

## Parafoveal access to word stem during reading: An eye movement study

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### ABSTRACT

Previous studies (Hyönä, Yan, & Vainio, 2018; Yan et al., 2014) have demonstrated that in morphologically rich languages a word's morphological status is processed parafoveally to be used in modulating saccadic programming in reading. In the present parafoveal preview study conducted in Finnish, we examined the exact nature of this effect by comparing reading of morphologically complex words (a stem + two suffixes) to that of monomorphemic words. In the preview-change condition, the final 3–4 letters were replaced with other letters making the target word a pseudoword; for suffixed words, the word stem remained intact but the suffix information was unavailable; for monomorphemic words, only part of the stem was parafoveally available. Three alternative predictions were put forth. According to the first alternative, the morphological effect in initial fixation location is due to parafoveally perceiving the suffix as a highly frequent letter cluster and then adjusting the saccade program to land closer to the word beginning for suffixed than monomorphemic words. The second alternative, the processing difficulty hypothesis, assumes a morphological complexity effect: suffixed words are more complex than monomorphemic words. Therefore, the attentional window is narrower and the saccade is shorter. The third alternative posits that the effect reflects parafoveal access to the word's stem. The results for the initial fixation location and fixation durations were consistent with the parafoveal stem-access view.

### 1. Introduction

When competent adult readers read a text, they fixate with their eyes almost every word. This is because foveal vision is needed to identify words that are visually rather complex stimuli. When fixating on a word, not only the foveally inspected word is recognized but readers also preprocess the word to the right (when reading from left to right). In eye-movement research on reading, a lot of effort has been invested in determining the nature of this so-called parafoveal preprocessing (for a review, see Hyönä, 2011). Research has shown that orthographic and phonological information is processed parafoveally; such parafoveal orthographic and phonological preprocessing then speeds up the foveal processing of that word when it is subsequently fixated. Recent studies have also found evidence for parafoveal semantic preprocessing (Hohenstein & Kliegl, 2014; Schotter, 2013) and parafoveal syntactic processing (Brothers & Traxler, 2016; Snell, Meeter, & Grainger, 2017). In the present study, the focus is on parafoveal morphological preprocessing. More specifically, we examined whether competent adult readers would be able to carry out morphological analysis parafoveally.

Earlier studies provided no support for the view that readers of

alphabetic languages (English and Finnish have been the studied languages) would parafoveally process the morphological structure of the word to the right of fixation (Bertram & Hyönä, 2007; Inhoff, 1989; Juhasz, White, Liversedge, & Rayner, 2008; Kambe, 2004; Lima, 1987). On the other hand, positive evidence in support of this notion has come from a study conducted in Hebrew (Deutsch, Frost, Pelleg, Pollatsek, & Rayner, 2003) and a study conducted in Chinese (Yen, Tsai, Tzeng, & Hung, 2008). Both Chinese and Hebrew are visually more condensed scripts than alphabetic scripts in that more information can be packed within a given space. More recently, Stoops and Christianson (2017, 2019) found that Russian readers can process inflectional morphology parafoveally. Using the gaze-contingent display change paradigm (Rayner, 1975), they observed a parafoveal preview cost when there was a discrepancy in the suffix available parafoveally and foveally. A similar result was obtained by Kim, Radach, and Vorstius (2012) for Korean.

Most importantly for the present study, Yan et al. (2014) reported a study conducted in Uighur that also provided evidence for parafoveal morphological preprocessing. Uighur is an alphabetic (Arabic-derived alphabet), morphologically rich language belonging to the Turkic language family. Yan et al. found that the initial fixation on a word lands

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closer to the word beginning for multimorphemic words comprising a word stem and two suffixes, compared to monomorphemic words. As the saccade to the critical word was programmed when the word was in the parafovea, this result provides evidence for parafoveal morphological analysis. A morphological effect on the initial fixation location was replicated by Hyönä, Yan, and Vainio (2018) for Finnish, another morphologically rich language.

The initial fixation location effect observed by Yan et al. (2014) and Hyönä et al. (2018) provides evidence for parafoveal morphological processing, but it is not indicative of the exact nature of the morphological analysis. Hyönä et al. reasoned that one possibility is that readers parafoveally perceive the suffix at the end of word and then launch a saccade closer to the word beginning, that is away from the suffix. This is plausible, as the letter cluster making up the suffix is highly frequent in the language studied. The plausibility of this notion is further strengthened by findings that letters at the end of the word are perceived better parafoveally than word-internal letters (e.g., Inhoff, 1989; Johnson, Perea, & Rayner, 2007). Targeting the incoming saccade away from the suffix results in the initial fixation landing closer to the center of the word stem. This in turn facilitates the recognition process. This interpretation was also supported by the result that readers were much more likely to make a refixation on the word, if the initial fixation landed on the suffix, not on the word stem (Hyönä et al., 2018).

The present study was designed to shed light into the nature of the morphological effect obtained by Hyönä et al. (2018). If the above reasoning for the source of the initial fixation location effect is correct, parafoveally denying the suffix will wipe out the morphological effect. We tested it by employing the gaze-contingent display change paradigm. In that paradigm, in one condition the target word is initially replaced with another stimulus. When the reader makes a saccade to the target word from the preceding word, the changed stimulus is replaced with the target word. Thus, the initially changed stimulus is only perceived in the parafovea when fixating on the preceding word. On the other hand, when fixated, the target word is always seen in the correct form. Changes in the target word are made during the incoming saccade to the target word. Due to saccadic suppression, readers will not see the actual change taking place. In the present study, in half of the trials the suffixes at the end of the suffixed word was replaced with other letters not comprising a morpheme. Yet, the word stem was always parafoveally available. An analogous manipulation was made to the monomorphemic words, for which the change of the ending letters meant that the word stem was not fully available parafoveally in the display change trials. For both word types, the changed stimulus perceived parafoveally comprised a pronounceable pseudoword. The changed condition was compared to the no-change condition, where the target word appeared in its correct form throughout the trial (i.e., it appeared in its correct form also when perceived parafoveally).

Three alternative predictions were entertained. The first prediction, spelled out above, assumes that parafoveal morphological analysis takes place in the form of perceiving the suffix as a highly frequent letter cluster. According to the affix stripping (Taft & Forster, 1975) or the morpho-orthographic segmentation (Rastle, Davis, & New, 2004) account, the affix is first stripped of the word, which then allows access to the word stem. If so, in the display change trials where the suffix is not available, the morphological structure effect in the initial fixation location should be wiped out. In other words, the initial saccade to the target word would not land closer to the word beginning in the suffixed than monomorphemic words.

The second prediction contends that the parafoveal morphological effect is due to processing difficulty (Yan et al., 2014). The suffixed word as a morphologically complex word (contains three morphemes) is more difficult to process parafoveally, leading to a shorter incoming saccade to the target word and longer fixation durations on the target word. Here the assumption is that the saccade is programmed to the current edge of the perceptual span. The processing difficulty account makes an analogous prediction to the first one. In the changed condition, all target words are pseudowords, so they would incur a similar difficulty to parafoveal

processing, leading to similar initial fixation locations for the monomorphemic and suffixed words. On the other hand, the no-change condition should replicate the previously observed morphological effect in initial fixation location. Moreover, according to this account, presenting pseudowords in the parafovea (i.e., the display change condition) should generally shorten the incoming saccade to the target word, leading to the initial fixation landing closer to the word beginning than in the no-change condition.

According to the third prediction, the effect reflects parafoveal access to the word stem (Grainger & Beyersmann, 2017). In other words, readers parafoveally attend to the word stem and use the stem information as one source of information in saccade programming. Word stem is much shorter in suffixed than monomorphemic words; thus, the initial fixation will land closer to the word beginning for suffixed than monomorphemic words. Moreover, the morphological effect in initial fixation location should remain even when the suffix information is denied. This is because in display-change trials the word stem is parafoveally fully available for the suffixed words (in the display-change trials for the monomorphemic words the word stem is changed to a pseudoword). If this prediction is correct, having in the display-change condition the stem parafoveally available for the suffixed words but not for the monomorphemic words should also affect the word's subsequent foveal processing. As the word stem is parafoveally available in both preview conditions, the display-change manipulation should not influence foveal fixation time for the suffixed words. However, for monomorphemic words the word stem is only available in the no-change (identical) condition, which should result in longer fixation times in the change condition than in the identical condition, when the word is subsequently fixated in its correct form.

In the present study conducted in Finnish, the suffixed words contained two suffixes (a case inflection, possessive suffix and/or a plural marker; e.g., *purjeissa*, where *purje* means sail, *-i* is a plural marker, and *-ssa* an inessive case ending comparable to the English preposition *in*), which meant that the suffix part was comparable in length to the stem (their length varied from 3 to 5 letters). This made the suffix part visually more salient than if we had used single suffixes denoted by a single letter. Its parafoveal perceivability is further increased by the stem being relatively short, so the suffix did not extend very far into the parafovea when perceived during the fixation on the preceding word. Similarly, the stem being relatively short in the suffix condition increases the likelihood that it can be parafoveally perceived. All in all, we aimed at a strongest possible manipulation of the parafoveal perceivability of the morphological structure of the suffixed words. It is also noteworthy that in Finnish words containing two (or more) suffixes are highly common. To illustrate, we computed the frequency with which our target words appeared in the newspaper corpus in a form entailing at least two suffixes. The analysis showed that in 57% of the target word occurrences they appeared in a form that included two or more suffixes. In other words, for most nouns the multimorphemic form is the modal form they appear in text. This contrasts with English where word forms containing multiple inflections do not exist. Yet, the morphological structure of the suffixed words used in the present study resembles English words containing a stem, derivational ending and a plural marker, as in *players*.

We also examined whether the observed parafoveal preview effects would be modulated by preview time and/or preview space (Hohenstein, Matuschek, & Kliegl, 2017; Kliegl, Hohenstein, Yan, & McDonald, 2013). More precisely, we examined whether longer preview times due to fixating longer on the preceding word (i.e., usually the word from which the saccade to the target word was launched) prior to fixating the target word would affect the observed preview effects. The three alternative accounts spelled out above make different predictions regarding the effect of preview time in initial fixation location. Longer preview times may be associated with more elaborate parafoveal processing, leading to a more robust morphological effect. Thus, according to the suffix-processing account, long preview times would be associated with a more robust morphological effect in the initial fixation location in the no-change condition. In other words, it predicts a 3-way interaction between preview type, morphological structure of target

word, and preview time. On the other hand, the stem-access account predicts long preview times to be associated with more elaborate parafoveal processing of the word stem, which would lead to a more robust morphological effect in initial fixation duration in both parafoveal preview conditions. In other words, it predicts a 2-way interaction between morphological structure and preview time. In contrast, the processing-difficulty account assumes longer preview times to reflect local processing difficulty, which in turn would shrink the current perceptual span. Thus, longer preview times would diminish or wipe out the morphological effect in initial fixation location in the no change condition (it is predicted to be non-existent in the change condition). Thus, although similar to the suffix account, it predicts a 3-way interaction in the opposite direction.

In addition to preview time, we also examined whether fixating closer to the target word prior to launching a saccade to the target would strengthen the preview effects. The assumption here is that more extensive parafoveal processing may be made when fixation is close to the target word, in comparison to the preceding fixation positioned further away from the target word. Thus, analogous predictions as spelled out above for long preview time may be formulated for close launch distance, except for the processing difficulty account that predicts a larger morphological effect in initial fixation location for near launch sites in the no-change condition. Finally, combining long-preview time with short launch distance should produce a particularly pronounced effect in the predicted direction.

What predictions can be derived from the three accounts in regard to fixation time on the target word? The processing difficulty account predicts a morphological complexity effect in the no-change (identical) condition but no such effect in the change condition. The morphological effect in the no-change condition is predicted to be less pronounced with long preview times and more pronounced with near launch sites. Moreover, the change condition (all previews are pseudowords) should produce longer fixation times than the no-change condition. On the other hand, the stem-access view predicts no or little effect of preview type for suffixed words (the stem is parafoveally available in both preview conditions), but a clear effect of preview type for monomorphemic words, for which the stem is only available in the no change condition. This pattern should be most noticeable with long preview types and near launch sites. Finally, it is not completely clear what the suffix account would predict with respect to fixation time. At least, fixation time on the target should be longer for suffixed words when the suffix was absent in the parafovea compared to the case when it was present. This effect should be more pronounced with long preview times and near launch sites. No predictions can be derived for fixation time on the monomorphemic words.

## 2. Method

### 2.1. Participants

Sixty-eight students from University of Turku participated in the experiment. All were native speakers of Finnish. None of the participants had a diagnosis of reading disability. Before the experiment, the participants signed the informed consent form.

### 2.2. Apparatus

Eye movements were recorded with an Eyelink1000+ system (SR Research, Canada) in 1000 Hz. The sentences were presented on a BenQ XL2420Z monitor (1920 × 1080 resolution; frame rate 100 Hz) controlled by an Intel i5-4570 computer running at 3.20GHz under a Windows 7 environment. Participants were seated 69 cm from the monitor with their head positioned on a chin rest.

### 2.3. Materials

The experiment was run in Finnish. The materials were adopted from

Hyönä et al. (2018). They consisted of 50 pairs of sentences, where the target word was either monomorphemic or multimorphemic noun (stem and two inflectional suffixes). The multimorphemic words had either a case ending plus a possessive clitic (e.g., *eno-lle-en* = uncle-to-his/her -> 'to his/her uncle') or a plural suffix plus a case ending (e.g., *auto-i-ssa* = car-s-in -> 'in (the) cars'). The target words were 6–9 letters long. For the multimorphemic words, the length of stems and suffixes both varied from 3 to 5 letters; in other words, across the target word set, the stems and suffixes were roughly equal in length. Each multimorphemic target word was paired with a monomorphemic target word so that the pairs were closely matched for frequency ( $t < 1$ ) (the logarithmic lemma frequency/million was on average 1.58 for both word types; the standard deviation was 0.72 and 0.71 for the multimorphemic and monomorphemic words, respectively); for word length in characters (mean = 7.92; SD = 0.92; the length of each multimorphemic word was identical to its monomorphemic pair); and for initial trigram frequency ( $t < 1$ ), which was 76.3 (SD = 54.0) for the multimorphemic words and 75.1 (SD = 56.0) for the monomorphemic words (the values are per 1000 trigrams). The frequencies were computed on the basis of Turun Sanomat newspaper corpus comprising 22.7 million word tokens (Laine & Virtanen, 1999).

In order to minimize possible influences of sentence context, the sentence frame leading to the target was identical in the sentence pairs. The post-target word was either identical or at least the first three letters were identical within each pair; the sentence frames after the post-target word could vary to provide fluent sentence endings. The sentences were six to 14 words in length. The target words were always presented in the first text line but never among the first two or the last two words in the line. Each sentence frame appeared in two separate lists, once with a monomorphemic target word and once with a suffixed target word. Half of the sentences in each list contained a display change. The two lists were counterbalanced across participants. The order of sentences was individually randomized. The sentences were presented in four blocks; each block was preceded by four practice sentences. Each participant read 100 target sentences.

An eye-movement contingent display change paradigm (Rayner, 1975) was used to present half of the target words in the changed form when parafoveally available. In the display change condition, 3–4 letters were replaced with other letters so that the target word appeared as a pronounceable pseudoword. For the suffixed words, the two suffixes were replaced with other letters so that the word stem remained intact. For the monomorphemic words, a corresponding number of letters was initially changed from the word end so that only the first half of the word stem was parafoveally available. The changed letters did not form a morpheme. An invisible boundary was placed in the middle of the space preceding the target word. When the reader's eyes crossed this boundary, the target word was changed to its correct form. In other words, when fixated the target word always appeared in the intended form.

An example sentence pair is presented below with the target word appearing in bold (no bolding was used in the actual experiment). The no-change version displays the correct word form (i.e., as it appeared when fixated). The change condition shows how the target word appeared in the parafovea prior to its fixation.

#### *Suffixed target word*

1. No change: *Onnettomuuden jälkeen **purjeissa** havaittiin paha repeämä.*
2. Change: *Onnettomuuden jälkeen **purjehepe** havaittiin paha repeämä.*

(*purje-i-ssa* = 'sail-s-in')

(After the accident a bad rip in the sails was noticed.)

Monomorphemic target word

3. No change: *Onnettomuuden jälkeen **komisario** havainnoi ympäristöä systemaattisesti.*
4. Change: *Onnettomuuden jälkeen **komishepe** havainnoi ympäristöä systemaattisesti.*

(komisario = inspector)

(After the accident the **inspector** systematically observed the environment.)

The sentence contexts were written to be equally non-predictive for the two types of target words. In the norming study, a group of 10 participants who did participate in the eye-tracking experiment were presented the sentence beginnings and they were asked to produce a suitable word in the target word position. The results showed that a target word was mentioned only once in the entire norming study. Thus, all target words were unpredictable from the sentence context.

The sentences were presented one at a time in the middle of the screen and centered horizontally. Texts were displayed using 18 pt. Lucida Console mono-space font. With a viewing distance of 69 cm, each letter subtended 0.32 degrees of visual angle. A 13-point calibration grid was used to calibrate the eye-tracker prior to each experimental block.

## 2.4. Procedure

Participants were advised to read the sentences silently and were told they would be periodically prompted to repeat aloud some of the sentences immediately after reading them, either word by word or by reiterating the main idea of the sentence in their own words. Participants were then prompted to repeat 10 randomly selected sentences. They correctly reported back most of the prompted sentences with no more than one or two incorrectly reported sentences (few participants reported incorrectly two sentences).

After completing the study, the participants were asked if they detected anything out of the ordinary during reading. This was then followed by debriefing the participants about the changes that took place in a subset of the sentences and asked if they saw any of such changes. Two of the 68 participants reported having seen something but were unable to explain what exactly, and six reported having seen at least one actual change taking place.

## 2.5. Data handling and analyses

The dataset is available in the OSF repository (<https://osf.io/725wc/>). The statistical analyses were conducted with linear mixed effects models using the lme4 package (version 1.1–23; Bates, Mächler, Bolker, & Walker, 2015) in R (version 4.0.2; R Core Team, 2020). Before the analyses the data was trimmed as follows. First we excluded trials that contained a blink either on or around of the target word ( $n = 695$ , 10.2%), trials where target word was skipped ( $n = 64$ , 0.94%), and trials that contained track loss on the pretarget, target or post-target word ( $n = 184$ , 2.7%). Then we excluded from the preview change condition the trials, in which the actual display change took place later than 6 ms after the fixation onset (see McConkie & Loschky, 2002) on the target ( $n = 285$ , 4.19%). Consistently with the criteria used in the previous studies of Hyönä et al. (2018) and Yan et al. (2014), we also trimmed the data as follows. First fixations made to the target word that were either shorter than 60 ms ( $n = 16$ , 0.24%) or longer than 600 ms ( $n = 37$ , 0.54%) were removed. Target word gaze durations longer than 800 ms ( $n = 108$ , 1.59%) were removed. Trials where the launch site of the saccade leading to the target word was longer than 9 letters ( $n = 414$ , 6.09%) and trials where the word preceding the target word was skipped ( $n = 475$ , 6.99%) were removed. Finally, preview times (i.e., durations of last fixations made on the word preceding the target word) that were either shorter than 60 ms ( $n = 34$ , 0.05%) or longer than 600 ms ( $n = 49$ , 0.72%) were also removed. All of the above trimming resulted in an exclusion of 28.6% of the data.<sup>1</sup>

In line with past research, fixation-duration measures were

<sup>1</sup> It should be noted that the exclusion criteria overlap with each other for some of the trials. In other words, a trial may have fulfilled multiple exclusion criteria.

log-transformed before the analysis and sum contrasts were specified for the two fixed factors of preview type and morphological structure. In addition, we centered all covariates at meaningful reference values (i.e., lengths of the pre-boundary and target word at 8 letters, launch site at 4 letters, preview fixation duration at 200 ms). With these specifications the “(Intercept)” estimates an interpretable Grand Mean (GM) and the factor-related fixed effects estimate the difference from this GM or half the difference between their two levels when all covariates are at their reference values.

Separate LMMs were constructed for the initial fixation location, gaze duration, and first-fixation duration of the target word. Gaze duration and first-fixation duration exhibited the expected preview type x morphology interaction, but interactions with preview time and preview space (launch site) were only significant for gaze durations. Therefore, we present the analyses of gaze durations; the analysis for first-fixation duration is provided in the *Supplement* (see <https://osf.io/4m6au/>). The fixed factors of all the initial models included the examination of two three-way interactions. These were (1) preview type (identical vs. changed) x morphological structure (monomorphemic vs. suffixed) x preview time (linear trend of log of last fixation duration on the word preceding the target), and (2) preview type x morphological structure x launch site (linear trend of the distance from which the initial saccade to the target word was launched; the distance was measured from the target word beginning). In addition to these interactions, the models included the main effects of target-word and launch-word lengths.

Model selection was carried out by selecting a parsimonious LMM, that is, one that is not overparameterized (Bates, Kliegl, Vasishth, & Baayen, 2015); it is documented in the *Supplement*. Selection occurred without knowledge or consideration of fixed-effect estimates. The initial random-effect structures of the three models included grand means (GMs) for participants and items with all the above-mentioned covariates set as variance components (VCs) and estimation of the full matrix of correlation parameters. These models were always overparameterized. Removal of the VCs for the effects of preview type, morphological structure, and, for gaze duration, of launch-word length as well as assuming absence of evidence for reliable correlation parameters (i.e., assuming that they are zero) yielded LMMs that were supported by the data and did not differ significantly in goodness of fit from the most complex LMM according to a likelihood ratio test.

In a second step, nonlinear quadratic and cubic trends were checked for preview time and launch site. For fixation locations, neither main effects nor interactions with preview type or morphological structure increased the goodness of fit, but for gaze durations the inclusion of main effects of quadratic trends for preview time and launch site did so and for first fixation durations the inclusion of a quadratic trend for launch site was significant.

Observation-level residuals were inspected for all final models and no major misspecification was apparent (see the *Supplement* for diagnostic plots such as residuals over predicted values and qq-plots). Pre- and postprocessing used the following R packages: *broom.mixed* (Bolker & Robinson, 2020), *cowplot* (Wilke, 2019), *remef* (Hohenstein & Kliegl, 2020), *sjPlot* (Lüdtke, 2020), and *tidyverse* (Wickham et al., 2019).

There was no evidence for parafoveal-on-foveal effects of the experimental manipulations of preview type and morphological structure on the duration of last fixation before the boundary (usually the word from which the saccade to the target word was launched), as assessed with an LMM that followed the procedure described for the analyses of fixation location and durations on the target word. There were also no significant interactions between these factors and launch site (all absolute  $z$ -values  $\leq 1.43$ ). The fixation duration increased with the length of the launch word ( $z = 2.11$ ) and increased with the length of the saccade to the target word (i.e., a large launch site;  $z = 5.26$ ). These results are documented in the *Supplement*.

## 3. Results

Descriptive statistics of the eye movement measures for each level of

morphological structure and preview type are presented in Table 1. Fig. 1 displays the *observed* effects of the primary experimental manipulations of preview type and morphological structure of target word for fixation locations (panel a) and log of gaze durations (panel b). In the LMMs reported below, both interactions were significant and in the expected direction: The morphology effect is larger for identical than changed preview both for relative initial fixation location and for gaze duration. Readers saccade further into the target word and spend less time under identical than changed preview. The interaction was also significant for log of first-fixation duration (see *Supplement*). The interactions were further qualified by interactions with preview time and launch site.

### 3.1. Relative initial fixation location

In Table A1 we report the estimates for the parsimonious LMM. The critical interactions did not depend on the model selection. Not surprisingly, the main effects of target word length, the length of the preceding word, and launch site were all robust. However, the main effect of preview type was clearly non-significant ( $z < 1$ ). More importantly, there was a reliable main effect of morphology ( $z = 3.5$ ): Fixation location was further into the word for monomorphemic than suffixed target words.

The novel aspect of the present study was to examine whether the morphological effect is modified by the type of parafoveal preview provided of the target word. Indeed, the effect was qualified by two 3-covariate interactions ( $z$ -values  $> 2.5$ ), preview type  $\times$  morphological structure  $\times$  launch site and preview type  $\times$  morphological structure  $\times$  launch preview time. We followed up these interactions with a post-hoc LMM (Table A2) and graphs of the two interactions (see Figs. 2 and 3). In anticipation of the following analyses, we note that the interactions only qualify, but never reverse the interpretation of the main effect of morphology. In other words, the interactions detail whether the morphological effect is stronger for longer than shorter preview times or for near than far launch sites, and whether it is stronger under the identical-preview or the changed-preview condition.

In the *post-hoc* LMM, we specified the interactions between preview time and preview type and the interaction between launch site and preview type as nested within the levels of preview. In other words, we tested main effects and interactions of word type, preview time, and launch site separately for the identical and changed previews. The results are presented in Table A2.

As apparent from Table A2, the morphological structure  $\times$  preview type interaction was significant in the identical-preview condition, but just missed significance ( $z = 1.94$ ) in the change condition. However, the two-way interaction was further qualified by two three-way interactions. The morphological structure  $\times$  preview time  $\times$  launch site interaction is depicted in Fig. 2. With launch site as covariate, the initial fixation landed further into the target word for monomorphemic than suffixed targets for near launch sites in the identical condition (left panel of Fig. 2). This is a replication of the Yan et al. (2014) and Hyönä et al. (2018) studies. The effect is compatible with all three accounts formulated in the *Introduction*.<sup>2</sup>

<sup>2</sup> In this and in the following figures, partial effects (i.e., the effects after statistical control of fixed effects not involved in the interaction and after removal of between-item differences in mean and of between-subject differences in mean and effects specified as variance components in the random-effect structure (Hohenstein & Kliegl, 2020) are shown as solid lines. We also include smooths of the zero-order relations (i.e., dashed lines; a nonlinear simple regression of  $y$  on  $x$ ) to highlight the effects caused by the grouping of data by subjects and items. Shaded bands for partial effects are 95% confidence intervals computed from observation-level model residuals. Such a statistic is not readily available for zero-order relations because observations are not independent.

On the other hand, an analogous effect was observed in the change-preview condition for far launch sites (right panel of Fig. 2). In the post-hoc LMM, the interaction is significant only for the far launch sites in the changed-preview condition ( $z = 2.20$ ). The effect was not predicted. In retrospect, the finding may be explained as follows: When a reader fixates close to the word beginning (near launch site), they may be able to clearly perceive all letters of the parafoveal word. Thus, the reader may become aware of the fact that in the change condition the parafoveal target word is a non-word, regardless of the word type. Consequently, a saccade of similar length is programmed to the target word. On the other hand, when launching a saccade to the target from a far distance, the reader may not perceive the ending letters of the target word. Yet, the short stem located in the beginning of the suffixed word may be perceivable. A saccade may be programmed toward the stem, resulting in the initial fixation being closer to the word beginning in the suffixed than the monomorphemic condition.

There is an opposite, yet non-significant tendency in the change condition: The initial fixation tended to land closer to the word beginning for suffixed than monomorphemic words with short preview times (right panel of Fig. 3). A significant effect would have been incompatible with the suffix account and the processing difficulty account, which both predicted no effect in this condition. It would have also been incompatible with the stem account that predicted a larger morphological effect with longer preview times. Of course, we do not want to rule out that higher statistical power might have falsified these predictions.

### 3.2. Gaze duration

The parsimonious LMM for gaze duration (the summed duration of fixations on the target before exiting it) is presented in Table A3. The random-effect structure for this LMM estimates one less variance component (preview time) than the model for relative initial fixation location (including it in the model causes the LMM to be over-parameterized), but it includes quadratic trends for launch site and preview time as additional fixed effects.

The model for gaze duration showed a significant main effect of target-word length ( $z = 6.50$ ; longer gaze durations on longer target words), morphological structure ( $z = -6.55$ ; shorter gaze durations for monomorphemic words), preview type ( $z = -6.11$ ; shorter gaze durations for the identical condition), launch site ( $z_{\text{lin}} = 5.32$ ,  $z_{\text{qdr}} = -3.81$ ; longer gaze durations for far launch sites), and preview time ( $z_{\text{lin}} = 4.04$ ,  $z_{\text{qdr}} = -3.81$ ; longer gaze durations with longer preview times); the negative quadratic trends indicate a deceleration of the effects. Of special interest are the two higher-order interactions obtained for fixation location. Of these two, only the preview type  $\times$  morphological structure  $\times$  preview-time interaction was significant ( $z = 2.77$ , see Fig. 4a). The interaction indicates that the morphological effect (i.e., longer gaze durations on suffixed than monomorphemic words) increases with longer preview times only for suffixed targets in the preview-change condition. On the other hand, in the no-change (identical) condition the size of the morphological effect is not modulated by preview time.

There is a striking difference between the partial-effect fits (solid lines) and corresponding zero-order (dashed lines) relations. These differences can be traced to individual differences between subjects' GM in gaze duration. Fig. 4b (i.e., the bottom row) plots the partial effects when these individual differences are included along with the same zero-relations as in panel a. This result suggests that a subgroup of participants may process such constructions differently from the rest.

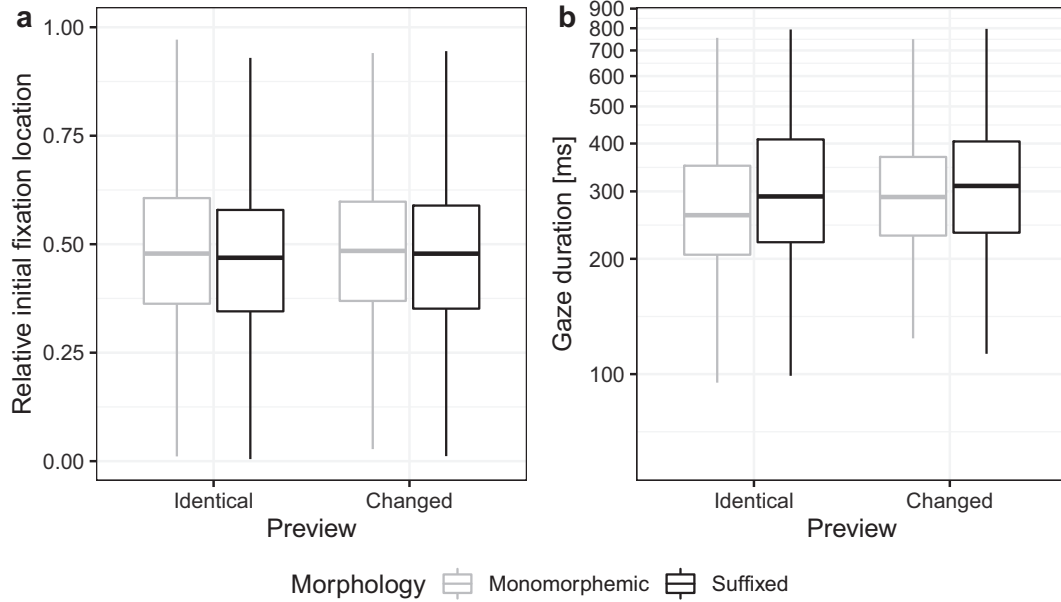
Note that gaze durations and preview times were back-transformed to *ms*, but they are plotted on log- $x$  and log- $y$  axes when this was the case. Therefore, the graphs are still in line with estimates of log gaze duration as dependent variable and use of log fixation duration as covariate in LMMs. Also launch sites (see Figs. 5 and 6) were back-transformed to number of letters rather than being shown for the centered values used in the LMM. However, a vertical line in each graph shows the reference value for the GM estimate.

**Table 1**

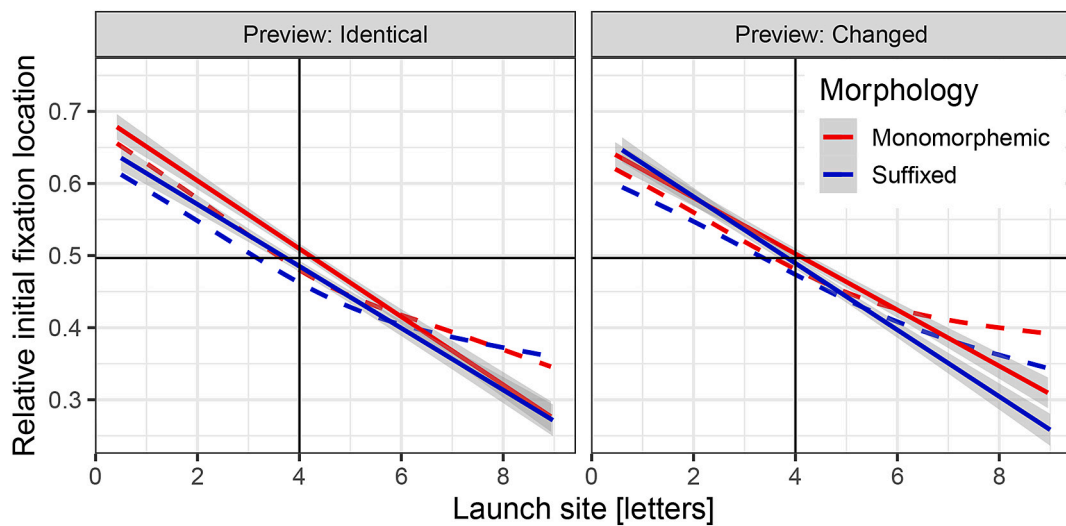
Descriptive statistics of eye movement data for levels of morphological structure (monomorphemic vs. suffixed) and preview type (identical vs. changed) and for the whole data.

| Preview    | Identical     |               |               | Changed       |               |               | Total         |
|------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| Morphology | Mono          | Suffixed      | Subtotal      | Mono          | Suffixed      | Subtotal      |               |
| N          | 1242          | 1205          | 2447          | 1213          | 1193          | 2406          | 4853          |
| Measure    | M (SD)        | M (SD)        | M (SD)        | M (SD)        | M (SD)        | M (SD)        | M (SD)        |
| IFL        | 3.81 (1.48)   | 3.66 (1.44)   | 3.74 (1.46)   | 3.81 (1.44)   | 3.69 (1.46)   | 3.75 (1.45)   | 3.74 (1.46)   |
| RFL        | 0.484 (0.188) | 0.466 (0.186) | 0.475 (0.187) | 0.485 (0.186) | 0.470 (0.187) | 0.476 (0.187) | 0.476 (0.187) |
| FFD        | 244 (78)      | 261 (90)      | 252 (85)      | 254 (79)      | 264 (91)      | 259 (86)      | 256 (85)      |
| GD         | 287 (112)     | 325 (134)     | 306 (125)     | 310 (112)     | 335 (138)     | 322 (126)     | 314 (126)     |

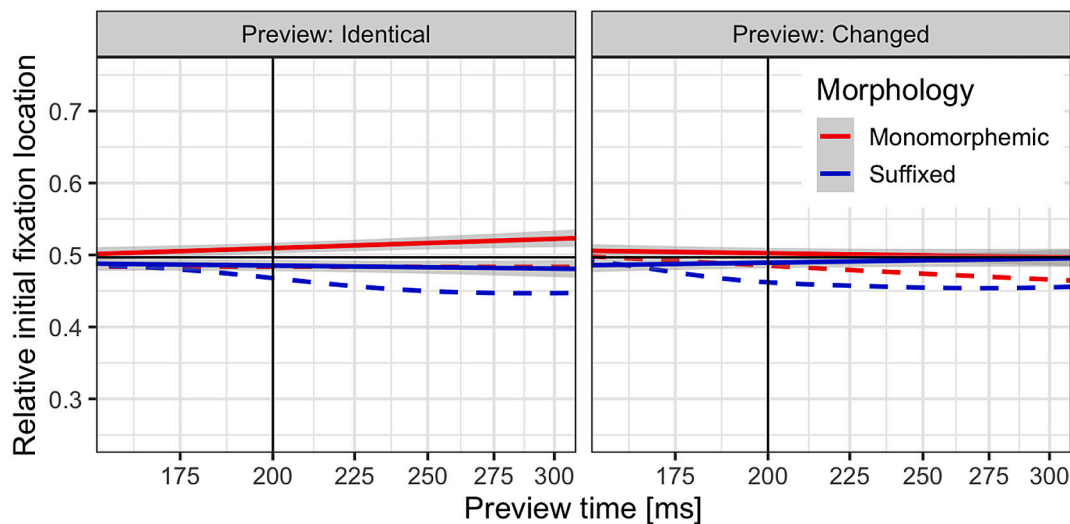
Note. Mono = monomorphemic, IFL = initial fixation location, RFL = relative initial fixation location, FFD = first fixation duration, GD = gaze duration.



**Fig. 1.** Interaction of preview type and morphological structure of target word for relative fixation location (a) and gaze duration (b).



**Fig. 2.** Partial effects (solid lines) of LMM and zero-order smooths of observed values (dashed lines; span = 0.75 letters) of initial fixation location (i.e., relative position of fixation within target word) as a function of launch site (in letters), target-word morphology (monomorphemic vs. suffixed), and preview type (identical vs. changed). Shaded bands for partial effects represent 95% CIs based on observation-level LMM residuals. Horizontal line is mean of dependent variable; vertical lines show where main effects of launch-site estimates were estimated in *post-hoc* linear mixed model (i.e., @ 4 letters).



**Fig. 3.** Partial effects (solid lines) of LMM and zero-order smooths of observed values (dashed lines; span = 0.75) of initial fixation location (i.e., relative position of fixation within target word) as a function of preview fixation time (i.e., last fixation duration on pre-target word), target-word morphology (monomorphemic vs. suffixed), and preview type (identical vs. changed). Shaded bands for partial effects represent 95% CIs based on observation-level LMM residuals. Horizontal line is mean of dependent variable; vertical lines show where main effects of preview time were estimated in *post-hoc* linear mixed model (i.e., @ 200 ms).

The second 3-way interaction of preview type  $\times$  morphological structure  $\times$  launch site was not significant ( $z = 0.86$ ). However, launch site entered two simple interactions. The significant morphological structure  $\times$  launch site interaction ( $z = 2.43$ ), depicted in Fig. 5a, suggests that gaze duration increases as a function of the launch site distance from the target word for monomorphemic words but not for suffixed words. We suggest that the reason gaze duration does not increase for suffixed words is due to the short stem of the suffixed words being perceivable even a bit further in the parafovea.

The significant preview type  $\times$  launch site interaction ( $z = 3.01$ ; Fig. 6a) suggests that the parafoveal preview effect is sizeable with near launch sites but non-existent with far launch sites. For both interactions, differences between partial effects and zero-order relations could be traced to individual differences in subjects' GM of gaze durations and the linear effect of launch-site on gaze duration (see Fig. 5b and Fig. 6b).

Finally, the significant morphological structure  $\times$  preview interaction ( $z = 3.33$ ) observed in first fixation duration (see *Supplement* for details) shows that parafoveally denying the last letters was more detrimental to the monomorphemic than suffixed words (see Table 1 and Fig. 1). This finding is consistent with the stem account.

#### 4. Discussion

The present study tested whether readers of Finnish parafoveally process words' morphological structure during reading. We employed the gaze-contingent display change paradigm (Rayner, 1975) to manipulate the parafoveal availability of morphological information. In the display change trials the word-final letters were initially replaced with other letters. In the case of suffixed words this meant that the letters constituting the suffix (e.g., *issa* in *purjeissa* = in sails; an example of an approximate counterpart in English could be *ers* in *players*) were replaced with other letters (e.g., *hepe* in *purjehepe*, where *hepe* is not a suffix; an English example could be *cit* in *playcit*) so that the suffix information was unavailable but the word stem stayed intact. In the case of closely matched monomorphemic words the display change affected the word stem, which was not available parafoveally (e.g., *komisario* was presented as *komishepe*, where *komis* is not an existing stem; an English example could be for *accocit* for *account*). We entertained three alternative predictions. According to the first alternative, the parafoveal morphological effect previously obtained by Yan et al. (2014) and Hyönä et al. (2018) is due to readers perceiving the suffix as a highly

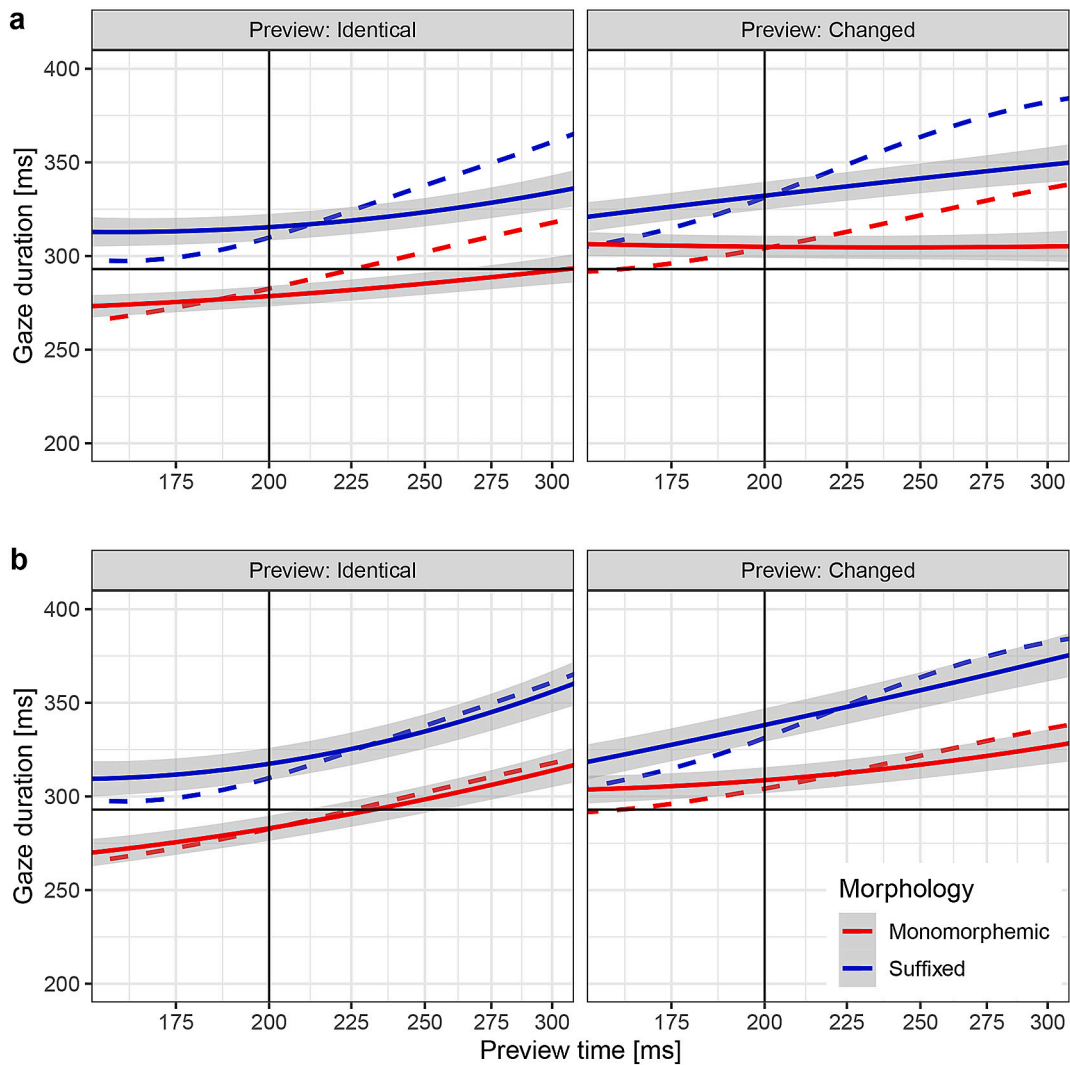
frequent letter cluster at the end of the word. The second alternative ascribes the effect to the parafoveal access of word stems rather than suffixes. The third possibility is that the effect reflects processing difficulty, as morphologically complex words (suffixed words contained a stem and two suffixes) are more difficult to recognize than monomorphemic words. As argued in more detail below, the results support the second prediction, that is, parafoveal access to word stem being behind the observed results.

Parafoveal morphological effects were examined using three eye movement measures of target word reading: initial fixation location, first fixation duration and gaze duration on the target word. Initial fixation location taps into saccadic programming during reading, while the fixation duration measures reflect the time course of processing. We discuss the observed results in these three dependent measures separately for the identical and the display change condition. The identical condition was a direct replication of the previous studies (Hyönä et al., 2018; Yan et al., 2014), whereas the display change condition allowed us to test the three alternative predictions mentioned above.

The identical preview condition closely replicated the previously observed results. Initial fixation location was located closer to the word beginning for suffixed than monomorphemic words, while fixation time (both first fixation and gaze duration) was longer on suffixed than monomorphemic words. The present study also showed that the fixation location effect was primarily observed for near launch sites, that is, when the fixation preceding target word fixation was close to the target word, and for longer preview times (the preceding fixation lasting for more than 200 ms). Both the launch site and the preview time effect are reflections of more extensive parafoveal processing. Parafoveal processing is more elaborate when done from a close distance and for a relatively long time.

##### 4.1. Evidence for parafoveal access to word stems

The novel results came from the display change condition that modified the morphological effect in the following way. The morphological effect in fixation location (i.e., the initial fixation location being closer to word beginning for suffixed than monomorphemic words) was present for relatively far launch sites (5–8 letters from the word beginning) and for short (175–225 ms) preview times, but not for near launch sites or longer preview times. We did not predict this pattern of results on the basis of the alternative theoretical accounts put forth. Yet, they



**Fig. 4.** (a) Partial effects (solid lines) of LMM and zero-order smooths of observed values (dashed lines; span = 0.75) of gaze duration as a function of preview fixation time (i.e., duration of last fixation on the pre-target word), morphological structure of target word (monomorphemic vs. suffixed), and preview type (identical vs. changed). Shaded bands (only partial effects) represent 95% CIs based on observation-level residuals. Horizontal line is the mean of the dependent variable; vertical lines show where main effects of preview time were estimated in the *post-hoc* linear mixed model (i.e., @ 200 ms). (b) Partial effects with individual differences in GM included in the fit; zero-order relations are identical to those in panel a.

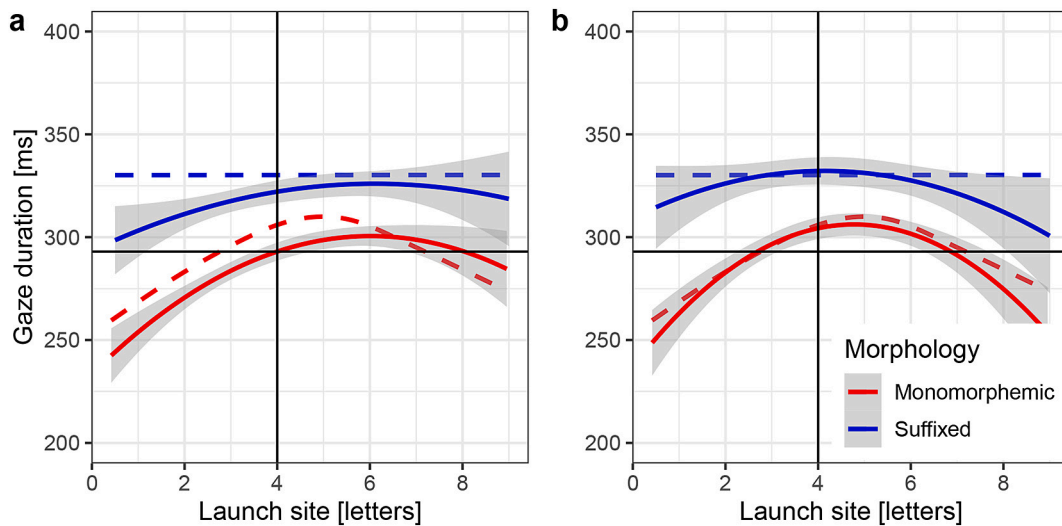
are readily explained by the parafoveal access to the short stems of the suffixed words that were parafoveally available in the change condition. When the reader fixates close to the target word prior to fixating it or when the preceding fixation is long, the reader is more likely to parafoveally perceive all letters of the target word. As in the change condition all the target words were pseudowords, the morphological effect in initial fixation location was wiped out. However, when the readers parafoveally perceived the target word from a farther distance or for a relatively short time, the readers were more likely to only perceive the beginning letters, which formed a stem in the suffixed words but not in the monomorphemic words. The availability of the stem was then used to modify the incoming saccade to the target word.

The above results in the initial fixation location in the display change condition are not readily interpretable by the suffix access view or the processing difficulty hypothesis. They both predict that the morphological effect is wiped out in the display change condition, although they predict that for different reasons. The suffix access view assumes that the effect reflects access to a highly frequent letter cluster at the end of the suffixed words. Once the ending letters are equated for the two word types, the effect should cease to exist, which did not happen. In other words, the effect remained regardless of whether the stem was followed

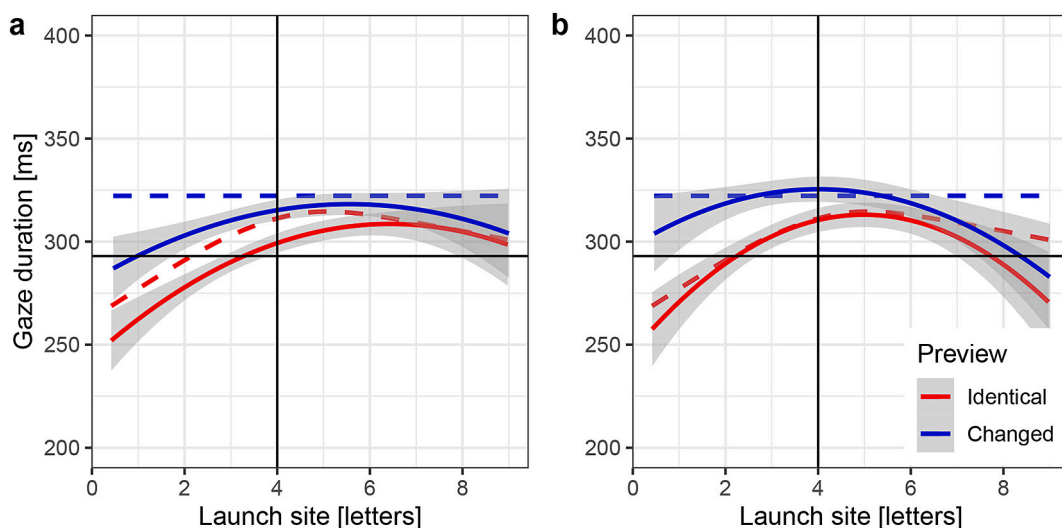
by a suffix or a non-suffix, although in the latter case it was limited to the relatively far launch sites and relatively short preview times (for reasons spelled out above).

The processing difficulty account explains the fixation location effect as a morphological complexity effect. In the display change condition all words were pseudowords, which should have made parafoveal processing generally more difficult (pseudowords are more difficult to process than words) but equally difficult between the two word types. However, the display change did not shorten the saccades in that they would generally land closer to the word beginning than in the identical condition. Moreover, the morphological effect remained even in the display change condition.

Gaze duration (and first fixation duration) provided further evidence for the notion of parafoveal access to word stems. When the suffix was parafoveally unavailable, first fixation and gaze duration on the suffixed noun were only minimally affected. On the other hand, a robust display change effect was obtained for parafoveally denying the stem of monomorphemic words (see Fig. 1b). For monomorphemic words, first fixation and gaze duration were considerably longer in the display change than in the no change condition. Further evidence for the parafoveal stem account comes from the finding that gaze durations on the



**Fig. 5.** (a) Partial effects (solid lines) of LMM and zero-order smooths of observed values (dashed lines; span = 0.75) of gaze duration as a function of launch site (in letters) and **morphological structure** of target word (monomorphemic vs. suffixed). Shaded bands (only partial effects) represent 95% CIs based on observation-level residuals. Horizontal line is the mean of the dependent variable; vertical lines show where main effects of launch site were estimated in the *post-hoc* linear mixed model (i.e., @ 4 letters). (b) Partial effects with individual differences in GM and launch-site effect included in the fit; zero-order relations are identical to those in panel a.



**Fig. 6.** (a) Partial effects (solid lines) of LMM and zero-order smooths of observed values (dashed lines; span = 0.75) of gaze duration as a function of launch site (in letters) and **preview type** (identical vs. changed). Shaded bands (only partial effects) represent 95% CIs based on observation-level residuals. Horizontal line is the mean of the dependent variable; vertical lines show where main effects of launch site were estimated in the *post-hoc* linear mixed model (i.e., @ 4 letters). (b) Partial effects with individual differences in GM and launch-site effect included in the fit; zero-order relations are identical to those in panel a.

suffixed words did not vary as a function of launch site, whereas gaze duration on the monomorphemic words did so (see Fig. 5). Presumably, this is due to the stem of the suffixed words being short and appearing in the word beginning so that it can be perceived even from a bit longer distance.

The pattern of results is readily interpretable by a non-morphological account put forth by Grainger and Beyersmann (2017). It is based on the idea that edge-aligned embedded word stems are readily activated during lexical access without the need for morphological decomposition of words into stems and affixes. The point is that word stems are often encountered as independent units separated by spaces, which strengthens their activation in the mental lexicon. Thus, they can be readily activated when appearing in morphologically complex words without morphological analysis. The notion of edge-aligned embedded

word stem activation has been offered by Grainger and Beyersmann to account for evidence supporting the existence of embedded stem activation in lexical decision and priming experiments (for supportive evidence in French, see Beyersmann, Casalis, Ziegler, & Grainger, 2015; Beyersmann, Cavalli, Casalis, & Colé, 2016; in English, see Beyersmann, Grainger, & Castles, 2019; Heathcote, Nation, Castles, & Beyersmann, 2018; in German, see Hasenäcker, Beyersmann, & Schroeder, 2016, 2020). Recently, using the fast priming paradigm (Sereno & Rayner, 1992), Mousikou and Schroeder (2019) extended the embedded stem activation to reading by demonstrating that “skilled readers activate embedded stems during word recognition, independently of whether these stems are combined with an affix or a nonmorphological unit” (p. 892). The present study demonstrates that edge-aligned word stems can readily be parafoveally perceived resulting in a modulation of saccadic

programming and in facilitation of subsequent foveal word processing.

#### 4.2. Implications for parafoveal processing in reading

It has been firmly established that having a word parafoveally available facilitates its subsequent foveal processing (for reviews, see Hyönä, 2011; Schotter, Angele, & Rayner, 2012). It has been coined the parafoveal preview benefit. Information extracted from a word parafoveally is then utilized to facilitate (speed up) its foveal processing. Several studies demonstrate that orthographic and phonological information is picked up parafoveally. However, there has been a long-standing debate whether semantic information can be parafoveally extracted. The seminal studies failed to find support for parafoveal semantic processing, whereas the more recent studies have been able to do so. Similarly, as reviewed in the Introduction, the notion of parafoveal morphological processing was not supported by the seminal studies, whereas more recent studies have provided evidence for it.

As discussed above, the present study has provided evidence for the view that word stem can be parafoveally processed (at least when it is short). It is clear that the effect cannot be a reflection of simply parafoveally extracting orthographic or phonological information from the beginning letters. If this were the case, there should be no difference in the eye movement record between the two word types. This is because the beginning 3–5 letters were always parafoveally available, regardless of the preview condition. Thus, the effects must be lexical-morphological in nature.

Above, we have argued that the present evidence supports the non-morphological view based on edge-aligned activation of word stem information. Yet, even though we found no support for the suffix access view, we cannot disregard the possibility for parafoveal morphological processing. Stoops and Christianson (2017) demonstrated that readers of Russian (another morphologically rich language) can parafoveally extract suffix information from the word ending. In order to do so, they administered three preview conditions so that in the changed conditions only the final letter was changed. In the identical condition, the nominative inflection denoted the word to be the sentence subject, in the morphologically related condition the inflection was replaced with an accusative inflection denoting sentence object, whereas in the third condition the final letter was replaced with a letter that made the target a non-word. Stoops and Christianson used sentence constructions where object and subject can appear with equal probability. Thus, a preview with the accusative case inflection (i.e., the morphologically related condition) was a possible continuation to the sentence. The main result was a preview cost (a difference between the identical and morphologically related condition) observed in late processing, as indexed by the total fixation time on the target. The preview cost is interpreted to reflect conflict resolution; in the morphologically related condition the target's syntactic role perceived in the parafovea was in conflict with its role when foveally processed. Most importantly, the syntactic role assignment based on suffix information was completed using parafoveal information. A similar pattern of results was obtained in their follow-up study (Stoops & Christianson, 2019), where an analogous morphological manipulation was made within a word (the target words were on average 13 letters long).

What consequences does the Stoops and Christianson (2017) study have for the interpretation of the present results? It does not discredit the parafoveal stem access account offered as the theory to account for the present results. However, it suggests that on the basis of the present study we cannot discredit the suffix account spelled out in the Introduction. It is namely possible that had we replaced a suffix with another suffix, as done by Stoops and Christianson, we may have observed a parafoveal morphological effect along the lines of the suffix account. Future studies similar to the Stoops and Christianson (2017) study are definitely warranted. It remains to be seen whether the results observed in Russian will generalize to other morphologically productive languages. There is some indirect evidence suggesting that they may not

necessarily generalize to Finnish. Vainio, Hyönä, and Pajunen (2008) found a delayed effect of morphological agreement in processing adjective-noun phrases that agreed in case and number (i.e., the same inflections were repeated both in the adjective and the noun). The effect was not apparent in the head noun preceded by an agreeing adjective, but only in the following word. Thus, Vainio et al. argue that the delayed effect of case agreement has an impact on syntactic integration but not on lexical access.

#### 4.3. Implications for eye movement control models

Although the present study was not designed as a test of the eye movement control models of reading, the results have consequences for them. The models can be divided into serial and parallel models, depending on whether they assume readers to process one word or multiple words simultaneously. The most influential serial model is the E-Z Reader model (Reichle, Rayner, & Pollatsek, 2003). According to it, readers attend to words one at a time. When the word's lexical processing has proceeded to a stage where lexical access is imminent (the so-called L1 stage), a saccade is programmed toward the center of the following word. Thus, depending on word length a saccade of longer amplitude is programmed to a long than a short word. Moreover, saccadic launch site modulates the execution of the actual saccade. When launched from a near position, the saccade is likely to overshoot its target (i.e., word center), whereas an undershoot is likely when launching a saccade from a far location (McConkie, Kerr, Reddix, & Zola, 1988). Prior to the saccade execution, during the so-called non-labile stage, the to-be fixated word is parafoveally previewed. However, during the non-labile stage, the saccade program cannot be modulated. Thus, despite the fact that the readers gain a parafoveal preview of the adjacent word, the incoming saccade is programmed toward the word center prior to the word's parafoveal processing. In sum, the E-Z Reader model is thus not able to explain the saccadic modification by morphological information.

Parallel models (SWIFT of Engbert, Nuthmann, Richter, & Kliegl, 2005; Glenmore of Reilly & Radach, 2006; OB1-Reader of Snell, van Leipsig, Grainger, & Meeter, 2018) assume that multiple words within the current attentional gradient are processed simultaneously albeit with different degrees of efficiency. Moreover, more recent versions of the SWIFT model (Risse, Hohenstein, Kliegl, & Engbert, 2014; Schad & Engbert, 2012) implement a dynamical modulation of the attentional span by local processing difficulty analogous to the zoom-lens metaphor of visual attention (see also Bicknell, Levy, & Rayner, 2020). This version of the model aligns closely with the processing-difficulty account entertained as one of the explanations for the morphological complexity effect. As this account is challenged by the current results, general notions of processing difficulty (i.e., word frequency and predictability) are probably not sufficient to explain the morphological effect in initial fixation location. Nor can they easily model initial fixation location effects caused by irregular letter clusters in the word beginning (Hyönä, 1995; White & Liversedge, 2004). Implementations of more sophisticated interfaces between motor programs and lexical access, inspired by theoretical accounts and constraints of sublexical processing remain an important desideratum.

How models could handle morphological structure in a principled way is not a serial vs. parallel issue. Rather it relates to the level of model specification. Most models currently use word frequency and word predictability and indirectly word length as sources of processing difficulty that translates into the modulation of activity levels, motor programs, and their dynamics. To the degree that morphological complexity is correlated with these indicators, models should be able to account for them. If effects of morphological structure do not fall out of a model's dynamics, this may suggest a theoretical underspecification. It may be necessary to take into account sublexical properties such as letter bigram frequencies and their position in words. Ideally such a modification should not be simply "hacked" into the model, but a change in

some fundamental model assumption should be motivated, such as a change from using word’s center as the default saccade target to being guided by its sublexical properties.

4.4. Limitations and future directions

It may be recalled that in the present study the stem and suffix part were comparable in length. From that perspective, they had equal power in affecting parafoveal processing. On the other hand, word stems are in a more advantageous position for parafoveal processing by being closer to the fixation during which parafoveal processing takes place (see White, Johnson, Liversedge, & Rayner, 2008, for the importance of word-initial letters in word processing). Yet, this is not the sole reason why stems were preferred over suffixes. As detailed above, the morphological effect in initial fixation location in the preview change condition was limited to relatively far launch sites, in other words, to cases where the word stem was quite far in the parafovea. Moreover, the view that word stems are readily perceivable in the parafovea was also supported by the finding that the morphological effect in initial fixation location was obtained with relatively short preview times (175–225 ms).

It is also noteworthy that the target words were relatively short (6–9 letters), at least in Finnish standards. This may have facilitated the parafoveal access to the word stem. The facilitation may come in two forms. First, the fact that the stem itself was short (3–5 letters) increased the possibility that all the letters constituting the stem could be parafoveally perceived. Second, the fact that the whole word was quite short may have diminished the lateral masking caused by the ending letters, compared to a case where the stem would be a part of a long word. Bertram and Hyönä (2003) examined the parafoveal processing of rather long two-constituent compound words (an average length of 12.6 letters), whose first constituent was either short (3–4 letters) or long (8–11 letters). The gaze-contingent display change paradigm was used. In the change condition, only the first 3–4 letters were kept intact, all the remaining letters were changed by random letters. Thus, in the short 1st constituent condition, the entire constituent was parafoveally available, which was not the case for the long 1st constituent compound words. Yet, they found no effects in the initial fixation location. It may be the case that the long word ending obscured the initial constituent, leading to a null effect. Also, one needs to keep in mind that the Bertram and

Hyönä (2003) study is not directly comparable to the present study, as the studied morphological structure was different. The beginning letters in their study comprised a compound word modifier, whereas the compound word head corresponding to the word stem appeared as the 2nd constituent.

One way to examine whether parafoveal access to word stems is due to the stem appearing in the word beginning is to extend the present findings to prefixed words, where the stem is preceded by a prefix (e.g., Mousikou & Schroeder, 2019). In Finnish, a completely analogous study to the present one could not be done, because the inflections always appear as suffixes. Moreover, prefixes change the word meaning (e.g. *toivo* = hope vs. *epätoivo* = despair), which is not the case with Finnish suffixed words. On the other hand, to further examine the role of suffixes in parafoveal word processing, an experiment may be conducted with pseudoword parafoveal previews by comparing pseudoword pairs (e.g., *farmity* vs. *farmald*) formed by combining an existing stem (*farm*) with either an existing suffix (*-ity*) or a non-suffix (*-ald*).<sup>3</sup> If readers readily access the suffix, the parafoveal access to the stem may be facilitated, compared with the non-suffix condition. In contrast, if word stem has priority in processing over affixes, the two pseudoword conditions would not differ from each other.

5. Conclusions

The present eye-tracking study of reading demonstrated that readers of a morphologically rich language (Finnish) are able to parafoveally perceive the stem of morphologically complex words so that they can program the saccade closer to the word stem. Moreover, the parafoveal availability of the word stem facilitated the word’s subsequent foveal processing. These findings are evidence for parafoveal lexical-morphological processing.

Acknowledgements

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The supplementary materials are available in the OSF repository (<https://osf.io/4m6au/>).

Appendix A. Appendix

Table A1  
A priori linear mixed model results for initial fixation location in the target word.

| Fixed effects                            | Estimates | 2.5% - 97.5% CI  | Statistic     |
|--|-----------|------------------|---------------|
| Grand mean (GM)                          | 0.497     | 0.473–0.520      | <b>41.63</b>  |
| Target-word length (twl)                 | –0.042    | –0.049 to –0.035 | <b>–11.70</b> |
| Launch-word length (lwl)                 | 0.019     | 0.019–0.023      | <b>10.03</b>  |
| Preview type (type)                      | 0.001     | –0.003–0.005     | 0.37          |
| Morphology                               | 0.009     | 0.004–0.015      | <b>3.54</b>   |
| Launch site (ls)                         | –0.044    | –0.048 to –0.039 | <b>–19.30</b> |
| Preview time (time)                      | 0.006     | –0.009–0.020     | 0.75          |
| Preview type x morphology                | 0.003     | –0.001–0.007     | 1.38          |
| Preview type x launch site               | –0.001    | –0.003–0.001     | –1.09         |
| Preview type x preview time              | 0.005     | –0.007–0.017     | 0.86          |
| Morphology x launch site                 | 0.001     | –0.002–0.003     | 0.64          |
| Morphology x preview time                | 0.004     | –0.008–0.015     | 0.62          |
| Preview type x morphology x launch site  | –0.003    | –0.005 to –0.001 | <b>–2.52</b>  |
| Preview type x morphology x preview time | 0.017     | 0.006–0.029      | <b>2.93</b>   |

(continued on next page)

<sup>3</sup> We are grateful to Reviewer 2 for suggesting this follow-up study.

**Table A1** (continued)

| Variance components | Estimates | 2.5% - 97.5% CI |
|---------------------|-----------|-----------------|
| σ GM.item           | 0.017     | 0.011–0.023     |
| σ GM.subj           | 0.095     | 0.081–0.115     |
| σ ls.subj           | 0.015     | 0.011–0.019     |
| σ time.subj         | 0.029     | 0.000–0.049     |
| σ twl.subj          | 0.017     | 0.010–0.023     |
| σ lwl.subj          | 0.010     | 0.007–0.014     |
| σ residual          | 0.139     | 0.136–0.142     |

*Note.* Durations were log-transformed. Statistics corresponds to z-statistic, because the number of observations is large enough to assume that t-distribution converged to normal distribution. Significant z-statistics ( $p < .05$ ) are set in bold; CIs for variance components are profiled shortest 95% intervals. N of subjects = 68, N of items = 100, N of observations = 4853.

**Table A2**

Post-hoc linear mixed model results for initial fixation location in the target word.

| Fixed effects                  | Estimates | 2.5% - 97.5% CI  | Statistic     |
|--------------------------------|-----------|------------------|---------------|
| Grand mean                     | 0.497     | 0.473–0.520      | <b>41.64</b>  |
| Target-word length             | –0.042    | –0.049 to –0.035 | <b>–11.70</b> |
| Launch-word length             | 0.019     | 0.016–0.023      | <b>10.03</b>  |
| Preview                        | 0.001     | –0.003–0.005     | 0.37          |
| Effects with identical preview |           |                  |               |
| Morphology                     | 0.012     | 0.006–0.019      | <b>3.65</b>   |
| Launch site                    | –0.045    | –0.050 to –0.040 | <b>–17.73</b> |
| Preview time                   | 0.011     | –0.008–0.030     | 1.11          |
| Morphology x launch site       | –0.002    | –0.005–0.001     | –1.28         |
| Morphology x preview time      | 0.021     | 0.004–0.038      | <b>2.48</b>   |
| Effects with changed preview   |           |                  |               |
| Morphology                     | 0.007     | 0.000–0.013      | 1.96          |
| Launch site                    | –0.043    | –0.048 to –0.038 | <b>–16.72</b> |
| Preview time                   | 0.000     | –0.018–0.019     | 0.04          |
| Morphology x launch site       | 0.004     | 0.000–0.007      | <b>2.20</b>   |
| Morphology x preview time      | –0.014    | –0.030–0.003     | <b>–1.64</b>  |

*Note.* Durations were log-transformed. Statistics corresponds to z-statistic because number of observations is large enough to assume that t-distribution converged to normal distribution. Estimates for variance components are as in Table 2. Significant z-statistics ( $p < .05$ ) are set in bold; CIs for variance components are profiled shortest 95% intervals. N of subjects = 68, N of items = 100, N of observations = 4853.

**Table A3**

A priori linear mixed model results for gaze duration in the target word.

| Fixed effects                            | Estimates | 2.5% - 97.5% CI  | Statistic     |
|--|-----------|------------------|---------------|
| Grand mean (GM)                          | 5.680     | 5.631–5.729      | <b>227.78</b> |
| Target-word length (twl)                 | 0.058     | 0.040–0.075      | <b>6.50</b>   |
| Launch-word length (lwl)                 | 0.006     | –0.002–0.015     | 1.49          |
| Preview type (type)                      | –0.028    | –0.037 to –0.019 | <b>–6.11</b>  |
| Morphology                               | –0.048    | –0.063 to –0.034 | <b>–6.55</b>  |
| Launch site – linear (ls)                | 0.020     | 0.013–0.027      | <b>5.32</b>   |
| Launch site - quadratic                  | –0.005    | –0.007 to –0.002 | <b>–3.81</b>  |
| Preview time – linear (time)             | 0.059     | 0.031–0.088      | <b>4.04</b>   |
| Preview time – quadratic                 | 0.054     | 0.005–0.102      | <b>2.18</b>   |
| Preview type x morphology                | –0.015    | –0.024 to –0.006 | <b>–3.33</b>  |
| Preview type x launch site               | 0.008     | 0.003–0.0130     | <b>3.01</b>   |
| Preview type x preview time              | 0.010     | –0.017–0.036     | 0.72          |
| Morphology x launch site                 | 0.007     | 0.001–0.012      | <b>2.43</b>   |
| Morphology x preview time                | –0.032    | –0.059 to –0.006 | <b>–2.38</b>  |
| Preview type x morphology x launch site  | 0.002     | –0.003–0.007     | 0.86          |
| Preview type x morphology x preview time | 0.037     | 0.011–0.064      | <b>2.77</b>   |
| Variance components                      | Estimates | 2.5% - 97.5% CI  |               |
| σ GM.item                                | 0.057     | 0.045–0.071      |               |
| σ GM.subj                                | 0.191     | 0.161–0.230      |               |
| σ ls.subj                                | 0.016     | 0.006–0.025      |               |
| σ twl.subj                               | 0.030     | 0.012–0.045      |               |
| σ lwl.subj                               | 0.012     | 0.000–0.020      |               |
| σ residual                               | 0.317     | 0.310–0.323      |               |

*Note.* Durations were log-transformed. Statistics corresponds to z-statistic because number of observations is large enough to assume that t-distribution converged to normal distribution. Significant z-statistics ( $p < .05$ ) are set in bold; CIs for variance components are profiled shortest 95% intervals. N of subjects = 68, N of items = 100, N of observations = 4853.

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