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Long-lag morphological priming and inflectional paradigm size effects in Estonian and Finnish text reading

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Abstract

Morphological priming and paradigm size effects have been established in single word reading studies, however, morphological priming effects in longer texts have not been observed, and, to the best of our knowledge, paradigmatic effects in text reading have not yet been examined. The current study utilized the Multilingual Eye-Tracking Corpus MECO (Siegelman et al., 2022) to explore paradigmatic and morphological priming effects during text reading in Estonian and Finnish, two morphologically rich Finno-Ugric languages. The results showed clear inflectional paradigm size effects for Estonian during text reading in several eye movement measures, but not for Finnish. This may be linked to the support from the inflectional paradigm being semantically more beneficial to the reader in Estonian than in Finnish. The current study also showed clear long-lag inflectional priming effects in text reading, unlike what was observed in prior studies in Dutch, English, and Spanish. This study is thus the first to show that inflectional priming can extend beyond word or sentence level and suggest that inflectional variants of a particular word in Estonian and Finnish get and remain activated even when text context is present.

Keywords: reading; eye-tracking; morphological processing; morphological priming; Estonian; Finnish; inflectional paradigms.

1 Introduction

Morphological processing, including the processing of inflected words like *cats* or *talked*, has been examined almost exclusively with single word paradigms (see e.g., Amenta & Crepaldi 2012, Feldman & Milin 2018 for overviews). Most often, studies have employed a lexical decision task, requiring participants to differentiate between presented words and pseudowords. Compared to normal reading, a task such as lexical decision is a relatively artificial language task (see e.g. Bertram 2011 and Coskun et al. 2023, for a discussion). This raises the question whether various morphological effects generally reported in single word studies also emerge in more natural language settings, such as text reading. In the current study, we employ Finnish and Estonian to focus on two types of morphological effects that have been examined in single word studies but not in text reading: the long-lag morphological priming effect and the inflectional paradigm effect.

Morphological priming involves initial exposure to a prime stimulus that is morphologically related to a subsequently presented target word. Numerous single word studies have reported that a word form such as *cats* is processed faster when preceded by a different inflectional variant of the word such as *cat* (see Amenta & Crepaldi, 2012)). Morphological priming has been found not only in studies where a target immediately follows the prime, but also when primes are separated from their target by 8-13 intervening items (Raveh & Rueckl, 2000). This long-lag priming effect implies sustained activation of the prime for a certain period of time.

Unseen inflectional variants within a specific inflectional word paradigm can also affect word processing speed. In morphologically rich languages like Estonian and Finnish, inflectional paradigms are typically very extensive, but their size, e.g., the number of different forms in which a word actually occurs, varies nevertheless considerably across words. For Estonian, it has been established that words with a large inflectional paradigm yield faster processing times than words with a small paradigm size (Lõo et al., 2018a,b).

Until now, both morphological priming and paradigm size effects have been established in single word studies, and morphological priming effects have also been found in some sentence reading studies with prime and target in close proximity (see e.g., Paterson et al., 2011). However, attempts to find priming effects in Spanish, English, or Dutch within longer text excerpts such as short stories (Kamienkowski et al., 2018) or books (Coskun et al., 2023) have been futile.

Morphological priming effects in text contexts are likely to be more pronounced in morphologically rich languages, such as Estonian and Finnish. These languages, characterized by their abundance of morphological variants, create overt morphological connections between words, which can significantly influence word processing. This effect is expected to be stronger in Estonian and Finnish compared to morphologically less rich languages, such as Spanish, English, or Dutch. Additionally, the considerable variability in the inflectional paradigm size of nouns in Estonian and Finnish may also impact word processing in text contexts. Given that inflectional variants are more frequently encountered in these languages, inflectional priming may play a more critical role in facilitating word processing than in languages with smaller or less complex inflectional paradigms.

The current study leveraged the Multilingual Eye-Tracking Corpus MECO (Siegelman et al., 2022) to explore the paradigm size effect and a specific variant of morphological priming, namely inflectional priming of nouns, in text reading, using the Estonian and Finnish datasets. MECO includes eye movement data on reading 12 short expository texts of 100-200 words in 13 different languages, including Finnish and Estonian, by approximately 50 adult readers per language. Initially written in English, the texts were translated or paraphrased into other languages in the project, allowing a comprehensive cross-linguistic comparison of adult reading behavior.

Compared to English, which mainly makes use of two nominal inflectional variants only, the singular and plural nominative, Estonian and Finnish make use of a wide range of nominal inflections, making these languages an excellent testbed for studying morphological effects during text reading. Before introducing the current study, we will provide a brief comparative introduction to Estonian and Finnish nominal morphology.

1.1 Estonian and Finnish inflection

Both Estonian and Finnish are agglutinative languages, where most grammatical relations are realized by adding suffixes to a word stem (Karlsson, 2015; Viitso, 2007). Estonian has 14 nominal cases in singular and plural. Many plural forms also have parallel forms (e.g., the inessive plural of *jalg* 'foot' can be realized as *jalgades*, *jalus*, or *jalges* 'foot, insessive plural'). Finnish also has 14 cases, and also some parallel forms (e.g., in the illative and partitive). Table 1 lists all the inflectional cases in Estonian and Finnish for the word 'auto', which means *car* in both languages. Most cases are similar in Estonian and Finnish. In fact, the only difference is that Estonian has the terminative case, whereas Finnish has the instructive case which Estonian does not have. In Finnish, the instructive and comitative case exist only in the plural, even if the meaning applies to both singular and plural.

Finnish is more agglutinative than Estonian. Unlike Finnish, Estonian contains fused case endings, where one suffix can express several meanings or grammatical functions. For example, in the Estonian nominal form *majasid*, *-sid* both conveys the partitive and plurality, while in the Finnish form *taloja*, these functions are marked separately with the suffix *j* indicating plurality and the suffix *a* the partitive function. Estonian case endings are also often shorter than Finnish case endings. For example, in Estonian the inessive case is marked with a single segment suffix *-s*, whereas in Finnish the inessive suffix contains three segments *-ssA*.

Table 1: Estonian and Finnish inflectional paradigms of *auto* 'car' with 28 members each. Case endings marked in bold.

Case	Singular in Estonian	Plural in Estonian	Singular in Finnish	Plural in Finnish	Meaning
Nominative	auto	auto**d**	auto	auto**t**	car(s)
Genitive	auto	auto**de**	auto**n**	auto**jen**	of car(s)
Partitive	auto**t**	auto**sid**	auto**a**	auto**ja**	car(s)
Illative	auto**sse**	auto**desse**	auto**on**	auto**ihin**	into car(s)
Inessive	auto**s**	auto**des**	auto**ssa**	auto**issa**	in car(s)
Elative	auto**st**	auto**dest**	auto**sta**	auto**ista**	from car(s)
Allative	auto**le**	auto**dele**	auto**lle**	auto**ille**	onto car(s)
Adessive	auto**l**	auto**del**	auto**lla**	auto**illa**	on car(s)
Ablative	auto**lt**	auto**delt**	auto**lta**	autoilta	from car(s)
Translative	auto**ks**	auto**deks**	auto**ksi**	auto**iksi**	as car(s)
Terminative	auto**ni**	auto**deni**	-	-	to car(s)
Essive	auto**na**	auto**dena**	auto**na**	auto**ina**	as car(s)
Abessive	auto**ta**	auto**deta**	auto**tta**	auto**itta**	without car(s)
Comitative	auto**ga**	auto**dega**	-	auto**ineen**	with car(s)
Instructive	-	-	-	auto**in**	by means of car(s)

Furthermore, opposite to Finnish, some grammatical cases in Estonian are not expressed in suffixes at all. In Finnish, the genitive singular is marked with an *-n* (*talo* and *talon* 'house, nominative and genitive singular', *sää* and *sään* 'weather, nominative and genitive singular', *lapsi* and *lapsen* 'child, nominative and genitive singular'). In Estonian, the genitive singular case can be syncretistic with the nominative case when the stem ends with a vowel (e.g., *maja* 'house, nominative/genitive singular'). Alternatively, it is formed by adding a stem vowel to the nominative singular. However, in that case, there are no set rules with which vowel a genitive ends (e.g., *ilm* and *ilma* 'nominative and genitive singular, weather', *laps* and *lapse* 'child, nominative and genitive singular', *kool* and *kooli* 'school, nominative and genitive singular').

Finnish also has the possibility to express possessive relations through suffixes. Moreover, it uses suffixes and clitics very extensively, for instance, to denote stress (-*pA*), emphasis (-*hAn*), inclusiveness and focus (-*kin*) or questioning (-*kO*). Estonian has no possessive suffixes and only a few clitics (e.g., -*ki* and -*gi*, expressing inclusiveness and focus). In terms of morphological stem changes, Finnish has retained consonant gradation to a greater extent than Estonian.

Given these different characteristics, a Finnish word form like *talo+ssa+ni+kin* has to be expressed with two different words in Estonian *minu maja+s+ki* and four different words in English *'also in my house'*. In other words, compared to English, the number of possible different inflectional forms is very large in Estonian, but even larger in Finnish. To anticipate, the range of the realized inflectional paradigm size in the current study is also considerably larger in Finnish than in Estonian (see Figure 1 and Table 1).

The morphological richness of both Estonian and Finnish also yields a different scenario with respect to morphological priming. For instance, the 12 English texts in the MECO database (Siegelman et al., 2022) contain 577 nouns in English of which 32 percent have an inflectional suffix, mostly marking the plural. For

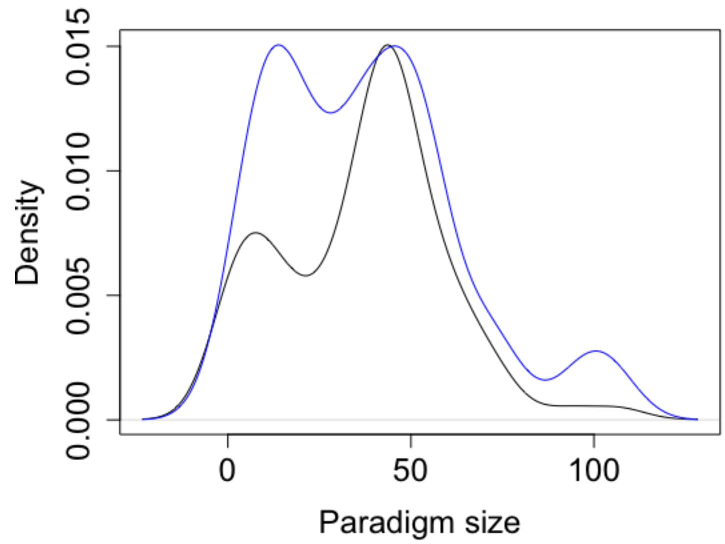

Figure 1: Estonian and Finnish paradigm densities for the nouns in the MECO texts. Estonian in black: N=173, Bandwidth=3.54; Finnish in blue: N=174, Bandwidth=8.13.

Estonian and Finnish, the percentage of inflected nouns amounts to 58 percent and 92 percent, respectively. The higher density of inflectional forms in the latter two languages implies that the distance between different morphological forms is generally smaller, whereas conversely, the chance of words being repeated in exactly the same form is higher in English.

1.2 Inflectional priming in single word studies

The goal of inflectional priming studies has been to establish how language users make use of morphological structure and at what point in time it affects lexical processing. Starting with the seminal study by Stanners et al. (1979), it has been established repeatedly that inflectional variants of the same lemma prime each other. Although the interpretation for this effect has differed across studies, they agree that morphological structure can affect word processing from early on (see e.g., Amenta & Crepaldi 2012, Feldman & Milin 2018 for overviews). To capture the time course of morphological processing, researchers have made use of both the unmasked and masked priming paradigms. Unmasked priming studies, in which primes are consciously processed, show inflectional priming effects in several languages. For instance, Raveh (2002) showed that English inflected primes were faster after uninflected targets using different durations for primes (150 ms vs. 250 ms). Feldman has reported similar inflectional priming effects for Serbian (Feldman, 1994).

To establish early involvement of morphological processes, masked priming studies have been conducted in which the prime is offered for a very short amount of time, 50 ms or even shorter. The short exposure time prevents conscious awareness of the prime, but several studies showed that even under these conditions, inflectionally related forms prime each other (e.g., Feldman 1994; Raveh 2002; Raveh & Rueckl 2000). Lõo et al. (2022) found not only a clear masked priming effect for inflected English forms (e.g., *bulls*-*bull*), but also showed, by means of quantile regression analyses, that the effect was already present within the first decile of the reaction times. They also showed that the priming with real inflected forms remained significant until the last deciles, whereas the pseudo-complex priming (*bully*-*bull*) was weaker across all deciles. This suggests that inflectional priming emerges at an early stage and that it may differ depending on whether the prime is semantically related to the target or not.

Several inflectional priming studies indicate that there are not only early effects of morphological structure in reading, but also that the effect may endure for an extended period. This phenomenon is referred to as long-lag inflectional priming. Feldman & Bentin (1994) showed clear inflectional priming effects for prime-target pairs in Hebrew that were separated by 7 to 13 unrelated items, both for prime-target pairs with similar orthographic patterns as for those with dissimilar orthographic patterns. Similarly, Raveh & Rueckl (2000) found solid inflectional priming effects in English for prime-target pairs separated by 8-13 intervening items. Comparable effects with regular inflections were observed in English, French, German and Spanish (Münte et al., 1999; Rodriguez-Fornells et al., 2002; Royle et al., 2012; Weyerts et al., 1996). The long-lag morphological priming effect cannot be solely attributed to semantic overlap, as there is little evidence for long-lag priming of semantically related but morphologically unrelated word pairs (*doctor*-*nurse*) (see e.g., Henderson et al. 1984). Thus, it seems that both form and meaning overlap are required for long-lag priming to occur.

Taken together, single-word priming studies suggest that activation of internal morphological structure in inflected word forms emerges very rapidly and lingers on for a considerable period of time. The latter finding raises the question to what extent there is prolonged activation of morphological structure when inflected words are embedded in a textual context. To examine this is one of the aims of the current study.

1.3 Paradigmatic effects in single words studies

Several studies focusing on single words indicate that word processing times are affected not only by the properties of the words being read, such as morphological structure, length, or frequency, but also by words that are morphologically related to them. One clear example pertains to the research on morphological family size, the number of derivations and compound words (e.g., *worker*, *handwork*, *work-hour*) derived from a simplex noun (e.g., *work*). That is, several studies showed that response times in visual lexical decision are shorter for simplex nouns with larger morphological families (Bertram et al., 2000; De Jong et al., 2003; Schreuder & Baayen, 1997). Moscoso del Prado Martín et al. (2004) showed that the morphological family size effect is semantic in nature, that is, they found that only semantically related family members (e.g., *työ* 'work' - *työläinen* 'worker') contributed to the family size effect, but not semantically more remote members (e.g., *urotyö* 'heroic deed').

Another example, closer to the current study, concerns the distribution of word forms in the inflectional paradigm of a complex word. One relevant measure here is inflectional entropy, which quantifies the average amount of information in an inflectional paradigm. The more uniformly the inflected forms are distributed within a paradigm, the higher the inflectional entropy of that paradigm. Inflected forms with higher inflectional entropy have been reported to be recognized faster than inflected forms with lower inflectional entropy (Milin et al., 2009; Moscoso del Prado Martín et al., 2004).

A paradigm measure related to inflectional entropy is inflectional paradigm size. In most Indo-European languages, inflectional paradigms contain only a few inflectional variants (e.g., nominative, genitive, dative and accusative forms in German), but in Finno-Ugric languages like Estonian and Finnish there are many more possibilities, since several prepositions, possessive markers and other linguistic units need to be actualized as suffixes rather than as separate words. Consequently, the inflectional paradigm size for practically any given word is larger in Finnish or Estonian than in languages with simpler morphology. It is important to consider, though, that many forms of an inflectional paradigm are never realized, as they are semantically implausible. For instance, certain words do not easily take the plural (e.g., *selkärangat* 'spine, nominative, plural'), others do not combine very well with the essive (e.g., *autona* 'as a car, essive singular', see Table 1), others again do not combine well with possessive suffixes (e.g., *aurinkosi* 'your sun'), and so forth. Consequently, many formally possible word forms are not found in language corpora (Karlsson, 1986). The actual number of inflectional forms realized for any given word thus depends to a large extent on the semantic range or potential of that word as a concept. Additionally, the frequency of the word itself plays a role, with more frequent words typically appearing in more inflectional forms.

For Estonian, it has been established that words with larger realized inflectional paradigms are recognized faster in a visual lexical decision task and read aloud faster in a naming experiment (Lõo et al., 2018a,b). Bertram et al. (2000) suggested that the activation of a large number of morphological descendants leads to significant overall activation in the central lexicon, allowing participants to respond quickly. This suggestion pertained to the morphological family size effect, but we contend that the same holds for the inflectional paradigm size effect and that this effect entails substantial interconnectivity in the mental lexicon through inflectional relatedness. Interestingly, Lõo et al. (2018a) also found an inflectional paradigm size effect in a semantic categorization task. In line with this, Lõo et al. (2018b) showed by two naming tasks that the size of the inflectional paradigm has a stronger effect in the later deciles of the reaction times. Taken together, the results suggest that, similar to what has been found for the morphological family size effect, there is a semantic contribution to the inflectional paradigm size effect.

In summary, various paradigmatic effects have been reported in previous studies, suggesting that - even when an isolated single word is read - inflectionally related word forms of the same paradigm are activated. However, it is not clear whether such effects remain present within a sentence or text context. The second aim of the current study is to investigate that.

1.4 Morphological priming and paradigmatic effects in sentence and text reading context

With the growing interest in eye movement research in reading, numerous studies have now explored morphological effects within sentence contexts (for a survey, see Bertram 2011 and Bertram & Hyönä 2023). However, very few sentence and text context studies have investigated the role of morphological priming during reading. There are nevertheless some exceptions. Paterson et al. (2011) found in a morphological priming during sentence reading study that morphologically and semantically related words (e.g., *marsh–marshy*) prime each other, whereas words that are opaquely related (e.g., *secretary–secret*) or only orthographically related (e.g., *extract-extra*) do not. The study included prime-target pairs embedded in declarative sentences with 2 to 3 intervening words ("The forest had a marshy path leading to a marsh where students studied wildlife"). Other priming effects within sentence context were found with some specific eye movement paradigms in which the prime was replaced by the target after 30-50 ms (Deutsch et al., 2018; Mousikou & Schroeder, 2019) or where prime and target where adjacent to each other (Dann et al., 2021). In other words, one can conclude that morphological priming can be extended from single-word studies to sentence content studies where prime and target are in close proximity to each other.

However, just as one could argue that making lexical decisions is not a common activity for the average reader, one could also argue that encountering morphologically related words within the same sentence is not all that common in typical reading scenarios. In other words, to increase ecological validity, morphological priming needs to be studied within larger text contexts. To our knowledge, there are only two studies to date that have undertaken this task.

Kamienkowski et al. (2018) examined an eye-tracking corpus of L1 Spanish passage reading of 10 texts with on average 3,300 words per text. They reported no change in processing times in an inflected form after its base form (*trees* following *tree*) or a base form occurring after its inflected form (*tree* following *trees*). In contrast, they reported a priming repetition effect, that is, when a word was repeated in exactly the same form (*tree* preceding *tree* or *trees* preceding *trees*), the second instance was read faster than the first one.

This repetition effect was independent of the distance between the prime and target, which ranged from 1 to 1,000 words. Similar findings were reported by Coskun et al. (2023) on the basis of the GECO corpus (Cop et al., 2017), which includes the registration of eye movements during the reading of Agatha Christie's novel 'The Mysterious Affair at Styles' by multiple readers in English L1, Dutch or English L2. That is, no effect of inflectional priming was observed in L1 and L2, indicating that this priming effect is difficult to find in a broader textual context, at least in morphologically limited languages. However, once again, a robust effect of word repetition priming was observed in L1 or L2, although the distances between repeated words were even longer than in Kamienkowski et al. (2018), more specifically, the median lag was 6,357 words.

With respect to morphology-related paradigmatic effects, Schmidtke et al. (2021) did not find an effect on the entropy of conceptual relations in English compound processing in sentence context, using a very large dataset. Baayen et al. (2011) demonstrated the effect of paradigm typicality (relative entropy) in self-paced sentence reading tasks in Serbian. However, we are not aware of any study that has examined the role of inflectional entropy or paradigm size in text context.

1.5 The current study

Until now, morphological priming effects have been found in sentence reading but not in text reading context, and inflectional paradigm size has not been investigated in text reading context at all. The current study sets out to investigate whether these effects can be observed in two languages with a very rich inflectional morphology, Estonian and Finnish. As in Kamienkowski et al. (2018) and in Coskun et al. (2023), we compared the processing of nouns in the text context in the baseline condition with the processing of nouns in the identity priming condition and the inflectional priming condition. The former condition was the first appearance of a noun in the text, while the latter two included words that appeared for the second time, either in identical form or in an inflectional variant. Slightly different from Kamienkowski et al. (2018) and Coskun et al. (2023) and to accommodate rich Finno-Ugric morphology, we created a broad category of inflectional priming, including base-inflected (*uks*-*uksed* 'door, nominative singular-door, nominative plural'), inflected-base (*uksed*-*uks* 'door, nominative plural-door,nominative singular') and inflected-inflected (*uksed*-*ustest* 'door, nominative plural- door, elative plural') prime-target pairs. Coskun et al. (2023) encouraged future studies to replicate their study in other languages, but also to include subsequent instances of base and target words, as 'it is possible that morphological priming in L1 reading starts to emerge after the second occurrence.' To address this issue, we added a fourth condition to our study, namely the enhanced inflectional priming condition, which includes target words (e.g., *ustest*) that have two or more inflectionally related primes (e.g., *uksed*-*uks*-*ustest*- or *uksed*-*uksed*-*ustest*). We expect that there will be a processing advantage for the inflectional priming condition compared to the baseline condition and that this effect will be enlarged when considering the enhanced inflectional priming condition. We do not expect a clear difference between Estonian and Finnish, as texts in both languages contain numerous inflectional variants.

The inflectional paradigm size, which is in the focus of our second goal, varies from 2 to 56 word forms in Estonian and from 1 to 104 word forms in Finnish (see Table 2) and will be treated as a continuous variable. We hypothesize that there are three possible outcomes concerning the effect of inflectional paradigm size in text context. Just as was found in single word studies, we may find that a larger inflectional paradigm size comes with shorter word processing times due to greater paradigmatic support. However, larger paradigms also imply more word form possibilities and hence more competition among paradigm members, which may lead to word processing delays. A third alternative is that there are other contextual cues that override the potential impact of paradigm size, yielding no impact of this variable whatsoever. Given that paradigms are larger in Finnish than in Estonian, the first option predicts stronger positive effects for Finnish than Estonian, and the second option predicts stronger negative effects.

In this study, we consider three different eye movement measures to assess the time course of inflectional priming and the effect of inflectional paradigm size: Gaze Duration, Total Fixation Duration, and Rereading. In this way, we can establish whether the effects emerge immediately in first pass reading, whether they only emerge at a later time point, or whether they immerse in first pass reading and continue to have an impact at later stages.

2 Method

2.1 Participants

The current study made use of the Multilingual Eye-movement Corpus (MECO) (Siegelman et al., 2022). The corpus contains eye-tracking data on reading encyclopedic texts from 13 languages in their mother tongue, including Estonian and Finnish. 52 native Estonian speakers (age range: 18-30 years; 16 males, 36 females) and 49 native Finnish speakers (age range: 19-35 years; 7 males, 42 females) were recruited for the study. All participants had normal or corrected to normal vision.

2.2 Materials

The participants read 12 one-page encyclopedic Wikipedia-style texts. They were all about common topics, such as historical figures (e.g. the Roman God Janus), events (e.g., World Environment Day) or phenomena (e.g., Beekeeping). The texts were all originally in English and were later translated or paraphrased into their respective languages (see Siegelman et al. 2022 for details on the translation procedure).

The length of the texts varied from 7-13 sentences (102-143 words) in Estonian and Finnish. From the texts, we first selected all Estonian nouns (n=586) and Finnish nouns (n=596). We limited our data sets to nouns only to control for possible effects of part of speech and to make our analysis comparable to previous studies on inflectional processing (Lõo et al., 2018a,b, 2023). To make our study comparable to previous studies on long-lag morphological priming (Coskun et al., 2023; Kamienkowski et al., 2018), we also excluded nouns that occurred only once in the text (about 50% of nouns in both languages) and nouns that occurred more than twice in the exact same form (about 10% of nouns in both languages). These restrictions limited our data set to 207 nouns for Estonian and 191 nouns for Finnish. Finally, we removed from the remaining data those nouns for which we did not have frequency or inflectional paradigm size information from our respective language corpora (33 nouns in the Estonian data and 16 nouns in the Finnish data). This left us with the final data set that contains 173 nouns for Estonian and 174 nouns for Finnish.

2.3 Procedure

Eye movements in Finnish reading were recorded with an EyeLink Portable Duo and eye movements in Estonian with an Eyelink 1000+ eye tracker (SR Research, Ontario, Canada), using a sampling rate of 1000 Hz and a 9-point calibration. A chin and a head rest were used to minimize head movements. Each text was fully displayed on a single screen using 1.5-line spacing. The Estonian site used a 23 inch screen and the Finnish site a 17 inch screen. The font for Estonian texts was 20 point Consolas and for Finnish 22 point Courier New. Participants were instructed to read silently for comprehension and press the space bar when they finished reading. Comprehension questions about the content of the text followed each text, serving as an attention check. Participants also completed a language background questionnaire and conducted individual differences tests to measure several cognitive skills, including some other language skills. This data is not considered in the current study.

3 Analyses

3.1 Predictor and response variables

We focused on three eye-tracking measures as response variables to capture both early and late reading: (1) Gaze Duration (i.e., the summed duration of all fixations on the word before the gaze leaves the word for the first time) (2) Total Fixation Duration (the summed duration of all fixations on the word), (3) Rereading (a binary index of whether the gaze came back to the word or not after the gaze left the word for the first time).

The duration of first fixation was also considered, but no effect occurred in this very early reading measure.

There were two independent variables of interest. One was Priming condition (with four categorical levels: baseline, identity priming, inflectional priming, enhanced inflectional priming). We considered as priming only occurrences within the same text, rather than between the different texts. Priming conditions were coded as follows:

(1) Baseline - the noun appeared in the text for the first time, but it also occurred later in the text as the exact same form or as a different inflectional variant (104 occurrences in Estonian, 77 occurrences in Finnish).

(2) Identity priming - the noun appeared once in the text before and in the exact same surface form, e.g., *alguses* 'beginning, inessive singular'- *alguses* 'beginning, inessive singular' (39 occurrences in Estonian, 25 occurrences in Finnish).

(3) Inflectional priming - the noun appeared in the text once before in a different inflectional variant, but not in the exact same form, e.g., *maailma* 'world, genitive/partitive singular'- *maailmas* 'world, inessive singular' (46 occurrences in Estonian, 53 occurrences in Finnish).

(4) Enhanced inflectional priming - the noun appeared more than once in the text before, but not in the same form, e.g., *uksed* 'door, nominative plural'-*uksed* 'door, nominative plural'-*ustest* 'door, elative plural' or *lipp* 'flag, nominative singular'-*lipud* 'flag, nominative plural'-*lippe* 'flag, partitive plural' (33 occurrences in Estonian, 36 in Finnish).

In the baseline condition, we considered eye movements to the first occurrence of the word, in the identity and inflectional priming conditions eye movements to the second word occurrence, and in the enhanced inflectional priming eye movements to the last word occurrence.

The second independent variable of interest was the Inflectional Paradigm Size, the number of inflectional variants of the target nouns in corpora of Estonian and Finnish (range: 2-56 in Estonian, 1-104 in Finnish). Estonian inflectional paradigm size counts, lemma and surface frequency information were extracted from the 15-million token Balanced Corpus of Estonian (Kaalep & Muischnek, 2005) and Finnish inflectional paradigm size counts, lemma and surface frequencies from the Finnish Turun Sanomat newspaper corpus comprising 22.7 million word forms by using the lexical search program WordMill (Laine & Virtanen, 1999). Surface frequency captures the total number of occurrences of a particular form in the corpus. Lemma frequency is the cumulative frequency of a complete inflectional paradigm. Word length was determined by counting the number of characters in a word. Table 2 gives an overview of the lexical-statistical characteristics of these variables.

Furthermore, we considered several other morphological characteristics (e.g., stem change, compounding, number of morphemes, case, number) of Estonian and Finnish nouns as control variables. However, besides compounding, that is, a binary index of whether a noun was a compound word or not, none of them significantly influenced Estonian and Finnish reading times.

Finally, we considered the priming distance (i.e., the distance in the number of words between the baseline and the primed word) as a control variable. Like previous studies, it was not a significant predictor. It was not possible to consider compound constituent and derivational priming with the current dataset, as there were only a few occurrences of compound and derivational constituents being repeated in the texts.

See Table 2 for an overview of the predictor variables in the two languages.

Table 2: Estonian and Finnish predictor variables.

	Estonian	Finnish
Compounding	no: 142, yes: 31	no: 142, yes - 32
Surface frequency	1-4,229 (M=391.1)	1-44 024 (M=969.4)
Lemma frequency	2-5,1041 (M=4,021.3)	2-14,6456 (M=8,391)
Word length	3-20 (M=7.7)	4-22 (M=8.8)
Paradigm size	2-56 (M=21.3)	1-104 (M=37.7)

3.2 Collinearity

Collinearity between numeric predictors can influence regression analyses (see e.g., Tomaschek et al., 2018). Specifically, collinearity can cause suppression or enhancement (see e.g., Friedman & Wall, 2005), which changes the original relationship between the predictor and the dependent variables, making it stronger, weaker, or reversing the direction.

Therefore, collinear predictors were run both together and separately in regression models to ensure that the effects of suppression or enhancement between the correlated predictors would not affect the final results. To assess collinearity, we calculated Pearson's product-moment and Spearman rank correlations between our eye movement measures and predictor variables and among our predictor variables. Differences between the two coefficients suggest that the relationship between the variables may be nonlinear or that they are not normally distributed. Tables 3 and 4 suggest that the frequency of the lemma, the surface frequency, and the size of the inflectional paradigm were correlated with each other in both data sets according to both coefficients. However, they also suggest that Pearson's correlation coefficients underestimate the correlation strength between the lemma frequency and the paradigm size, as well as between the surface frequency and the lemma frequency. Variables in current data sets may not be normally distributed and one may want to use nonlinear regression modeling. Model comparisons showed that models with surface frequency had lower AIC scores than models with lemma frequency. Therefore, we included only surface frequency in the final regression models.

Table 3: The Pearson's product-moment and Spearman-rank correlation coefficient values of continuous variables in Estonian. Pearson correlations are shown above the diagonal and are marked in gray, Spearman correlations below the diagonal in black. Pairs with values over 0.6 are marked in bold. gaze dur=gaze duration; total fixation dur=total fixation duration; surface freq = surface frequency; lemma freq = lemma frequency; paradigm size = inflectional paradigm size.

	gaze dur	total fixation dur	word length	surface freq	lemma freq	paradigm size
gaze dur	**1.00**	0.54	0.32	-0.11	-0.12	-0.23
total fixation dur	0.56	**1.00**	0.26	-0.08	-0.09	-0.18
word length	0.30	0.27	**1.00**	-0.20	-0.26	-0.55
surface freq	-0.13	-0.13	-0.27	**1.00**	0.28	0.23
lemma freq	-0.21	-0.18	-0.43	0.55	**1.00**	**0.60**
paradigm size	-0.20	-0.18	-0.47	0.45	**0.81**	**1.00**

Table 4: The Pearson and Spearman-rank correlation coefficient values of continuous variables in Finnish. Pearson correlations are shown above the diagonal and marked in gray, Spearman correlations below the diagonal in black. Pairs with values over 0.6 are marked in bold. gaze dur=gaze duration; total fixation dur=total fixation duration; surface freq = surface frequency; lemma freq = lemma frequency; paradigm size = inflectional paradigm size.

	gaze dur	total fixation dur	word length	surface freq	lemma freq	paradigm size
gaze dur	**1.00**	0.54	0.24	-0.06	-0.11	-0.14
total fixation dur	0.22	**1.00**	0.21	-0.07	-0.08	-0.14
word length	0.24	0.24	**1.00**	-0.15	-0.20	-0.52
surface freq	-0.10	-0.13	-0.46	**1.00**	**0.61**	0.30
lemma freq	-0.11	-0.13	-0.52	**0.86**	**1.00**	0.49
paradigm size	-0.12	-0.14	-0.51	**0.74**	**0.92**	**1.00**

3.3 Modelling strategy

For regression analysis, we used generalized additive mixed effects models (GAMMs, Hastie & Tibshirani 1990; Wood 2017; the R-package *mgcv*, version 1.8). GAMMs allow the testing of nonlinear relationships between the dependent and the predictor variables as well as between other predictor variables. Gaze durations and total fixation durations were modeled using a regression model with a Gaussian distribution, and for rereading, we applied a model with a binomial distribution.

Gaze durations below 50 ms and above 1500 ms and total fixation durations below 50 ms and above 2000 ms were considered outliers and removed from both data sets (3% of the data in Estonian, 1% of the data in Finnish).

We used the Box-Cox transformation framework implemented in the *powerTransform* function from the *R* package *car* (Fox & Weisberg, 2019) to determine whether a transformation was necessary for each variable. Based on this analysis, we applied a square-root transformation to the paradigm size, and a logarithmic transformation to the frequency. Additionally, we square-root transformed the dependent variables to better approximate a normal distribution.

Final models were obtained by pursuing an exploratory step-wise forward fitting modeling approach in which the contribution of each individual predictor was compared against the model containing random effects and control variables. This procedure was followed by a backward model fitting procedure in order to reassess each predictor's contribution by comparing the AIC scores. Random effects contained random intercepts for readers and texts (Coskun et al., 2023; Kuperman, 2022). Following Baayen & Linke (2020), we did not add the word random intercept to the models to avoid excessively high concurvity between random intercepts and fixed effects.

To avoid overfitting and following Baayen et al. (2017), we did not include any random slopes in our models. Pairwise comparisons between different levels of Priming condition were conducted by using each of the four levels as the reference level. Final regression models for gaze duration, total fixation duration and rereading are presented below. The effects for gaze duration and total fixation duration were in general similar, but were stronger for total fixation duration.

4 Results

4.1 Estonian gaze duration

First, we investigated gaze duration effects of the Estonian nouns. Here and in the sections below, we first report the effects of control variables and then proceed to critical effects. Compounding, surface frequency, and word length emerged as significant control variables in the model. Words that were compounds were read faster than words that were not compounds (β=0.54, t=2.60, p=0.009). The upper left panel of Figure 2 shows that gaze durations increased linearly with increasing word length. The upper right panel of Figure 2 shows that the surface frequency had an inverse U-shaped effect on the gaze duration. Infrequent and frequent words were read with shorter durations than medium-frequency words. The effect levels off in a higher frequency range.

Next, we turn to our variables of interest. Both Priming condition and Inflectional paradigm size had significant facilitatory effects. The effect of Priming condition can be seen in the left panel of Figure 4. Compared to the baseline condition (i.e., the word was read for the first time), words in the enhanced inflectional priming condition (i.e., the word had been read multiple times before but not in the exact same form) were read the fastest (β=-1.03, t=-5.89, p<0.0001), followed by the inflectional priming (i.e., the word had been read once before but not in the exact same form, β= -0.44, t=-2.88, p=0.004) and identity priming conditions (i.e., the word had been read once before in the exact same surface form, β= -0.44, t=-2.82, p=0.004).

We also compared other condition levels with each other. Pairwise comparisons showed that the priming

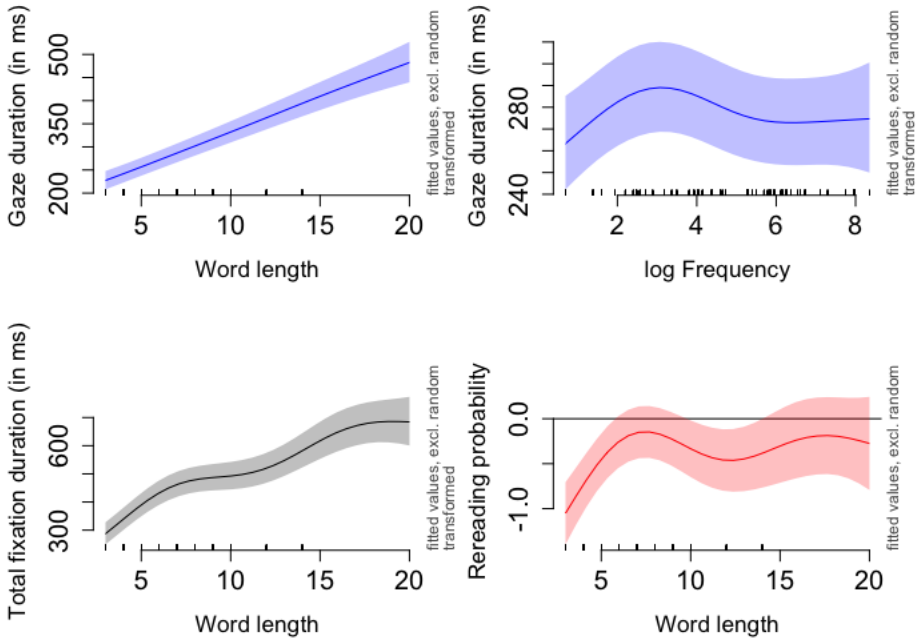

Figure 2: Predicted values of Word length and Surface frequency fitted to Estonian gaze duration, and word length fitted to total fixation duration and rereading. The shadows represent 95 % confidence bands (SE=1.96) of the regression line for individual predictors. Y-axes of gaze duration and total fixation duration were back-transformed to milliseconds.

was significantly greater for the enhanced inflected priming than for the identity priming (β=0.59, t=2.92, p=0.004) and the inflectional priming (β=0.59, t=3.08, p=0.002). The difference between the identity and the inflectional priming categories was not significant. This effect of Priming condition is illustrated in the left panel of Figure 4.

The left panel of Figure 3 illustrates the effect of the inflectional paradigm size on the duration of gaze. Words with more paradigm members were read faster than words with fewer paradigm members. The effect was linear. The full summary of Estonian gaze duration model is in Table 5 in the Appendix.

In summary, both the priming condition and the size of the inflectional paradigm emerged as significant predictors as early as in gaze duration.

4.2 Estonian total fixation duration

Next, we investigated the cumulative reading measure, the total fixation duration, which taps into later stages of word processing. Compounding and surface frequency were not significant control variables in the total fixation duration model. Word length emerged as a significant control variable. Longer words were read with longer total fixation duration than shorter words. This effect is slightly nonlinear and stronger for shorter

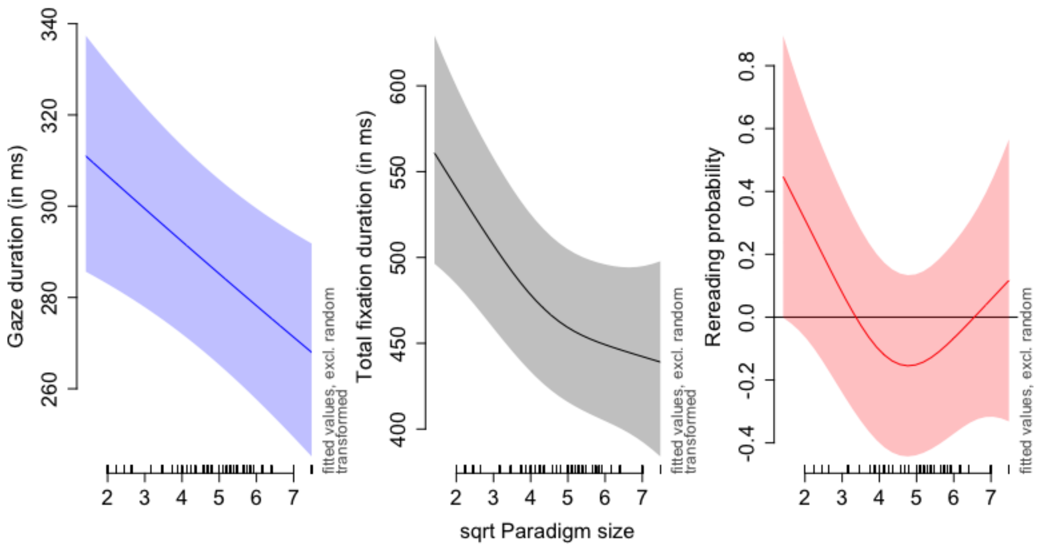

Figure 3: Predicted values of paradigm size fitted to back-transformed Estonian gaze duration, back-transformed total fixation duration and rereading. The shadows represent 95 % confidence bands (SE=1.96) of the regression line for individual predictors.Y-axes for gaze duration and total fixation duration were back-transformed to milliseconds.

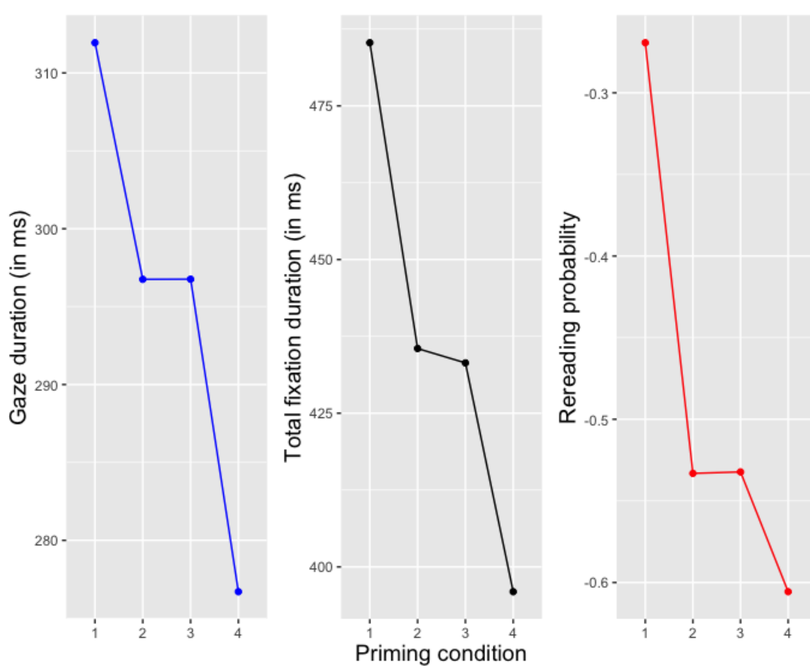

Figure 4: Predicted values of priming condition fitted to Estonian gaze duration, total fixation duration and rereading. 1-baseline, 2-identity priming, 3-inflectional priming, 4-enhanced inflectional priming. Y-axes for gaze duration and total fixation duration were back-transformed to milliseconds.

words (see the lower left panel of Figure 2).

The priming condition and the size of the inflection paradigm were significant predictors of eye movements. As shown in the middle left panel of Figure 4, compared to the baseline condition, the words in the enhanced inflectional priming condition read the fastest (β=-2.13, t=-8.74, p<0.001) , followed by the words in the inflectional priming (β=-1.22, t=-5.77, p<0.0001) and in the identity priming conditions (β=-1.16, t=-5.39, p<0.0001). Pairwise comparisons showed that words in the enhanced inflectional priming condition were read significantly faster than words in identity and inflectional priming conditions (β= 0.97, t=3.43, p<0.0001; β= 0.91, t=3.40, p<0.001). The difference between identity priming and inflectional priming conditions was not significant.

The middle panel of Figure 3 illustrates the effect of the size of the inflectional paradigm on the total fixation. duration. Words with more paradigm members were read faster than words with fewer paradigm members, while the effect is steeper in the lower paradigm size range. The full summary of Estonian total fixation duration model is in Table 6 in the Appendix.

In summary, like in the gaze duration model, Priming condition and Inflectional paradigm size were significant predictors of total fixation duration.

4.3 Estonian rereading

Finally, we investigated effects in rereading the Estonian nouns, i.e., the measure of whether the reader came back to the word or not after the gaze left the word for the first time. Compounding and word frequency did not yield significance. The lower right panel of Figure 2 shows that longer words were more likely to be read again, but that the effect levels off at medium-length words.

The right left panel of Figure 4 shows that compared to the baseline condition, words in the enhanced inflectional priming condition (β=-0.33, t=-3.81, p<0.001), in the inflectional priming (β=-0.26, t=-3.81, p<0.001), as well as in the identity priming condition (β=-0.26, t=-3.44, p<0.0001) were less likely to be read again. Pairwise comparisons showed that there were no significant differences between the other priming conditions.

The right panel of Figure 3 shows that there was a small U-shaped effect of Paradigm size on rereading. Words from larger paradigms were less likely to be reread than words from smaller paradigms. Words from very large paradigms were, in turn, more likely to be reread. The full results of Estonian rereading model are summarized in Table 7 in the Appendix.

In summary, we saw the effects of Priming condition and Paradigm size in both early and late reading measures in Estonian. We next turn to introducing the Finnish reading results.

4.4 Finnish gaze duration

First, we investigated gaze duration effects of Finnish nouns. Compounding, Surface frequency, and Word length emerged as significant control variables in the model. As shown in Table 8, Finnish compound words were read faster than words that were not compound words.

Figure 6 shows that reading times increased with increasing word length. This effect was mostly linear. Longer words were read with longer gaze duration than shorter words. The model was less confident with very long words.

Examination of the critical effects showed that Priming condition had a significant effect on gaze durations. The left panel of Figure 5 shows the effect priming condition. Compared to the baseline condition, words in the inflectional priming condition were read the fastest (β=-0.63, t=-4.93, p<0.0001), followed by words in the identity priming (β=-0.50, t=-3.06, p=0.002). There was no significant difference between the enhanced inflectional priming and baseline conditions.

Pairwise comparisons between the identity priming and enhanced inflectional priming conditions (β=-0.41, t=-2.21, p=0.04) and between the inflectional priming and enhanced inflectional priming conditions (β=-0.54, t=-3.24, p=0.001) showed significant differences. Pairwise comparisons between the other levels of the condition showed that the difference between the identity and inflected priming conditions was not significant. The effect of the inflectional paradigm size was also not significant.

The full summary of Finnish gaze duration model is in Table 8 in the Appendix.

4.5 Finnish total fixation duration

Next, we investigated the effects of the total fixation duration of Finnish nouns. Compounding, surface frequency and word length emerged as significant control variables in the model. Finnish compound words were read faster than words that were not compounds (β=1.51, t=7.17, p<0.0001). The upper right panel of Figure 6 shows that the surface frequency had a nonlinear effect on the total fixation duration. More frequent words were read faster than less frequent words, but there was no effect of surface frequency from low to medium frequency range. The lower right panel of Figure 6 shows that longer words were read slower than shorter words and the model was again less confident with long words.

The middle panel of Figure 5 shows that Priming condition had a significant effect on total fixation durations in Finnish. Compared to the baseline condition, words in the inflectional priming condition were read the fastest (β=-1.73, t=-9.84, p<0.001), followed by the identity priming condition (β=-0.88, t=-3.89, p=0.0001), and enhanced inflectional priming condition (β=-0.55, t=-2.58, p=0.001).

Pairwise comparisons between other conditions showed that words in the inflectional priming condition

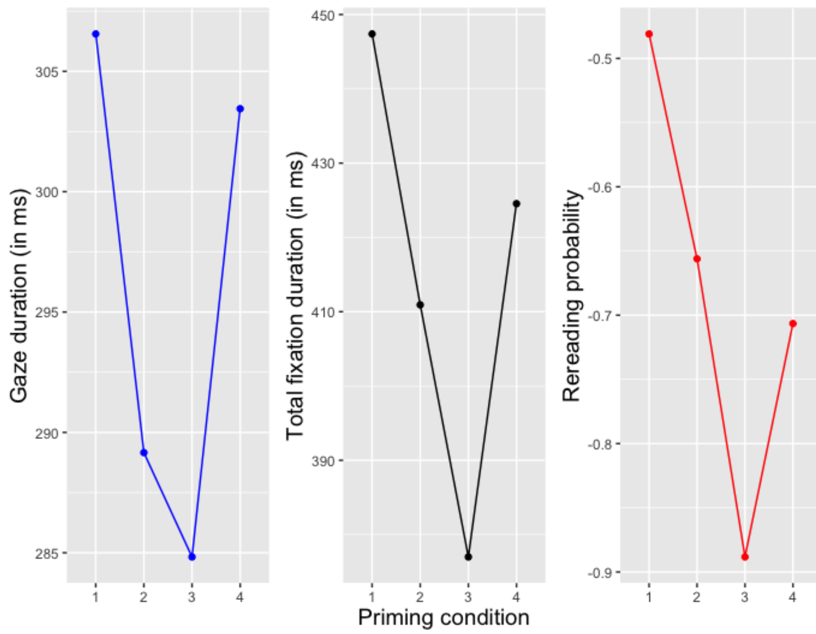

Figure 5: Predicted values of Priming condition fitted to Finnish gaze duration, total fixation duration and rereading. 1-baseline, 2-identity priming, 3-inflectional priming, 4-enhanced inflectional priming. Y-axes of gaze duration and total fixation duration were back-transformed to milliseconds.

were read faster than words in the identity (β=0.85, t=3.3, p=0.0001) and enhanced priming conditions (β=1.18, t=5.15, p=0.0001). The difference between identity and enhanced priming condition was not significant. The effect of inflectional paradigm size was also not significant.

The full summary of Finnish total fixation duration model is in Table 9 in the Appendix.

4.6 Finnish rereading

Finally, we examined effects of rereading in Finnish. Compounding and frequency did not significantly influence the rereading. The lower right panel of Figure 6 shows that there was a nonlinear effect of word length on Finnish rereading. Shorter words were more likely to be reread than longer words, but very long words were again less likelt to be reread.

The right panel of Figure 5 shows that compared to baseline, words in the inflectional priming (β=-0.40, t=-5.84, p<0.0001) and in the enhanced inflectional conditions (β=-0.55, t=-2.58, p=0.001) were less likely to be reread. The difference between baseline and identity conditions was not significant. Pairwise comparisions showed that there were small significant differences between the inflectional and identity conditions (β=0.23, t=2.34, p=0.02) as well as between the inflectional and enhanced inflectional conditions (β=0.18, t= 2.00, p= 0.05).

As already shown in gaze duration and total fixation duration, inflectional paradigm size also did not

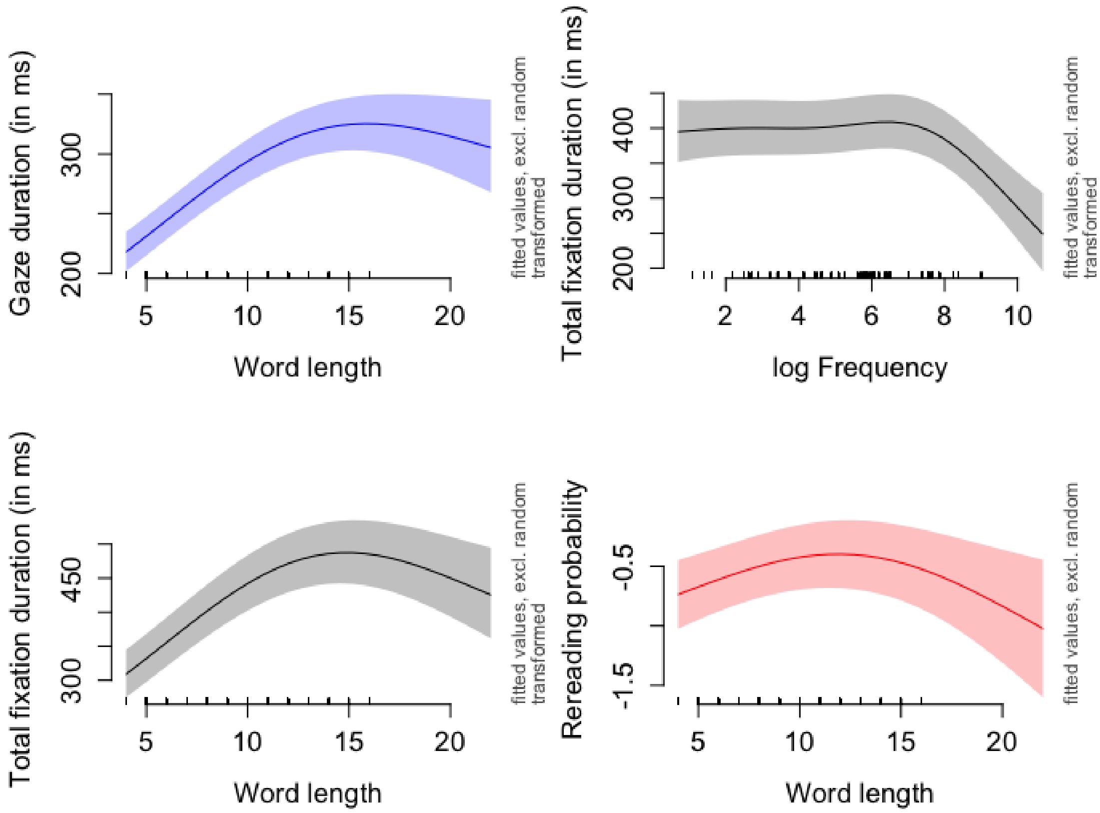

Figure 6: Predicted values of Word length fitted to Finnish gaze duration, Frequency and word length fitted to total fixation duration and Word length fitted to rereading. The shadows represent 95 % confidence bands (SE=1.96) of the regression line for individual predictors. Y-axes of gaze duration and total fixation duration were back-transformed to milliseconds.

significantly influence rereading. The full results of Finnish rereading model are summarized in Table 10 in the Appendix.

5 Discussion and conclusions

The present study investigated the effects of long-lag morphological priming and inflectional paradigm size in text context in two morphologically rich languages, Estonian and Finnish. The texts were short wikipedia style texts covering common but not thoroughly known topics, including events, phenomena and historical figures. The texts were read in Estonian or Finnish by native academically educated speakers of Estonian or Finnish, respectively. Processing of words was assessed by gaze duration, an eye movement measure that taps into first-pass word processing and total fixation duration and rereading, two measures that tap into the later stages of word processing. The results showed identity priming and inflectional priming effects in both languages, but enhanced priming effects were stronger and appeared earlier in Estonian than in Finnish.

Moreover, whereas a clear effect of inflectional paradigm size appeared in all measures in Estonian, no such effect emerged in Finnish.

The clear effect of identity priming in all three measures and in both languages is in line with what was found in previous text reading studies (Coskun et al., 2023; Kamienkowski et al., 2018). It indicates that the activation threshold for recently encountered word forms decreases, facilitating their processing upon subsequent encounters. Unlike what was found in two earlier studies in Dutch, English, and Spanish on long-lag morphological priming in text context, the current study also showed clear inflectional priming effects in gaze duration, as well as in total fixation duration and in rereading. This implies that inflectional relatives do not only speed up the processing of a word during the first pass, but that they also diminish the need to return to that word. The discrepancy with earlier text reading studies (Coskun et al., 2023; Kamienkowski et al., 2018) can be mostly likely ascribed to the higher density of inflectional forms in the Estonian and Finnish texts than in the Spanish, English and Dutch texts, due to the larger number of inflectional variants that nouns have in these languages. Consequently, the distance between inflectional variants is much shorter than in earlier text context studies. It is possible that morphologically less rich languages exhibit inflectional priming in texts with a higher density of inflectional variants as well. However, such density may be rather unnatural in languages like English or Dutch, whereas for Estonian and Finnish this is a standard scenario and inflectional priming can therefore be utilized more frequently in natural language processing in these languages.

One peculiar difference between Estonian and Finnish readers is related to the enhanced inflectional priming effect. Coskun et al. (2023) encouraged future studies to investigate whether morphological priming starts to emerge after the second occurrence. As in our case, morphological priming was already found during the second occurrence, we can infer that we should find stronger priming effects beyond the second occurrence than at the second occurrence itself. This was indeed the case for Estonian, but for Finnish no effect of enhanced morphological priming was observed in gaze duration, and only mild effects were observed in total fixation duration and rereading. The effect of enhanced inflectional priming in Finnish was even smaller than that of inflectional priming. This means that upon encountering a Finnish inflectional variant of a word for the third or fourth time, the priming advantage is smaller than when it is encountered for the second time. We do not have a clear explanation for this. One possibility lies in the specific inflectional variants that are encountered beyond the second time. For instance, morphophonological changes (e.g., *katu* ‘street, nominative singular’-*kadulla* ‘street, inessive singular, on the street’, *tauko* ‘break, nominative singular’- *tauossa* ‘break, inessive singular, at a break’) may occur more often beyond the second time than at the second time in Finnish data. However, our data set is too small and we cannot assess this issue reliably, so we leave it to future studies to further explore this topic.

As for the inflectional paradigm size effect, this effect was present in gaze duration and got even stronger in later measures such as total fixation duration and rereading in Estonian. Thus, we can conclude that in Estonian inflectional variants of a particular word become and remain activated when an extensive passage-long context is present. This extends the findings of the single-word studies that yielded similar results (Lõo et al., 2018a,b). Possibly, a large inflectional paradigm that resonates on the background helps in the semantic specification of a given word, which would be in line with the results of the semantic classification task of Lõo et al. 2018a. The results also align with results from a recent production study in Estonian examining spontaneous speech which showed that paradigm relations influence acoustic durations of words, even when context is available (Lõo et al., 2023).

The question that then remains is why the inflectional paradigm size did not affect Finnish word processing, neither in the earlier (gaze duration) nor in the later reading measures (total fixation duration and rereading). As noted, Finnish inflectional paradigms are more extensive than Estonian ones, and this may also mean that they are semantically more diverse. In their family size study, Bertram et al. (2000) found that semantically distantly related family members did not contribute to the family size effect, in fact, they were obscuring it. We suspect that something similar is the case in this study, with Finnish having semantically less proximate inflectional paradigms than Estonian. Again, we leave it to future studies to further explore this issue.

In general, it should be noted that even though the experimental findings are quite convincing, long-lag priming and paradigmatic effects in text context can be studied with more precision under experimentally controlled circumstances. Cross-linguistic explorations like the current one would especially benefit from this kind of control, matching for semantic proximity and size of the inflectional paradigm, as well as for morphophonologcal variation. Another meaningful experimental control would be to systematically manipulate the distance between the prime and the target and to explore at what point the morphological connection attenuates to the point of disappearance from the behavioral record.

At any rate, the MECO corpus allowed us to do specific explorations of the role of morphological factors on word processing. These explorations showed that there is a textual reality to inflectional paradigms, at least in Estonian. This study is also the first to show that inflectional priming is not confined to single word or sentence context studies, but that it can appear under more ecologically valid circumstances as well, that is, during the reading of short texts for comprehension, at least in languages like Estonian and Finnish.

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A Summary tables of Estonian and Finnish GAMM models

Table 5: Summary of GAMM model fitted to sqrt Estonian gaze duration.

A. parametric coefficients	Estimate	Std. Error	t-value	p-value
(Intercept)	17.0528	0.2921	58.3883	< 0.0001
Compound: yes	0.5366	0.2062	2.6023	0.0093
Priming condition: Identity	-0.4353	0.1546	-2.8152	0.0049
Priming condition: Inflectional	-0.4350	0.1511	-2.8793	0.0040
Priming condition: Enhanced inflectional	-1.0274	0.1745	-5.8874	< 0.0001
B. smooth terms	edf	Ref.df	F-value	p-value
s(Word length)	2.0287	2.4918	114.3081	< 0.0001
s(log Surface frequency)	3.2328	3.6879	4.0913	0.0032
s(sqrt Paradigm size)	1.0000	1.0001	9.3587	0.0022
s(Text ID)	9.5120	11.0000	11.7569	< 0.0001
s(Subject ID)	47.7967	51.0000	16.8782	< 0.0001

Table 6: Summary of GAMM model fitted to sqrt Estonian total fixation duration.

A. parametric coefficients	Estimate	Std. Error	t-value	p-value
(Intercept)	21.3559	0.5067	42.1456	< 0.0001
Compound: Yes	0.0222	0.3039	0.0732	0.9417
Priming condition: Identity	-1.1598	0.2150	-5.3948	< 0.0001
Priming condition: Inflectional	-1.2158	0.2104	-5.7773	< 0.0001
Priming condition: Enhanced inflectional	-2.1301	0.2437	-8.7401	< 0.0001
B. smooth terms	edf	Ref.df	F-value	p-value
s(Word length)	3.8150	3.9739	76.9619	< 0.0001
s(log Surface frequency)	3.1000	3.5830	1.7104	0.1009
s(sqrt Paradigm size)	2.2035	2.7482	8.9592	< 0.0001
s(Text ID)	10.2477	11.0000	24.2559	< 0.0001
s(Subject ID)	48.4843	51.0000	19.7429	< 0.0001

Table 7: Summary of GAMM model fitted to Estonian rereading.

A. parametric coefficients	Estimate	Std. Error	t-value	p-value
(Intercept)	-0.2223	0.1401	-1.5865	0.1126
Compound: Yes	-0.2598	0.1083	-2.3994	0.0164
Priming condition: Identity	-0.2638	0.0780	-3.3807	0.0007
Priming condition: Inflectional	-0.2630	0.0763	-3.4484	0.0006
Priming condition: Enhanced inflectional	-0.3363	0.0882	-3.8115	0.0001
B. smooth terms	edf	Ref.df	F-value	p-value
s(Word length)	3.7249	3.9468	41.3047	< 0.0001
s(log Surface frequency)	1.3059	1.5393	0.4997	0.7807
s(sqrt Paradigm size)	2.6905	3.2557	12.8051	0.0066
s(Text ID)	9.8043	11.0000	119.3650	< 0.0001
s(Subject ID)	46.1577	51.0000	454.0195	< 0.0001

Table 8: Summary of GAMM model fitted to Finnish gaze duration.

A. parametric coefficients	Estimate	Std. Error	t-value	p-value
(Intercept)	16.4428	0.2534	64.8816	< 0.0001
Compound: Yes	1.5186	0.2119	7.1678	< 0.0001
Priming condition: Identity	-0.5040	0.1648	-3.0574	0.0022
Priming condition: Inflectional	-0.6319	0.1281	-4.9339	< 0.0001
Priming condition: Enhanced inflectional	-0.0890	0.1537	-0.5788	0.5627
B. smooth terms	edf	Ref.df	F-value	p-value
s(Word length)	1.9791	1.9989	88.3666	< 0.0001
s(sqrt Paradigm size)	1.6900	1.8995	1.7481	0.2496
s(log Surface frequency)	3.5035	3.8584	4.0908	0.0017
s(Text ID)	9.9057	11.0000	10.6321	< 0.0001
s(Subject ID)	43.5986	48.0000	10.1850	< 0.0001

Table 9: Summary of GAMM model fitted to Finnish total fixation duration.

A. parametric coefficients	Estimate	Std. Error	t-value	p-value
(Intercept)	20.0093	0.4755	42.0764	< 0.0001
Compound: Yes	1.2576	0.2921	4.3046	< 0.0001
Priming condition: Identity	-0.8803	0.2270	-3.8780	0.0001
Priming condition: Inflectional	-1.7354	0.1764	-9.8377	< 0.0001
Priming condition: Enhanced inflectional	-0.5472	0.2122	-2.5789	0.0099
B. smooth terms	edf	Ref.df	F-value	p-value
s(Word length)	1.9863	1.9998	95.2062	< 0.0001
s(sqrt Paradigm size)	1.0002	1.0003	0.0181	0.8935
s(log Surface frequency)	3.6563	3.9298	9.0380	< 0.0001
s(Text ID)	10.4846	11.0000	26.7048	< 0.0001
s(Subject ID)	45.2518	48.0000	17.1995	< 0.0001

Table 10: Summary of GAMM model fitted to Finnish rereading.

A. parametric coefficients	Estimate	Std. Error	t-value	p-value
(Intercept)	-0.5603	0.1323	-4.2349	< 0.0001
Compound: Yes	-0.0541	0.1105	-0.4897	0.6243
Priming condition: Identity	-0.1751	0.0887	-1.9755	0.0482
Priming condition: Inflectional	-0.4073	0.0697	-5.8437	< 0.0001
Priming condition: Enhanced inflectional	-0.2256	0.0829	-2.7210	0.0065
B. smooth terms	edf	Ref.df	F-value	p-value
s(Word length)	1.9282	1.9941	14.7620	0.0008
s(sqrt Paradigm size)	1.0001	1.0002	0.0022	0.9640
s(log Surface frequency)	2.1249	2.6128	8.1637	0.0534
s(Text ID)	9.5518	11.0000	104.6238	< 0.0001
s(Subject ID)	44.1195	48.0000	555.6608	< 0.0001

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