plural). If not in the nominative case, the target word appeared in

1 The optimal viewing location as defined by O'Regan and Lévy-Schoen (1987) is the center of the word and is thus not exactly the same as the preferred viewing location, defined by Rayner (1979) as the mean fixation location on a word, which is somewhat to the left of center. This discrepancy is likely to mean that the actual landing location is not the targeted location (see later discussion).
Table 1

Examples of Target Sentences and Their English Translations for Experiments 1 and 2

<table>
<thead>
<tr>
<th>Morpheme type</th>
<th>Target sentence</th>
<th>English translation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experiment 1</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Short initial morpheme</td>
<td>Siinä tapauksessa, että väri/aasteliko täytyy kokonaan muuttaa, nousevat kirjan painatuskustannukset aivan toiselle tasolle.</td>
<td>In case the color scale needs to be completely modified, the printing costs of the book will raise to a totally new level.</td>
</tr>
<tr>
<td>Long initial morpheme</td>
<td>Siinä tapauksessa, että moottori/öljy täytyy vaihtaa, suosittelem, että käyttäjissä vähän paremmatnytistä öljyjä.</td>
<td>In case the motor oil needs to be changed, I recommend the use of a little better quality oil.</td>
</tr>
<tr>
<td><strong>Experiment 2</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unique initial morpheme</td>
<td>Toimittaja tajusi yhtäkki, että kalvosin/nappi puuttui Ahtisaaren vasemmasta hihasta.</td>
<td>The journalist suddenly realized that a cufflink was missing from Ahtisaari's left sleeve.</td>
</tr>
<tr>
<td>Frequent initial morpheme</td>
<td>Toimittaja tajusi yhtäkki, että kansi/johtaja puuttui haastateltavien joukoksa.</td>
<td>The journalist suddenly realized that the mass leader was missing among the interviewees.</td>
</tr>
</tbody>
</table>

Note. For presentation purposes, target words appear here in bold with the morphemic boundary shown by a slash, which was not the case in the actual experiments.

either the partitive case (two occasions in each condition) or the genitive case (once in the long-initial-morpheme condition and twice in the short-initial-morpheme condition).

The critical sentences were presented in two blocks, and the order of blocks was counterbalanced across participants. Each word pair always appeared in separate blocks. Thus, each participant saw all the critical compound words. Within each block, the order of sentences was randomized. There were 40 filler sentences among the critical sentences.

Procedure. The eyetracker was first calibrated with a 9-point calibration grid that extended over the entire screen area. Ten practice sentences were presented before the actual experiment. Study participants were instructed to read each sentence for comprehension. They were told that they would occasionally be asked to paraphrase the sentence they had just finished reading. Before the presentation of each sentence, participants were required to gaze at a fixation point in the center of the screen. In case of a calibration drift, the calibration was automatically corrected. The experimental session took a maximum of 30 min.

Results and Discussion

**Fixation locations.** The question of central interest in Experiment 1 was whether the locations of the initial fixations on the target words were affected by the length of the initial morpheme. The relevant data are presented in Table 2. In the main analysis, all fixations were included. In a subsidiary analysis, all trials on which any fixation duration was less than 50 ms or greater than 400 ms were excluded from the computations (the values from the subsidiary analyses are in parentheses in Table 2). Because the patterns of data were virtually identical for the two analyses, only the main analysis is reported below. As can be seen from Table 2, the length of the first morpheme had virtually no effect on the initial landing position on the word (i.e., the location of the first fixation on the word), but it had a small effect (about half a character) on the location of the second landing position. The latter effect, though small, was highly reliable, as indicated both by a significant Fixation Number × Morpheme Length interaction (indexing the length of the saccade from Fixation 1 to Fixation 2), \( F_1(1, 24) = 15.05, p < .001, \text{MSE} = 13.77, F_2(1, 50) = 24.23, p < .001, \text{MSE} = 17.34, \) and by a simple effects test of the effect of morpheme length on the second-fixation location, \( F_1(1, 24) = 13.43, p < .002, \text{MSE} = 24.77, F_2(1, 50) = 16.91, p < .001, \text{MSE} = 39.49. \)

The above analyses of the location of the second fixations, however, included both forward and regressive saccades on the word. In order to discover whether the difference between the conditions could possibly be due to differential

<table>
<thead>
<tr>
<th>Eye movement measure</th>
<th>Short initial morpheme</th>
<th>Long initial morpheme</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location of fixation (in character spaces from beginning of word)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>First fixation*</td>
<td>4.65 (4.61)</td>
<td>4.59 (4.58)</td>
</tr>
<tr>
<td>Second fixation*</td>
<td>8.19 (8.15)</td>
<td>8.66 (8.63)</td>
</tr>
<tr>
<td>Second fixation, forward saccades only</td>
<td>8.79</td>
<td>9.04</td>
</tr>
<tr>
<td>Percentage of regressive saccades from Fixation 1</td>
<td>8.0</td>
<td>3.9</td>
</tr>
<tr>
<td>Probability of a first fixation(^b)</td>
<td>98.9 (96.7)</td>
<td>99.2 (98.5)</td>
</tr>
<tr>
<td>Probability of a second fixation(^b)</td>
<td>74.1 (72.0)</td>
<td>77.2 (75.5)</td>
</tr>
<tr>
<td>Probability of a third fixation(^b)</td>
<td>26.4 (24.5)</td>
<td>29.8 (29.6)</td>
</tr>
<tr>
<td>Gaze duration (in ms)(^c)</td>
<td>413 (412)</td>
<td>423 (422)</td>
</tr>
<tr>
<td>First-fixation duration (in ms)(^c)</td>
<td>200 (195)</td>
<td>189 (186)</td>
</tr>
<tr>
<td>Second-fixation duration (in ms)(^c)</td>
<td>185 (183)</td>
<td>191 (186)</td>
</tr>
</tbody>
</table>

\(^a\)Values in parentheses are for analyses that excluded trials with fixation durations less than 50 ms and greater than 400 ms. \(^b\)Values in parentheses are the percentages of all trials that were recorded in these conditions; that is, they are the joint probabilities of (a) making a fixation on a word and (b) that each fixation duration on that word was between 50 ms and 400 ms.

Table 2

**Experiment 1: Various Reading Indexes as a Function of Condition**

numbers of regressive saccades in the two conditions, we reanalyzed the data and excluded those trials on which the saccade going from Fixation 1 to Fixation 2 was a regression. This cut the size of the effect in half (see Table 2), but the difference was still highly reliable: for the interaction between fixation number and morpheme length, $F(1, 24) = 18.39, p < .001, \text{MSE} = 3.74, F_1(1, 50) = 11.21, p < .002, \text{MSE} = 9.59$; for the simple effects test on Fixation 2, $F(1, 24) = 9.12, p < .01, \text{MSE} = 10.1, F_2(1, 50) = 4.62, p < .05, \text{MSE} = 28.56$. Consistent with the effect being smaller when regressions were excluded, there were about twice as many intraword regressions when the first morpheme was short as when it was long (see Table 2), $F(1, 24) = 10.93, p < .005, \text{MSE} = 5.14, F_2(1, 50) = 19.40, p < .001, \text{MSE} = 1.42$.

In summary, the length of the initial morpheme had no effect on where readers landed on the word initially, but it reliably influenced the location of the second fixation. Although the effect was small, saccade length effects are generally small. Moreover, because the mean intraword saccade length was about 4 characters, a mean difference of about half a character was not that small relative to the baseline. The finer analyses indicated that some of this effect was due to there being more regressive saccades when the initial morpheme was short, but there was still a significant effect on the size of forward saccades when regressive saccades were excluded.

The finding of a difference in the location of the second fixation for short and long initial morphemes does not necessarily mean that the observed difference in eye behavior is produced by morphemic analysis; some other confounding variable may have produced the effect. One alternative explanation is that some orthographic difference between the sets of words in the two morpheme length conditions was causing the difference. To assess whether this was plausible, we did some additional analyses on the second-fixation location data. One orthographic variable that has been pointed to as being confounded with morphemic (or syllabic) boundaries is a "bigram frequency trough" (Seidenberg & McClelland, 1989; but see Rapp, 1992). That is, infrequent letter combinations tend to occur at morphemic and syllabic boundaries. This bigram frequency "trough" may tend to attract attention and eye movements. As a consequence, one would predict that the second-fixation location would be further into the word for longer initial morphemes.

To test this hypothesis, we examined the frequencies of the bigrams in the region spanning the morphemic boundary in Experiment 1. We reasoned that the more frequent the morpheme-spanning bigram (i.e., the bigram containing the last letter of the initial morpheme and the first letter of the second morpheme) is relative to the frequency of its bigram neighbors, the shallower the "trough," and hence the weaker the effect would be. In other words, as the "trough" disappears, the expected second-fixation location for both conditions should regress to the average over both conditions. Thus, as the trough disappears, either (a) the mean fixation location should increase for the short initial morpheme words, (b) the mean fixation location should decrease for the long initial morpheme words, or (c) both of these should occur. The measure of "troughness," or relative bigram frequency, that we chose (similar to that of Rapp, 1992) was the difference between the frequency of the morpheme-spanning bigram and the minimum frequency of its two bigram neighbors. The correlations over items, however, between this troughness measure and the second-fixation locations were small and contrary to what was predicted. That is, the correlation between troughness and the second-fixation location was positive (.123) for the words with short initial morphemes and negative (-.055) for the words with long initial morphemes.

A second possibility for confounding is that the length of the initial morpheme was confounded with the length of the initial syllable. This is not as much of a problem as it would be in English, however, because most morphemes in Finnish are multisyllabic. Even so, we could not completely control initial syllable length and there was a small average difference in initial syllable length between the two morpheme conditions (about half a letter). However, when the difference in initial syllable length was used as a predictor in a regression analysis with the difference in second-fixation location as the dependent variable, the intercept (i.e., the estimated value of the difference in fixation location when initial syllable length is equated) was 0.47 characters, $r(49) = 3.802, p < .001$, and the difference in syllable length had virtually no effect as a predictor ($r = .001$). A third possibility for confounding was that the frequency of the

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2 A. W. Inhoff (personal communication, 1997) suggested that there might be an effect of the length of the first morpheme on the initial fixation when only those trials in which the launch site (i.e., the location of the fixation prior to landing on the target word) is close to the target word are counted. That is, the morpheme length may be processed in parafoveal vision only when the eye is relatively close to the target word. Consequently, we conducted follow-up analyses in which the initial launch site had to be within either 3 or 4 characters from the beginning of the target word. There was a suggestion of an effect (the first fixation location was about one sixth of a character further into the word when the initial morpheme was long); however, the effect was not even close to significant in either analysis ($p > .20$).

3 We also examined the location of the third fixation. Even though there were substantially fewer third fixations (see Table 2), there was over a character's difference in the location of the third fixation between the two morpheme length conditions, $F(1, 22) = 30.93, p < .001, \text{MSE} = 0.863, F_1(1, 50) = 6.086, p < .025, \text{MSE} = 1.421$.

4 To use an English example, if the word was cowboy, the measure would be the lesser frequency of ow and bo minus the frequency of wb.

5 Virtually the same pattern of results was obtained with two other measures of "troughness": (a) the frequency of the morpheme-spanning bigram and (b) the average of the frequencies of the two spanning bigrams minus the frequency of the morpheme-spanning bigram. Moreover, it is doubtful that these small correlations are due to a restricted range effect, because the frequencies of the morpheme-spanning bigram ranged from about 100 per million words to over 20,000 per million words for each condition (with standard deviations above 3,000 per million words in each condition). (There were similar ranges in the other measures of "troughness.")
initial morpheme was not equated for the two conditions, although the difference was not particularly large (697 per million vs. 225 per million). To evaluate the possible influence of uncontrolled effects of first-morpheme frequency, we included in the regression analysis the difference in the log of the first-morpheme frequency. (In this and subsequent treatments of morpheme frequency, all allomorphs of the morpheme were counted, even though the spelling might have changed slightly.) There was a small influence of the initial morpheme frequency on the location of the second fixation, which suggested that higher frequencies tend to lead to fixations further into the word (consistent with the results of Experiment 2); however, the regression effect was not significant \((p > .20)\). Moreover, the intercept of the regression equation was still about half a character (using both the difference in syllable length and the difference in log frequency as predictors) and was significantly different from zero, \(t(48) = 3.82, p < .001\).

In summary, the data indicate that the length of the initial morpheme influenced the location of the second fixation on a word even when the most plausible confounding variables were controlled for. Another confound is that morpheme length (in number of letters) is highly correlated with the number of phonemes and the number of syllables in the initial morpheme; such a confound is inevitable in a language with a shallow orthography like Finnish. However, we think it is much more likely that the visual width of the morpheme would control the size of the saccade rather than the "phonological size" of the morpheme.

Other measures. The above analyses indicate that the length of the initial morpheme affects the location of the initial refixation on the target words. We were also interested in determining whether the length of the initial morpheme had any other effects on processing. First, we examined the gaze duration on the target word: the sum of all fixation durations before the reader left the target word. (The mean gaze duration is conditional on there being at least one fixation on the word.) There was only a small difference between the conditions (413 ms for short initial morphemes vs. 423 ms for long initial morphemes), which was not reliable, \(F_1(1, 24) = 1.76, p > .10, MSE = 657, F_2 < 1\). However, there was a difference in the pattern of individual fixation durations: Words with longer initial morphemes had shorter first fixations but longer second fixations, as indicated by a significant Fixation Number \(\times\) Morpheme Length interaction, \(F_1(1, 24) = 12.01, p < .005, MSE = 160, F_2(1, 50) = 18.50, p < .001, MSE = 213\) (see Table 2). When analyzed separately, the 11-ms difference between the first-fixation durations was reliable, \(F_1(1, 24) = 15.18, p < .001, MSE = 103, F_2(1, 50) = 18.40, p < .001, MSE = 172\), but the 6-ms difference between the second-fixation durations was not, \(F_1(1, 24) = 2.859, p = .10, MSE = 177, F_2(1, 50) = 3.240, p = .07, MSE = 328\).

Another analysis of interest was whether the length of the first morpheme had any effect on the probability of a second fixation. (As shown in Table 2, the target words were virtually always fixated at least once.) In fact, there was a small effect, with words with shorter initial morphemes receiving second fixations about 3% less often. However, this effect was only marginally reliable, \(F_1(1, 24) = 3.202, p = .08, MSE = 0.0043, F_2(1, 50) = 4.79, p < .05, MSE = 0.0055\), for the simple effects test on the probability of a second fixation. Moreover, 7 participants contributed most of the trials in which the target word was fixated only once, and when these participants were excluded from the analyses, (a) there was virtually no effect of morpheme length on the probability of a second fixation and (b) the effects of morpheme length on second-fixation location that were reported in the prior section were unchanged and were all highly reliable over the 18 remaining participants. Thus, shorter initial first morphemes appeared to allow some participants to skip a second fixation; however, the saccade length effects reported above were not an artifact of this differential fixation probability. We also examined the probability of making a third fixation. Here, there was a reliable difference, with words with short initial morphemes receiving significantly fewer third fixations, \(F_1(1, 25) = 7.188, p < .025, MSE = 0.0026, F_2(1, 51) = 5.845, p < .025, MSE = 0.0073\). This difference is likely to account for the small difference in gaze duration between the conditions.

Analyzes conditional on initial fixation location. As indicated in the introduction, according to visual guidance models of eye movement control, low-level visual factors are important in controlling eye movements. In particular, these models place a lot of importance on the effect of the location of the initial fixation on the subsequent behavior of the eye on a word. Accordingly, we divided the first-fixation locations into three regions: those that landed on Letters 1–4 of the target word (i.e., on the first morpheme of almost all words), those that landed on Letters 5–8 of the target word (i.e., on the first morpheme of most long-morpheme words and on the second morpheme of most short-morpheme words), and those that landed on locations after Letter 8 (i.e., on the second morpheme of almost all words). Because there were, on average, fewer than four initial fixations per participant that landed to the right of Letter 8 (resulting in many missing data cells for many participants in this condition), our analyses focus on the first two regions (see Table 3).

The location of the first fixation appeared to have a small effect on the degree to which the length of the first morpheme influenced the location of the second fixation: The difference was only 0.27 characters when the initial fixation was on the first four letters, but it was 0.64 characters when the initial fixation was on the second four letters (see Table 3). The former effect was only marginally significant, \(F_1(1, 24) = 2.837, p = .10, MSE = 0.327, F_2(1, 50) = 4.466, p < .05, MSE = 0.856\), whereas the latter effect was significant, \(F_1(1, 24) = 8.241, p < .01, MSE = 0.628, F_2(1, 50) = 7.394, p < .01, MSE = 1.074\). The interaction of morpheme length with fixation number (reflecting the size of the initial intraword saccade on the target word), however, was significant both when the initial fixation was on Letters 1–4 and when it was on Letters 5–8: \(F_1(1, 24) = 4.808, p < .05, MSE = 0.110, F_2(1, 50) = 4.219, p < .05, MSE = 0.372\); \(F_1(1, 24) = 9.937, p < .01, MSE = 0.285, F_2(1, 50) = 6.466, p < .025, MSE = 0.602\), respectively.

In addition, as would be expected, the location of the
Table 3

Experiment 1: Various Reading Indexes as a Function of Morpheme Length and Whether the Initial Fixation Landed on Letters 1–4 or Letters 5–8 of the Target Word

<table>
<thead>
<tr>
<th>Eye movement measure</th>
<th>Fixation 1 on Letters 1–4</th>
<th>Fixation 1 on Letters 5–8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Short 1st morpheme</td>
<td>Long 1st morpheme</td>
</tr>
<tr>
<td>Number of first fixations (N = 51)</td>
<td>19.0</td>
<td>27.1</td>
</tr>
<tr>
<td>Mean location (in character spaces from beginning of word) of first fixation</td>
<td>17.6</td>
<td>18.1</td>
</tr>
<tr>
<td>First-fixation duration (in ms)</td>
<td>7.21</td>
<td>9.07</td>
</tr>
<tr>
<td>Second-fixation duration (in ms)</td>
<td>174</td>
<td>212</td>
</tr>
<tr>
<td>Gaze duration (in ms)</td>
<td>479</td>
<td>381</td>
</tr>
<tr>
<td>Intraword regressions from Fixation 1 to Fixation 2</td>
<td>0.5</td>
<td>0.3</td>
</tr>
</tbody>
</table>

initial fixation affected the number of intraword regressions from Fixation 1 to Fixation 2 (see Table 3). When the initial fixation was on the first four letters, there were very few intraword regressions, and the rate was only slightly influenced by the morpheme length (p > .20). In contrast, when the initial landing position was on the second four letters, the same pattern was observed as in the overall data, with there being more regressions back to an earlier position on the word when the initial morpheme was short, $F_1(1, 24) = 12.7, p < .002, MSE = 2.13, F_2(1, 50) = 13.50, p < .001, MSE = 0.890$.

Perhaps the most interesting aspect of this analysis was how the location of the initial fixation modulated the pattern of fixation durations. First consider the fixation durations when the initial fixation was on the first four letters of the target word. The first fixation was 18 ms shorter than the second, $F_1(1, 24) = 11.53, p < .005, MSE = 708, F_2(1, 50) = 50.78, p < .001, MSE = 506$, but what is more interesting, as can be seen in Table 3, is that there was virtually no effect of morpheme length on either fixation ($F_s < 1$). In contrast, when the initial fixation fell on the second four letters of the target word, the first fixation was 18 ms longer than the second, $F_1(1, 24) = 6.316, p < .025, MSE = 1,346, F_2(1, 50) = 15.46, p < .001, MSE = 633$, and the same pattern was obtained as in the overall data: When the first morpheme was long, the first-fixation duration was shorter but the second-fixation duration was longer. The interaction between fixation number and morpheme length was significant, $F_1(1, 24) = 22.82, p < .001, MSE = 222, F_2(1, 50) = 26.82, p < .001, MSE = 404$, as were the effects of morpheme length on fixations 1 and 2 individually: $F_1(1, 24) = 29.32, p < .001, MSE = 119, F_2(1, 50) = 27.64, p < .001, MSE = 330; F_1(1, 24) = 5.658, p < .05, MSE = 308, F_2(1, 50) = 4.130, p < .05, MSE = 649$, respectively. There was also a large effect of initial landing position on the gaze duration on the word, with gaze durations being 94 ms longer when the initial fixation was on the first four letters, $F_1(1, 24) = 66.40, p < .001, MSE = 3.344, F_2(1, 50) = 98.30, p < .001, MSE = 4.843$; however, there was no main effect of the length of the first morpheme nor any interaction between that and initial landing position ($F_s < 1$).

In summary, the location of the initial landing position modulated some of the effects we were examining. Most notably, the location of the initial landing position influenced the pattern of fixation durations. When the initial fixation was on the first four letters, the fixation was short and unaffected by the length of the morpheme. In contrast, when the initial fixation was on the second four letters (i.e., somewhere near the middle of the word), the first fixation was relatively long and was affected by the length of the first morpheme. That is, it appears that the lexical variable of first-morpheme length was not controlling the decision of when the eye should move when the initial fixation was near the beginning of the word. This is consistent with data reported for the reading of isolated words by O’Regan, Lévy-Schoen, Pynte, and Bruagallère (1984) and O’Regan and Lévy-Schoen (1987), who found that when the initial fixation was located in a “bad” location (i.e., far from the middle of the word), the duration was short, and a relatively automatic corrective eye movement was made to a more advantageous viewing location (presumably nearer the middle of the word). This finding has also been extended to normal reading (McConkie, Kerr, Reddix, Zola, & Jacobs, 1989; Rayner et al., 1996; Vitu et al., 1990). However, in the reading studies, the average durations of fixations in bad regions can be affected by word frequency, at least for short (5- and 7-letter) words (see Rayner et al., 1996).

Even if the initial fixation duration is unaffected by initial morpheme length when the initial fixation is on the first four letters, it does not necessarily mean that no meaningful lexical processing is done during the first fixation—it only means that the decision to move the eye is not controlled by morpheme length when the eye is in a bad location. If no processing is being done during these first fixations, one would expect gaze durations to be almost 200 ms longer (i.e., the length of the initial fixation) when the initial fixation is in a bad location. The fact that there was an almost 100-ms lengthening of gaze duration in this condition, however, suggests that less processing was done during these first fixations than during first fixations that were located closer to the middle of the word. In addition, there was modulation of the length of the initial saccade even when the initial fixation was on Letters 1–4, which indicates that some meaningful processing of the word was taking place. Unfortunately, it is hard to draw firm causal conclu-
sions from these analyses because they are correlational. That is, participants may get less preview information about a word on some trials than on others. Less preview information would lead to longer gaze durations and might also lead to participants’ fixating nearer the beginning of the word.6

In contrast, when the initial fixation is near the middle of the word, morphemic variables appear to play a significant role in both the initial fixation duration and where the eye goes next. Moreover, there is a relatively simple explanation for the observed influence of initial morpheme length on the pattern of fixation durations when the initial fixation location is on Letters 5–8. Letters 5–8 would be a bad location for picking up information about the first morpheme when it is short (as the first fixation would be on the second morpheme), whereas they would be a better location for picking up information about the first morpheme when it is long (as the first fixation would then be on the first morpheme). The pattern of first-fixation durations would thus make sense if one assumes that they are influenced by the ease of encoding the first morpheme. In contrast, if the initial fixation location is on Letters 5–8, the reader would be more likely to extract information about the second morpheme on the first fixation when the first morpheme is short, which could speed subsequent fixations.

Summary. The data of Experiment 1 indicated that the length of the initial morpheme of a two-morpheme compound word influenced the pattern of eye movements on the word. Of greatest interest is that it influenced the location of the second fixation but not the location of the first fixation. The length of the initial morpheme produced only a small and unreliable difference in the gaze duration on the word. However, the length of the first morpheme modulated the pattern of fixation durations, with short initial morphemes leading to somewhat longer first fixations and somewhat shorter second fixations. The latter pattern appears to be due to those initial fixations that were on Letters 5–8 and hence in a poor place for processing the initial morpheme but in a better place for processing the second morpheme.

Experiment 2

In Experiment 1 we demonstrated that the length of the initial morpheme in a two-morpheme compound word affected the pattern of fixation locations and durations on the word. As indicated earlier, we designed Experiment 2 to examine whether the frequency of the initial morpheme would also influence the pattern of fixation locations and durations. However, in Experiment 2, our primary focus was on whether the initial fixation durations on the word would be influenced by the frequency of the initial morpheme when the familiarity of the compound word was held constant.

Method

Participants. Twenty-four students from the introductory psychology course, all of whom were native Finnish speakers, participated in the experiment as a part of the course requirement.

Apparatus. The apparatus was the same as that used in Experiment 1.

Materials and design. Two sets of two-noun compound words (12–14 characters long) were used as target items: One set had a frequent beginning morpheme, and the other set had a unique beginning morpheme. By definition, a first morpheme was frequent when there were many compound words starting with the same initial morpheme in the dictionary of modern Finnish (in our sample of words, the minimum was 45); in contrast, for our unique-beginning compound words, there were only one or two compound words beginning with the initial morpheme.7

There were 28 words of each kind. The average length of target words was matched across the two word types; it was 12.9 characters for frequent-beginning words and 13.0 characters for unique-beginning words. The length (in characters) of the initial morpheme was 6.0 for frequent-beginning words and 7.6 for unique-beginning words; the length of the second morpheme was 7.0 for frequent-beginning words and 5.4 for unique-beginning words. Because many of the unique-beginning compound words did not have a frequency count in the Saukkonen et al. (1979) corpus (which is relatively small), we matched the words on the basis of familiarity ratings instead of frequency accounts. A group of 18 students who did not take part in the actual experiment rated 41 unique-beginning and 47 frequent-beginning words for their familiarity using a 7-point scale (1 = highly uncommon, 7 = highly common). The average familiarity rating for the 28 frequent-beginning words selected for the experiment was 4.49, and that for the unique-beginning words was 4.47.

The frequency of the initial morpheme as a separate word differed notably between the two word types. All the first morphemes of the unique-beginning words were of low frequency (the average was 9 per million), whereas those of the frequent-beginning words were all frequent (the average was 551 per million). The average bigram frequency (Laine & Virtanen, 1996) of the morpheme boundary was 2,466 per million for the frequent-beginning words and 5,903 per million for the unique-beginning words. The average trigram frequency of the word beginning was 1,423 per million for the frequent-beginning words and 671 per million for the unique-beginning words (our trigram frequency measure gives the frequency with which a word begins with a particular trigram).

As in Experiment 1, the target words were embedded near the beginning of sentences, but not in the initial word position. Two words, one from each compound word type, were paired, and the

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6 In fact, regression analyses showed that the mean “launch site” for fixating the target word (i.e., the location of the fixation prior to fixating the target word) differed for different sentence frames. This indicates that uncontrolled factors other than the target word are likely to affect both the initial landing position on a word and measures such as the first-fixation duration on the word.

7 Other types of morpheme frequency measures exist. For example, Baayen (1994) defined the productivity of Dutch affixes (e.g., -heid, corresponding to -ness in English) on the basis of the frequency with which it appeared in novel morphologically complex words in a newspaper corpus. Taft (1979), in contrast, distinguished between base and surface frequency in his study of English inflected words. However, the measure used by Taft and Zhu (1995) comes closest to our measure. They compared four types of Chinese characters: unique first position (a morpheme only occurs in one word in the first position), unique second position (a morpheme only occurs in one word in the second position), nonunique first position (the morpheme occurs in several words but only as the first character), and nonunique second position (the morpheme occurs in several words but only as the second character).
sentence frames for each word pair were identical up through the word immediately following the target word (Word $N + 1$); however, the sentences differed markedly after Word $N + 1$. (See Table 1 for an example of a sentence pair.) The target words almost always appeared in the nominative singular case; in the frequent-beginning condition the target word was once in the genitive and twice in the partitive case, and in the unique-beginning condition it was once in the genitive and once in the partitive case. As in Experiment 1, there were two blocks of sentences in which the sentence frames containing each word pair appeared in separate blocks. The order of the blocks was counterbalanced across subjects. Thus, each participant saw all the critical target words. Within each block, the order of target sentences was randomized. There were 40 filler sentences among the critical sentences.

Procedure. The procedure was identical to that of Experiment 1.

Results and Discussion

The focus in Experiment 2 was on whether the frequency of the first morpheme in the word had a significant effect on eye movement behavior and, in particular, on the total processing time on the word and on the durations of the initial fixations. The frequency of the first morpheme could plausibly have an effect on several variables: duration of fixations on the target word, the number of fixations on the target word, and the location of the fixations on the target word. We conducted two analyses that are presented in Table 4. In the primary analysis, all fixations were included. In the secondary analysis (the results of which are presented in parentheses in the table), individual fixations that were less than 50 ms and greater than 400 ms were excluded. Because there were few such fixations, and because the results are so similar from the two analyses, we discuss only the primary analysis below.

Duration of fixations. The most global measure of the time to access the lexical entry of a word is gaze duration. As can be seen in Table 4, the frequency of the initial morpheme had a substantial effect on gaze durations, with the words with unique morphemes being fixated 87 ms longer, $F_1(1, 23) = 38.83, p < .001, MSE = 2,357, F_2(1, 27) = 15.68, p < .001, MSE = 6,676$. The difference in gaze durations, however, merely indicates that the frequency of the initial morpheme had some effect on accessing the word. Of greater interest was how early the frequency of the morpheme had an effect on the processing of the target word. As can be seen in Table 4, the morpheme affected early stages of processing on the target word because the first-fixation durations were 9 ms longer when the word had a unique initial morpheme, $F_1(1, 23) = 7.167, p < .02, MSE = 143, F_2(1, 27) = 12.73, p < .002, MSE = 94$. Second-fixation durations were also 9 ms longer when the target word had a unique initial morpheme; however, the effect was only marginally reliable over items, $F_1(1, 23) = 4.740, p < .05, MSE = 181, F_2(1, 27) = 3.784, p = .06, MSE = 204$. There was only a 2-ms difference in the duration of third fixations (both $F$s < 1); there were also relatively few third fixations (see below).

Probability of fixations. As can be seen in Table 4, readers virtually always fixated the target words at least once. They also fixated the target word at least twice about 85% of the time, and there was virtually no difference between the two conditions in the probability of a second fixation. However, there was an appreciable difference in the probability of a third fixation: The words with unique initial morphemes were fixated a third time about 45% of the time, whereas the words with common initial morphemes were fixated a third time only about 30% of the time, $F_1(1, 23) = 25.86, p < .001, MSE = 8.21, F_2(1, 27) = 24.07, p < .001, MSE = 7.57$. Thus, the longer gaze duration time on the words with unique initial morphemes is largely accounted for by longer initial fixations, longer second fixations, and a greater probability of having to make more fixations on the target word.

Fixation locations. It is also of interest to see where initial fixations were directed and whether the type of initial morpheme had any effect on that. First, note in Table 4 that there was a small but reliable difference between the two conditions in the location of the first fixation: The first fixation was about 0.2 characters further into the word when the initial morpheme was a common one, $F_1(1, 23) = 4.234, p < .05, MSE = 0.102, F_2(1, 27) = 6.251, p < .02, MSE = 0.087$. The difference was more pronounced on the second fixation, with a little over a 0.5-character difference, $F_1(1, 23) = 14.75, p < .002, MSE = 0.255, F_2(1, 27) = 20.40, p < .001, MSE = 0.190$. There were a few more regressions from the first to the second fixation in the unique-morpheme condition (see Table 4), but the difference was not close to reliable (both $p$s > .10).

---

Table 4

<table>
<thead>
<tr>
<th>Eye movement measure</th>
<th>Unique initial morpheme</th>
<th>Common initial morpheme</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaze duration (in ms)*</td>
<td>522 (507)</td>
<td>435 (425)</td>
</tr>
<tr>
<td>First-fixation duration (in ms)*</td>
<td>197 (192)</td>
<td>188 (186)</td>
</tr>
<tr>
<td>Second-fixation duration (in ms)*</td>
<td>197 (191)</td>
<td>188 (185)</td>
</tr>
<tr>
<td>Probability of a first fixation*</td>
<td>99.7 (93.3)</td>
<td>99.9 (95.1)</td>
</tr>
<tr>
<td>Probability of a second fixation*</td>
<td>87.1 (80.1)</td>
<td>85.3 (79.2)</td>
</tr>
<tr>
<td>Probability of a third fixation*</td>
<td>44.8 (44.1)</td>
<td>29.8 (29.1)</td>
</tr>
<tr>
<td>Location of fixation (in character spaces from beginning of word)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>First fixation*</td>
<td>4.63 (4.11)</td>
<td>4.84 (4.61)</td>
</tr>
<tr>
<td>Second fixation*</td>
<td>8.71 (8.29)</td>
<td>9.33 (8.78)</td>
</tr>
<tr>
<td>Percentage of regressive saccades from Fixation 1</td>
<td>8.3</td>
<td>6.5</td>
</tr>
</tbody>
</table>

*Values in parentheses are for analyses that excluded trials with fixation durations less than 50 ms and greater than 400 ms.  
Values in parentheses are the percentages of all trials that were recorded in these conditions; that is, they are the joint probabilities of (a) making a fixation on a word and (b) that each fixation duration on that word was between 50 ms and 400 ms.

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8 Because the word after the target word was the same in both conditions in Experiment 2, we also examined spillover, or the duration of the initial forward fixation after leaving the target word, to see if there were any delayed effects of first-morpheme frequency. However, the spillover duration was the same (201 ms) in both conditions.
Interim summary. The frequency of the initial morpheme of a compound word had a large effect on how it was processed. Even though the compound words were equated on familiarity, compound words with unique initial morphemes took almost 100 ms longer to process. Moreover, the frequency of the initial morpheme affected very early processing of the word: First-fixation durations were longer and the initial fixation was slightly closer to the beginning of the word when the first morpheme was unique. In addition, subsequent fixation probabilities were higher and subsequent fixation durations were longer for compound words with unique beginnings.

Regression analyses. The data indicate that the frequency of the initial morpheme had a significant effect on processing of the target word. As in Experiment 1, however, there may have been confounding variables that were causing the effects instead of the frequency of the initial morpheme. For the fixation-duration measures, a confounded measure that could most plausibly influence fixation durations is the orthographic regularity of the morpheme (i.e., more common morphemes are composed of more common letter sequences). To assess this possibility, we performed regression analyses on the differences in fixation duration (for various fixation measures) using the difference in average bigram frequency of the initial morpheme as the predictor variable. This predictor had no significant effect on either gaze duration, first-fixation duration, or second-fixation duration (rs < 1), and the intercept values for the difference in gaze duration, first-fixation duration, and second-fixation duration were 83 ms, 9 ms, and 7 ms, respectively, which were quite similar to the values in the original analysis: t(26) = 3.661, p < .001; t(26) = 3.462, p < .002; t(26) = 1.838, p = .11, respectively. This variable also had virtually no effect on either fixation locations or the number of first, second, third fixations (rs < 1).

A second possible confounding may explain why the first-fixation location was influenced by the frequency of the initial morpheme. Less frequent morphemes are more likely to have irregular letter clusters at the beginning of the word, and an irregular letter cluster in the beginning of a word may attract a fixation closer to the word’s beginning (Beauvillain et al., 1996; Hyöna, 1995). We conducted two regression analyses to assess this possibility. Both used the difference in the initial fixation location between the frequent-initial-morpheme and unique-initial-morpheme conditions (between a matched pair of items) as the dependent variable; one used the difference between the word-initial trigram frequencies as the predictor, and the other used the ratio between the word-initial trigram frequencies as the predictor. In both analyses, the regression was in the predicted direction—a larger trigram frequency difference or ratio led to a larger difference in fixation location—but neither the difference in frequency nor the ratio in frequency was a significant predictor (rs < 1). Moreover, in both analyses, the intercept of the regression line (i.e., the best estimate of the morpheme frequency effect when trigram frequency effects are partialed out) was approximately the same as the difference between the two conditions reported in Table 4. For the analysis using the difference in trigram frequency as the predictor, the intercept was not significantly different from zero (p = .11), but for the analysis using the ratio as the predictor, it was (p = .017).

Analysis on initial fixation location. As in Experiment 1, we were interested in examining how the initial landing position on the word affected the pattern of data. To make the analyses comparable to those of Experiment 1, we focused on two initial landing regions: Letters 1–4 of the target word and Letters 5–8 of the target word. These accounted for virtually all of the first fixations (see Table 5). Many of the features of this analysis mirrored those of Experiment 1. First, consider the pattern of fixation durations. When the initial fixation was near the beginning of the word, the initial fixation was shorter than the second fixation. Moreover, there was no reliable effect of morphemic frequency on fixation duration: The 7-ms and 9-ms differences in the first- and second-fixation durations, respectively, in the subject analyses were not significant (ps > .10) nor were the respective 3-ms and 5-ms differences in the item analyses (ps > .20). When the initial fixation was in the middle of the word, the pattern was different, with significantly longer first fixations than second fixations and with first fixations on words with frequent initial morphemes being 13 ms shorter (19 ms shorter in the item analysis) than first fixations on words with unique morphemes, $F_1(1, 23) = 8.907, p < .01, MSE = 232, F_2(1, 27) = 13.50, p < .002, MSE = 352$.

As in Experiment 1, the location of the initial landing position had some influence on how much the initial morpheme affected the location of the second fixation. When the initial landing position was on the first four letters, there

| Table 5 | Experiment 2: Various Reading Indexes as a Function of Morpheme Length and Whether the Initial Fixation Landed on Letters 1–4 or Letters 5–8 of the Target Word |
|---------|-------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Eye movement measure | Fixation 1 on Letters 1–4 | Fixation 1 on Letters 5–8 |
| Number of first fixations (N = 28) | Unique 1st morpheme | Common 1st morpheme | Unique 1st morpheme | Common 1st morpheme |
| Number of second fixations (N = 28) | 12.8 | 10.9 | 14.7 | 16.3 |
| Mean location of second fixation (in character spaces from beginning of word) | 7.83 | 8.03 | 8.80 | 9.46 |
| First fixation duration (in ms) | 183 | 176 | 208 | 195 |
| Second fixation duration (in ms) | 204 | 195 | 187 | 185 |
| Gaze duration (in ms) | 541 | 466 | 487 | 399 |
was only a 0.20-character effect of the initial morpheme frequency ($F_8 < 1$), whereas when the initial landing position was on the second four letters, there was a 0.66-character effect, $F_1(1, 23) = 11.94, p < .005, \text{MSE} = 0.436$, $F_2(1, 27) = 16.95, p < .001, \text{MSE} = 0.421$. The initial landing position also influenced whether the initial morpheme had an effect on whether the word was refixated. As can be seen in Table 5, if the initial landing position was near the beginning of the word, the word was almost always refixated. In contrast, if the initial landing position was on the second four letters, readers were less likely to refixate the word, but the conditional probability of a first refixation did not seem to be influenced by the initial morpheme. However, when the initial fixation was on the second four letters of the word, readers made 1.6 fewer third fixations on the word when the initial morpheme was frequent, $F_1(1, 23) = 10.55, p < .005, \text{MSE} = 3.16, F_2(1, 27) = 8.635, p < .01, \text{MSE} = 3.65$, in spite of the fact that there were more initial fixations in the region for this condition.

As in Experiment 1, there was a large effect of initial fixation location on gaze duration, with gaze durations being about 60 ms shorter when the initial fixation was on the second four letters than when it was on the first four letters, $F_1(1, 23) = 26.94, p < .001, \text{MSE} = 3.247, F_2(1, 27) = 17.06, p < .001, \text{MSE} = 4.064$. However, the initial landing position did not significantly modulate the morphemic effect: There was a 75-ms difference when the initial landing position was at the beginning of the word and an 88-ms difference when the initial landing position was in the middle of the word ($F_8 < 1$ for the interaction). As in Experiment 1, the cost in gaze duration for landing at the beginning of the word (about 60 ms) was much less than the initial fixation duration, indicating that participants were processing useful information during this fixation.

Analysis of Block Effects

Both experiments used a blocked design in which all the target words were used in a matched design in which one target word in each pair appeared in Block 1 and the other target word in the pair appeared in Block 2. This design was used instead of the usual counterbalanced design (in which only one of the two target words would be seen by a given participant) in order to increase the power of the design. The weakness of the design we used was that there might be "block effects." More specifically, there is a concern that the effects we observed occurred only with the second presentation of the sentence-initial frame and thus might be unlikely to generalize to typical reading situations. As a result, we reanalyzed the data in each experiment using block as a factor.

In fact, there were almost no block by treatment effects. For all the effects reported in Experiments 1 and 2, the only block by treatment effect that was significant over both subjects and items was that for the location of the second fixation in Experiment 2, $F_1(1, 23) = 42.55, p < .001, F_2(1, 27) = 4.569, p < .05$, and the direction of the interaction was such that the difference between conditions virtually disappeared in Block 2. All the other block by treatment effects had $F$s less than 1 in the item analyses, but two other effects had significant block by treatment effects in the subject analysis. First, there was a significant block by treatment effect in Experiment 1 on first-fixation duration, $F_1(1, 23) = 5.397, p < .05$, with the effect increasing in Block 2; however, the treatment effect was still significant when only Block 1 was considered, $F_1(1, 23) = 4.301, p < .05$. Second, there was a significant block by treatment effect on the number of second fixations in Experiment 2, $F_1(1, 23) = 4.246, p < .05$, with the effect decreasing in Block 2. There were also significant main effects of block on gaze durations and number of second and third fixations in both experiments, with gaze durations and the number of fixations decreasing in the second block. However, it is unclear whether these main effects were due to participants’ seeing the frame a second time or were just general practice effects due to participants’ being more comfortable reading while using the experimental apparatus during the second half of the experiment.

General Discussion

In the introduction we raised two major issues: (a) whether morphemic analysis affects where the eyes are guided when processing a word and (b) whether morphemic analysis affects the durations of fixations on a word. The current experiments indicate a positive answer to both questions. First let us consider the where question. In Experiment 1, the length of the initial morpheme appeared to have no influence on the location of the initial landing position; however, it did have an influence on the location of both the first and second refixations on the word. When the initial morpheme was about eight letters long, the second fixation was, on average, about a half a character further into the word than when the initial morpheme was four letters long.

What Guides Where the Eyes Move in a Word?

These data indicate that a purely visual guidance model cannot account for refixations on a word; that is, something is guiding the refixations on the target compound words other than purely visuomotor strategies influenced merely by word length and the distance of a fixation from the center of a word. However, the initial fixation data from Experiment 1 are consistent with a purely visual guidance mechanism. Note that the initial fixation location is reasonably close to the preferred viewing location. That is, the mean location of the initial fixation was about 4.6 characters into the word (i.e., on the 5th character), or a bit over 2 characters from the middle of the word (on average, at Letter 7.0). A model for the location of the initial landing position on a word has been proposed by McConkie et al. (1988), and it

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9 For comparison purposes, the median preferred viewing location for 10-letter English words was near the end of the fourth letter (Rayner, 1979), which is a bit over 1.0 letter to the left of the middle of the word (Letter 6.0). These data are in agreement with those of Dunn-Rankin (1978).
accounts for initial landing positions with a purely visual eye-guidance strategy. McConkie et al. presented data indicating that the landing position effects can be accounted for by assuming that the reader is targeting the middle of a word for the location of the initial fixation, but that (a) there is a bias to undershoot, as in virtually all motor movements (Meyer, Kornblum, Abrams, Wright, & Smith, 1988); (b) there is random variation; and (c) both bias and random variation increase, the further the “launch site” of the saccade is from the beginning of the target word.

As indicated above, however, the pattern of refixations appear to be at least partly guided by processing of the morphemic components of the word. In the introduction, we outlined one simple model for how this might be done: The morphemes in a word guide eye movements just as words do. If this is so, then the target for a fixation on the second morpheme would be in the center of that morpheme, or at about Locations 8.5 and 10.5 for words with short and long initial morphemes, respectively. However, this is not what one would expect for the average second-fixation location in these two conditions because these would be the targeted locations, and, as indicated by the McConkie et al. (1988) data and model, one would expect the actual saccades to undershoot the targets on average, so that the mean fixation locations would be less far into the word. If one uses the mean landing positions of about 2.8 and 3.8 on four- and eight-letter English words, respectively (using Rayner, 1979, as a guide), one would predict that the mean second-fixation locations would be 7.8 (4 + 3.8) and 10.8 (8 + 2.8) in the short- and long-initial-morpheme conditions, respectively. The actual mean locations of 8.7 and 9.3 characters indicate that the actual fixation locations are further into the word than would be expected for the words with short initial morphemes and are not as far into the word as would be expected for the words with long initial morphemes. That is, the mean locations appear to be a compromise between pure morphemic guidance and pure visual guidance.

Other aspects of the data also indicate that not all initial refixations are guided by morphemic processing. When the initial fixation landed on the first four letters of the word, it appeared that there was only marginal control of eye movements by morphemes. There was a small (about one quarter of a character) and marginally significant difference in where the eyes landed on the second fixation; however, there was little other evidence that the first morpheme had been processed on this fixation. First-fixation durations were quite brief when the initial fixation was in this location and were unaffected by the length of the initial morpheme. In contrast, when the initial fixation landed near the middle of the word, first-fixation durations were longer and were significantly influenced by the length of the initial morpheme. In addition, there was a bigger modulation of the location of the second fixation by the length of the initial morpheme (about three quarters of a character). All of these differences indicate that morphemic processing was more complete when the initial fixation was nearer the middle of the word.

The pattern of data thus indicates that there is a compromise between the visual guidance model and a pure morphemic guidance model. When the initial fixation is near the beginning of the word, guidance of the fixation appears largely affected by oculomotor factors; the initial fixation is short and the saccade leaving it appears to be directed at the center of the word. However, because the location of the second fixation appeared to be influenced by the length of the initial morpheme even in these cases, it appears that there was some morphemic guidance. In contrast, when the initial fixation is nearer the middle of the word, it appears that the length of the initial morpheme has an influence on the length of the initial fixation and has a substantial influence on the location of the second fixation.

There are likely to be other influences on the location of the second fixation. Most notably, regressions back to the beginning of the word are unlikely to be the result of saccades directed at the second morpheme. It is more plausible that saccades were directed back there because the first morpheme had not been processed on the first fixation. This hypothesis is strengthened by the fact that many more such regressions occurred when the initial fixation was in the middle of the word and the first morpheme was short. In that case, the key information for identifying the initial morpheme would have been further from fixation than when the first morpheme was long.

Now let us consider the data from Experiment 2. Although the focus in that experiment was on the duration of fixations, the locations of fixations were also affected by the frequency of the initial morpheme. Most notably, the frequency of the initial morpheme had a small (about one quarter of a character) but significant influence on the location of the initial fixation on a word. There are a few previous studies that also hint at the possibility that a semantic or morphemic variable may have an effect on the initial fixation location (Hyönä et al., 1989; Inhoff et al., 1996; Underwood, Clewes, & Everatt, 1990), although the effect is not always replicable (Hyönä, 1995; Rayner & Morris, 1992) and it is not clear from those studies what factor is responsible for the effect. One possible interpretation is that if the initial morpheme is low in frequency, its parafoveal preprocessing may be more difficult, and hence on some fraction of the trials, the reader’s saccade is directed closer to the word’s beginning than it is with high-frequency words. This interpretation implies that difficulty in parafoveal processing is capable of influencing the saccade trajectory (foveal processing difficulty can influence the saccade trajectory; see the discussion of refixations on target words below). Although plausible, this parafoveal-processing-difficulty hypothesis needs further corroborating evidence from subsequent studies to be taken seriously.

In compliance with the processing-difficulty hypothesis outlined above, our data further indicate that the frequency of the initial morpheme had an influence on the location of refixations. The second-fixation location was over half a character further into the word when the first morpheme was frequent than when it was unique. This makes sense if the reader processes a frequent morpheme more quickly and thus is more likely to program a saccade to the second morpheme rather than to program another fixation to the first morpheme or to let oculomotor guidance strategies program...
the second saccade (presumably close to the middle of the word). It should be noted that the difference in the location of the forward refixations cannot be accounted for by the difference in the length of the initial morpheme because it was slightly longer, not shorter, for the unique-beginning words.

In summary, it appears that refixations on a word are likely to have several causes. In some cases, oculomotor strategies take over (especially when the initial location is near the beginning of the word) and a refixation is guided toward the middle of the word. In other cases, however, it appears that saccades are directed toward the second morpheme. Whether the reader can accurately target the middle of this morpheme when there are no spaces to guide the saccade is an open question. Moreover, there appear to be regressive saccades back to the initial morpheme when it has not been adequately processed. These appear to occur chiefly when the initial fixation was near the middle of the word and the first morpheme was short or unique.

What Guides When the Eyes Move Within a Word?

The second major question involved the control of the duration of eye fixations. To some extent this has been considered in our discussion of the where question, but it is worth pulling the data together. The data of Experiment 2 indicated that the frequency of the initial morpheme influenced the duration of the initial fixation, marginally influenced the duration of the second fixation, and had a quite substantial influence on the number of times the word had to be refixated. These data all indicate that accessing the initial morpheme can be quite rapid (perhaps aided by parafoveal preview) and can even influence the first decision when to move. It is less clear, however, exactly how morphemic analysis influences the duration of individual fixations.

One possibility builds on the Taft and Forster (1976) "file drawer" metaphor for the processing of compound words. That is, Taft and Forster viewed lexical access of multisyllabic words as having two stages, with the first stage being the identification of an "access code" such as the initial morpheme or orthographic or phonological syllable and the second stage being access of the complete word. If this is so, it is possible that when the first stage is complete, a signal goes out to make an eye movement to the part of the word not included in the access code (e.g., the second morpheme) and that when access of the whole word is complete, a signal goes out to make an eye movement to the next word. However, as we have seen above, there probably are also signals to make eye movements based on purely oculomotor considerations (e.g., when a fixation is far from the center of the word, an immediate signal goes out to target a saccade to the center). It is obviously a difficult question how all these potentially competing signals to program eye movements get scheduled. One solution that has been proposed (by Morrison, 1984, and elaborated on by Rayner & Pollatsek, 1989, Pollatsek & Rayner, 1990, and Reichle, Pollatsek, Fisher, & Rayner, 1998) is not to posit any central executive but to posit that eye movements can be programmed in parallel (i.e., that programming a later eye movement does not have to wait for the execution of an earlier eye movement) but that, under certain specified conditions, later eye movements can cancel earlier eye movements (Abrams, 1992; Becker & Jürgens, 1979). At present, the Reichle et al. (1998) model can give a good quantitative account of fixations between words but would have to be modified to account for "intelligent" refixations, such as those observed in the present study. We do not attempt an account here both because of space considerations and because such a modeling exercise will make more sense when we have more data on how morphemes and other subword units affect eye movements in reading.

Processing of Compound Words in Finnish

Before closing, we wish to broaden the discussion beyond the effects of morphemes on eye movement control to briefly discuss the effects of morphemic analysis on processing of compound words in Finnish. One possibility is that morphemes may control individual eye movements in reading but have little or no effect on lexical access. In Experiment 1, for example, the length of the initial morpheme influenced the pattern of eye movements on the word but had no clear effect on the total fixation time on the word, and thus we can draw no firm conclusions about the role of morpheme length on lexical access. In addition, there is no transparent reason why the length of the initial morpheme would have any simple effect on the time to access a compound word.

In contrast, the data of Experiment 2 clearly indicate that morphemic analysis has an effect on lexical access. Not only were the initial fixation times and locations affected by the frequency of the initial morpheme but the gaze duration on the word (likely a good indicator of lexical access time) was almost 100 ms shorter when there was a frequent initial morpheme (even though the overall familiarity of the compound words was equated). This indicates that the time to access the initial morpheme is an important determinant of lexical access, at least for compound words in Finnish. This raises the question of how access of the initial morpheme relates to access of the compound word. There appear to be two relatively simple contrasting hypotheses about this.

One is the Taft and Forster (1976) "file drawer" metaphor. In this model, the word is "looked up" in a prestored location in two stages. The first stage is looking up the "file drawer" indexed by an "access" code such as the initial morpheme, and the duration of this stage is presumably influenced by the frequency of this access code in the language. The second stage is looking for the actual word in the file drawer, and the duration of this stage is influenced by the frequency of the actual word in the file drawer relative to the frequency of other words that are in the same file drawer. An alternative model is a more compositional one in which the compound word is not accessed but instead constructed on-line (see Andrews, 1986; Sandra, 1990). Compositional models assume the meaning of a compound word to be computed from its constituent meanings each time a compound is encountered (at least with low-frequency and semantically transparent compounds). The
predictions of this model are less clear, but the initial stage should be primarily determined by the frequency of the initial morpheme as a word and the second stage by the frequency of the second morpheme as a word (cf. Sandra, 1990).

To date, the empirical evidence concerning the lexical access of isolated compound words (Andrews, 1986; Lima & Pollatsek, 1983; Monsell, 1985; Sandra, 1990) is fairly discouraging with respect to Taft and Forster's (1976) dual-stage search model. Although it is generally observed (consistent with the search model) that decreasing the frequency of the initial morpheme of a compound word increases lexical access time, studies have also found that decreasing the frequency of the second constituent also increases lexical access time—a finding at odds with Taft and Forster's model and more consistent with compositional models (Andrews, 1986; Sandra, 1990). The results from the lexical decision task, however, may not generalize to normal reading because lexical decision latencies tap postaccess decision making that is likely to be unrelated to postaccess processes in text comprehension. Moreover, strategic factors having to do with the stimulus environment are shown to modulate the pattern of results in lexical decision (see Andrews, 1986). In particular, for compound words, the types of nonword foils are likely to be critical in determining the pattern of results.

The on-line nature of the eye movement record has potential for distinguishing between these models, although it is unlikely that any particular eye movement measure is a pure index of a putative "initial stage" or "second stage." Both models predict that the first stage of processing should be shorter for words with frequent initial morphemes and thus successfully predict that frequent initial morphemes should lead to shorter first-fixation durations on the target word (because the first-fixation duration is likely to index the initial processing stage to some degree). In contrast, their predictions about the length of the second stage of processing and total lexical access time appear to differ for our set of stimuli. For example, the Taft and Forster (1976) model predicts that the second stage should actually take longer for the frequent-beginning words of Experiment 2 because these words often have other, more frequent, compounds in the "file drawer" (a median of 21 more frequent compounds for the 28 frequent-beginning compound words), whereas the unique-beginning words do not have any competitors in the file drawer. In contrast, a compositional model would predict that the duration of the second stage should largely be determined by the frequency of the second morpheme. The mean frequency of the second morpheme for the words with frequent first morphemes (113) was a bit higher than that for the words with unique first morphemes (78), although the median frequencies for the two sets (37) were the same. Thus, the compositional model would predict that later stages of processing should be somewhat shorter for the words with frequent first morphemes. Obviously, no individual eye movement measure can be confidently used as a measure of second-stage processing time, but both of the most plausible reliable measures of later processing time—second-fixation duration and gaze duration minus first-fixation duration—were shorter for words with frequent beginnings. This pattern is only slightly suggestive of a more compositional analysis of these compound words, however, because it is plausible that these measures are also strongly influenced by the frequency of the initial morpheme.

The effects of the frequency of the second morpheme on processing the target words can also be assessed by regression analyses in which the dependent variable is the difference in processing time for a particular fixation duration measure between a matched pair of words in the two experimental conditions, and the independent variable is the difference in the frequency of the second morpheme for this pair of words. The difference in second-morpheme frequency had virtually no effect on either first-fixation duration or second-fixation duration—both ts(26) were close to 0—and the values of the y-intercepts (reflecting the "true effect" of first-morpheme frequency with second-morpheme frequency controlled for) were virtually the same as in Table 4. The statistical significance of these differences was virtually the same as in the main analysis, r(26) = 3.492, p < .01, and r(26) = 1.871, p < .10, respectively. In contrast, both the difference in gaze duration, r(26) = −2.5, p < .05, and the difference in gaze duration minus the first-fixation duration, r(26) = −2.45, p < .05, decreased significantly with an increasing difference in the frequency of the second morpheme, which suggests that the frequency of the second morpheme influences later processing of the word and supports the compositional analysis hypothesis. As with the first- and second-fixation measures, the intercepts of the regression lines for both these measures were significantly different from zero (both ps < .001) and little different from the means in Table 4, indicating that the frequency of the first morpheme also had large effects on later processing. The above analyses, however, are only suggestive, and an experiment is needed in which first-morpheme frequency, second-morpheme frequency, and word frequency are manipulated independently.

**Generalizability of the Present Results**

Our data indicate that processing of the words used in the present experiments is significantly influenced by processing of the component morphemes. This indicates that morphemic processing can influence processing of words and modulate eye movement behavior within a word. However, at present, we cannot say that much about the generalizability of the results. We selected (relatively low-frequency) Finnish compounds as a test case because (a) productive compounding is frequent in Finnish and hence the morphemes are likely to be treated as independent units and (b) these words are long and so it is less likely that all of the letters can be seen clearly within a given fixation. Thus, we would hesitate to generalize either to situations in which the compounds are shorter or to languages in which compounding is not as productive.

A recent study by Beauvillain (1996) in French, however, suggests that the influence of morphemes on how words are processed in reading is not limited to such extreme cases. She demonstrated that the pattern of fixation durations was
different for prefixed and suffixed words and was further-
more modulated by the frequency of these morphemes. The
participants in that study, however, were not reading text
when their eye movements were being monitored. Instead,
Beauvillain used a semantic comparison task—participants
saw the target word followed by a second word presented to
the right and were asked to judge whether they were
semantically related. It is clearly a bit hazardous to general-
ize from this task to what would happen when participants
read text. However, because the gaze durations in Beauvi-
lain's experiments (typically between 400 and 450 ms for
read text. However, because the gaze durations in Beauvil-
la~n's experiments (typically between 400 and 450 ms for
words of comparable frequency, it seems unlikely that a
radically different pattern would be obtained when such
words were encountered in text. Obviously, however, we
need more experiments to determine the extent to which
morphemic processing influences reading.

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