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Silent morphological information in a word's spelling also affects natural reading behavior

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Abstract

Previous research suggests that, when performing experimental tasks, readers rely on the morphological information incorporated in a word's spelling even if this information is not reflected in the word's pronunciation. We investigated whether readers do so as well when they read text for comprehension under more natural conditions, that is, when participants read tweets, which were not composed for experimentation, and when they can read and skip words in the order they would like to. Two eye-tracking experiments were conducted to investigate whether participants who read for comprehension suffer from reading a homophone of the intended word, which differs from the intended word in the morphological information in the spelling. Experiment 1 focused on Dutch homophone pairs of the first and the third person singular present tense, for which previous studies have shown that confusion of the forms leads to longer self-paced reading times. Experiment 2 focused on Dutch homophone pairs of the third person singular present tense and the past participle, for which several studies could not find that readers rely on the silent morphological information in the spelling. For both pairs of homophones, we found that reading is delayed by the incorrect homophone. This shows that, also during more naturalistic reading conditions, readers process words not only by phonological encoding, but also by directly extracting morphological information from the spelling. A proper orthographic representation of morphologically complex words is thus important for the reading of natural texts.

Keywords Reading for comprehension · Role of morphology · Homophony · Verbs · Dutch

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1 Introduction

Many languages indicate the function of a verb form (e.g., past participle or first versus third person singular) by means of affixes. For instance, in English, the <s> after a verb stem, as in *he speaks*, indicates the present tense form and reflects syntactic agreement between a singular subject and the verb form. A vast body of literature has shown that spelling errors affecting these inflectional affixes disturb the reading process (see Molinaro et al., 2011, for an overview). In nearly all of this research, the spelling errors not only provide incorrect morphological / syntactical information but also incorrect phonological cues (the spelling errors reflect incorrect pronunciations of the forms). Only a handful of studies indicate that the errors also affect reading when the spelling errors do not affect the words' pronunciations. The present study contributes to this latter line of research.

1.1 Word recognition via phonological encoding or direct orthography - lexicon mapping

Readers may use several ways to read words (e.g., Ehri, 1991). One way is by phonological decoding, also called phonological recoding: Graphemes and chunks of graphemes are sounded out to form phonemes, syllables, and words. These sound units are matched with the pronunciation representations of morphemes and words in the reader's mental lexicon. Phonological encoding is facilitated by a clear correspondence between graphemes and sounds.

Another way of reading words is by memory of sight (e.g., Taft, 1979), which can only be applied to words that the reader has seen before. Readers recognize words, without sounding them out (Ehri, 2005), by matching the orthographic strings to the words' orthographic representations stored in their mental lexicons. In this route, which we will call the direct orthography – lexicon route, the robustness of the grapheme – sound correspondence is of less importance.

1.2 Reading morphologically complex words

There is evidence that regular morphologically complex words are lexically stored – at least the highly frequent ones – and can thus be retrieved as whole-words from the mental lexicon (e.g., Alegre & Gordon, 1999; Bertram et al., 2000; Lehtonen & Laine, 2003; Lehtonen et al., 2006; Soveri et al., 2007; Stemberger & MacWhinney, 1986). Upon encountering such regular morphologically complex words, readers may retrieve them from their mental lexicons, either through the phonological route (the pronunciation representations of the words are activated) or by direct orthography – lexicon retrieval (the words' orthographic representations are activated).

A large body of evidence on visual word recognition suggests that regular morphologically complex words may also be decomposed into their constituent morphemes, which are then separately matched with the phonological or orthographic representations of the morphemes in the mental lexicon (Taft and Forster 1975, 1976). After the recognition of the morphemes, their combination is checked (licensing) and the meaning of the complex word is based on the combination of the morphemes.

The recognition of morphologically complex words by lexical retrieval of the whole word or via morphological decomposition are the basic elements of the so-called dual-route models of reading (Coltheart 1978, 2006; Coltheart et al. 1993, 2001; for an overview, see Rayner & Reichle, 2010). Schreuder and Baayen (1995) proposed a parallel dual-route race model, where the decompositional route and the lexical retrieval route are activated at the same time. The route that leads to a decision the fastest 'wins'.

1.3 The processing of agreement suffixes

A large body of literature has focused on how readers process correct and incorrect syntactic affixal agreement that is both reflected in the word's spelling and pronunciation. Molinaro et al. (2011) provided an overview of the results so far from event-related potential (ERP) studies. They conclude that incorrect agreement affects reading in two ways: it violates the reader's (syntactic) expectations based on the words in the preceding part of the sentence (the LAN component) and it leads to (non-syntactic) interpretation difficulties of the content of the sentence (as reflected in the N400). The sizes of the effects are probably modulated by readers' attention and their mood (e.g., Verhees et al., 2015).

The spelling errors investigated in most research on syntactic agreement have consequences for how the words are pronounced. This research thus leaves open the question whether these errors affect reading to the same extent and in the same way when the errors are purely orthographical. In that case, the errors can only affect the reading process when readers do not fully rely on phonological encoding, but also recognize words by matching the orthographic strings to the words' and morphemes' orthographic representations stored in their mental lexicons.

1.4 The processing of silent suffixes

Brysbaert et al. (2000) and Kempen et al. (1997) are exceptional in that they investigated whether readers can process grammatical information that is only present in the word's spelling and not in the word's pronunciation. They investigated whether readers can interpret the grammatical information in Dutch homophonous verb forms. Brysbaert and colleagues showed that readers can tell apart the tenses of homophonic Dutch verb forms that only differ from each other in whether they are spelled with single or double <t>, which are both pronounced as single [t] (e.g., present tense *betwisten* 'dispute' versus past tense *betwistten* 'disputed', both pronounced as [bətʋɪstən]). Similarly, Kempen et al. (1997) showed in an eye-tracking experiment that Dutch readers can distinguish between the functions third person singular present tense and the past participle for the verb *verwedden* 'to bet' for which these forms are homophonous (i.e., *verwedt* versus *verwed*, both pronounced as [vərʋɛt]), but they cannot for the verb *verspelen* 'to lose' (i.e., *verspeelt* versus *verspeeld*, both pronounced as [vərspe:lt]), although these forms are also homophonous for this verb.

In contrast to Kempen et al. (1997) and Brysbaert et al. (2000), Frenck-Mestre et al. (2008) and Carrasco-Ortiz and Frenck-Mestre (2014) investigated French. More importantly, they studied reading for comprehension. How readers exactly process complex words, including spelling errors, possibly depends on whether they are reading the text for proofreading or for comprehension. For instance, work by Daneman et al. (1995) on the reading of lexical homophone errors in English showed that gaze durations and total fixation times on target words are longer during proofreading than during reading for comprehension. Moreover, it has been shown that frequency effects (words are more quickly recognized the more often they occur) are larger in proofreading than in reading for comprehension (e.g., Kaakinen & Hyönä, 2010; Schotter et al., 2014).

Frenck-Mestre et al. (2008) and Carrasco-Ortiz and Frenck-Mestre (2014) contrasted the reading of agreement information that is only present in the words' spellings with agreement information that is also present in the words' pronunciations. For instance, they tested both the effect of replacing *mange* [mãʒə], the first person singular present tense of the verb *to eat*, with *manges* [mãʒə], the second person singular present tense, and with *mangez* [mãʒe], the second person plural present tense. In two ERP experiments, where they presented participants with simple declarative sentences word by word, they found that readers show sensitivity to both verbal agreement errors that do and do not affect the words' pronunciations, although the ERP responses were more robust to orally realized than to silent agreement errors. These results indicate that agreement errors may also influence reading if these errors do not affect how the words are pronounced. This suggests that readers may process verb forms both via orthography and phonological encoding.

1.5 The homophone dominance effect

Previous work investigating the effect of silent morphological information on reading focused on homophones: words that have identical pronunciations, but different functions, which are reflected in their spellings. Studies on the processing of homophones have documented the homophone dominance effect. This effect refers to the fact that the most frequent member of a homophone pair is typically processed more easily and quickly than the other member. For instance, both Dutch experienced spellers (e.g., Sandra et al., 1999) and young spellers (Frisson & Sandra, 2002; Sandra et al., 2004) less often confuse two homophones when the target (i.e., the one they have to spell) is the most frequent member. The bias towards the most frequent form is stronger for homophone pairs of which the members show larger differences in frequency (e.g., Berent & Van Orden, 2000).

The homophone dominance effect has been reported in a few reading experiments on Dutch, including Verhaert (2016) and Verhaert et al. (2016). Verhaert (2016) found that, when homophone verb forms are presented in isolation, university students more quickly respond to the more frequent member of a homophone pair. In a self-paced reading task, these participants processed the high frequent form more quickly even if it was the incorrect form. In a proofreading experiment, both Verhaert (2016) and Verhaert et al. (2016) found that secondary-school students ignored misspellings especially when they resulted in the most frequent member of the homophone pair.

Verhaert (2016) and Verhaert and colleagues (2016) have only obtained these results for homophone pairs of which one member was the first person and the other member the third (and second) person singular present tense of the verb, that is, when the misspelling resulted in an agreement error with the subject of the sentence. The results did not hold for homophone pairs of which one member was a finite form (the first person singular present tense) and the other member the past participle of the verb, a homophony that occurs in verbs with weak prefixes. Interestingly, Kempen et al. (1997), who also tested the latter type of homophones, only found robust effects for one out of the two verbs they tested, that is, for the homophone pair of which the members differ in the number of letters.

1.6 Eye gazes during reading

Frenck-Mestre et al. (2008), Carrasco-Ortiz and Frenck-Mestre (2014) and Verhaert (2016) studied reading in experiments in which participants were presented with the words of a sentence one by one. These types of experiments do not provide information about how participants normally process words since readers typically do not focus on every word and they often regress back to previous words.

Natural reading can better be studied when participants are presented with complete texts and their eye gazes are tracked (for a comprehensive overview, see Bertram, 2011). Dependent variables in the analyses of eye movements include the probability that readers fixate on a word, the duration of the first fixation, and the total duration of all fixations on a word.

Well replicated results from eye-tracking experiments show that the total duration of the fixations on a word indicates the ease of the processes associated with retrieving the meaning of the word, and, to a smaller extent, syntactic parsing. More complex processes, such as integrating the word into the rest of the sentence, are mostly completed while the eyes fixate on the next words (see also Carpenter & Just, 1983, and Just & Carpenter, 1980).

Importantly, readers do not only extract information from the word they are fixating on. During a fixation, information within 2° of the visual angle (or approximately eight characters) is within the foveal area (e.g., Rayner, 1998). In addition, the processing of information from the parafoveal area, which can be up to 5° of the visual angle, is initiated as well. As a consequence, short function words are often not fixated on (e.g., Engbert et al., 2002; Veldre & Andrews, 2018), but processed while the eyes fixate on neighboring words. For the study of eye fixations, this implies that, in order to understand how a word is processed, we should not only study the fixations on the word we are interested in, but also the fixations on the surrounding words.

Many studies have documented a so-called preview benefit. The processing of a word in the fovea is facilitated when the word in the parafovea can be easily processed, for instance, because it is highly frequent. Vice versa, the presence of an orthographic illegal sequence or a low-frequent word in the parafoveal area disrupts processing of the reading of the word in the fovea (i.e., the word that is fixated on at that moment; Angele et al., 2016; Drieghe et al., 2008).

1.7 The present study

The aim of the present study is to further investigate the role of silent morphological information in a word's orthography in reading. We extend previous research especially by investigating whether readers rely on this morphological information also under more naturalistic reading conditions than are typically tested. We encouraged participants to show natural reading in two ways. First, participants were presented with complete sentences and could focus on the words in the order they would like to and could skip words if they would like to. That is, instead of presenting the sentences word by word, we tracked participants' eye gazes when reading complete sentences. Moreover, we told participants that they had to read the text for comprehension (and thus should not proofread).

Second, we presented participants with short texts that are natural in the sense that the authors wrote these texts with the sole purpose of conveying information (i.e., without the intention of these texts being included in reading experiments). We presented participants with real tweets. Also the misspellings that our participants read were completely natural, since we selected tweets with misspellings of the two types that we based this study on (see below). In order to compare the reading of misspelled words with the reading of the correct spellings, we produced versions of these tweets in which these errors were corrected and presented these tweets as well (such that a given participant read half of the tweets with the original errors and half of the tweets with the errors corrected).

We focused on two Dutch homophone pairs that have also been studied by Verhaert (2016). The first reading experiment focused on homophone pairs that consist of verb forms differing in whether they agree with a first or a third person singular subject. The second reading experiment focused on pairs consisting of the third person singular present tense and the past participle of weak prefix verbs. For these latter pairs, neither Kempen et al. (1997) nor Verhaert (2016) found any evidence that swapping them affects reading. See Section 1.7.1. for more information on the two types of pairs.

In short, we focus on the following research questions:

– Does silent incorrect morphological information also affect natural reading behavior?
– Does silent incorrect morphological information affect natural reading behavior both for homophones that only differ in their agreement and for homophones that differ in whether they are a finite verb form versus a past participle?

1.7.1 Two types of homophone pairs

Experiment 1 focuses on homophones consisting of the first and the third person singular present tense. In Dutch, the first person singular present tense form is just the bare stem. A <t> is added to the stem for second and third person singular present tense, even where it is not audible. It is inaudible after stems ending in /d/ (spelled as <d>), which, due to final devoicing, is pronounced as [t]. An inaudible <t> leads to the first and the second / third form being homophones. For instance, the first and third person present tense verb forms of *vinden* are spelled as *vind* and *vindt*, respectively, but are both pronounced as [vɪnt]: Due to final devoicing of the /d/ and degemination, the affixal /t/ of *vindt* is not audible.

The two forms forming a homophone pair of this type are very comparable in that they occur in exactly the same position in Dutch sentences. Confusion of the forms leads to the same type of agreement error for each of them, that is, to an error in the agreement between the subject of the sentence and the person of the finite verb form. In the sentences that we studied, it was obvious from the preceding words that the verb form was a singular present tense form and to which subject (first or third person) it belonged. Readers could therefore spot the disagreement error as soon as they read this verb form.

In order to see how the results obtained in Experiment 1 generalize to other verbal suffixes, Experiment 2 focuses on pairs consisting of the third person singular present tense verb form of a weak prefix verb (for instance, verbs starting with <her>) and its homophone counterpart, the past participle. The past participle for a weak prefix verb consists of the verbal stem followed by the suffix [t]. The suffix is spelled as <d> if the stem-final sound is voiced before the infinitive affix <en>. As mentioned above, the second and third person singular present tense also end in the suffix [t], but this suffix is always spelled as <t>. The past participle and the second and third person singular present tense are thus homophones for weak prefix verbs but are not spelled identically for all verbs. For instance, the present tense second person singular and the past participle of *herhalen* 'to repeat' are spelled as *herhaalt* and *herhaald*, respectively, but are both pronounced as [hɛrha:lt].

The two verb forms forming a homophone pair of this second type have less comparable functions than those forming homophones of the first type. While, in Dutch, the third person singular shows agreement in person with the subject of the sentence, the past participle does not. The form of the past participle is only determined by its function as past participle, which is indicated by the presence of an auxiliary verb (typically *hebben* 'to have' or *zijn* 'to be'). Furthermore, the third person singular and the past participle cannot always occur in the exact same position in the sentence. In main clauses, the third person singular present tense verb form occurs in second position, while the past participle is positioned at the end. In subclauses, in contrast, both forms occur at the end and the past participle can occur both before and after the auxiliary verb. These differences may be the reason that Verhaert (2016) did not find any homophone dominance effects for pairs of this second type in most of her experiments (e.g., lexical decision, and self-paced reading), and that Kempen et al. (1997) only found an effect for the weak prefix verb *verwedden*, but not for *verspelen*. For a comprehensive description of Dutch morphology, see Booij (2019).

1.7.2 The statistical analyses: dependent variables and important predictors in the analyses

The dependent variables in our experiment are the probability of an eye fixation, the duration of the first eye fixation. and the total duration of all fixations. Because a misspelling of a word may affect the reading of the word itself as well as the reading of the preceding word and of following words (see Section 1.6), we will not only study the reading of the verb form itself but also the reading of the surrounding words. This will increase the probability that we will find effects of homophone confusion. Moreover, investigating the reading of which words in the sentence are delayed by a misspelled homophone will also provide information about how the incorrect member of a homophone pair affects the reading process.

Our main manipulation, and predictor for the dependent variables, is whether a verb form is spelled correctly or whether it is spelled like its homophone, i.e. incorrectly. We hypothesize that a correctly-spelled verb form is more easily processed than its homophone because the morphological information matches the verb form's grammatical function.

The verb forms composing a homophone pair differ from each other in their grammatical function, as described above (Section 1.7.1). The literature on homophone verb-spelling errors shows that some grammatical functions elicit more errors than others (e.g., the past participle elicits fewer errors than the third person singular present tense, Chamalaun et al., 2021). Possibly, the differences in grammatical function also affect the reading process: the misspelling of one function might be more detrimental to the reading process than the misspelling of the other function. In our statistical analyses, we therefore tested the effect of the function of the verb form on the dependent variables, and the interaction with the correctness of its spelling.[1]

Homophone confusion may especially hinder processing when the actually spelled, incorrect homophone member has a frequency that is relatively low compared to the frequency of the correct homophone member. Readers are less familiar with the homophone member and may therefore show processing delays because of both the incorrect morphological information and the unfamiliar form. In contrast, when the actually spelled, incorrect homophone member has a frequency that is relatively high, reading may hardly be hindered by the misspelling because any delay induced by the incorrect morphological information may be compensated for by the ease of processing a highly familiar form. That is, we may expect that we need to include relative homophone frequency as a predictor in order to detect an effect of the misspellings. The relative frequency was calculated by dividing the frequency of the presented verb form by the frequency of the verb form's homophone.

2 Experiment 1

2.1 Method

2.1.1 Participants

We tested sixty native speakers of Dutch from the Netherlands. Most of them were bachelor's or master's students at Radboud University in Nijmegen; a small number

[1] In Experiment 1, the two forms of the homophone pair differ in length in that one form has an additional <t>. One reviewer suggested that reading behavior is especially determined by this difference in length, rather than by difference in function. This would explain why Kempen et al. (1997) found effects for one pair of homophones but not for the other. We analysed all dependent variables from this experiment replacing the predictor of the grammatical function with the predictor indicating the length of the presented form (see Table A in the Appendix). Only the analysis of the fixation probability showed an effect of this new predictor, in interaction with correctness. This interaction suggests that a misspelling only affects the first person singular present tense, that is when <d> is erroneously replaced with <dt>. This new analysis thus reveals the same pattern as our analysis.

was recently graduated. The mean age was 22.7 years (*SD*: 3.5; range: 18-24). Dutch was the native language of all. None of the participants suffered from dyslexia, severe eye abnormalities, or other reading problems. Participants with glasses or soft contact lenses were allowed to participate if their vision was corrected-to-normal; hard contact lenses were not allowed as these lead to problems with eye-tracker calibration. Participants were rewarded with a €10 gift card; one participant received course credit instead. The experiment was approved by the Ethics Assessment Committee for the Humanities of Radboud University.

2.1.2 Materials

Prior to the main experiment, we conducted a small pilot study where five participants (who did not participate in the main experiments afterwards) read twenty tweets. This pilot study showed that it would be possible to test a total of 336 tweets within an hour. To ensure that participants would have enough time to finish the experiment within an hour, we limited the total number of tweets to 320.

Schmitz et al. (2018) demonstrated that about 10% of Dutch tweets contain homophone confusions. To keep our experiment as natural as possible, we maintained this percentage in the materials, which means that 32 out of the 320 tweets presented to a given participant contained the incorrect member of a homophone pair (just as they were originally posted on Twitter).

We selected 64 regular Dutch target verbs whose stems end in /d/ (<d>) and which therefore have homophonic first (ending in <d>) and third (ending in <dt>) person singular present tense forms (see Section 1 in the Appendix for the list of all target verbs).

Next, we selected 64 real tweets, one for each target verb, partially from TwiNL, a database of Dutch tweets posted from December 2010 onwards (Tjong Kim Sang & Van den Bosch, 2013), and partially via the Twitter search engine (https://twitter.com/search-advanced?lang=nl). For half of the target verbs, we selected tweets incorrectly containing the homophonous counterparts of the first person singular present tense forms (i.e., erroneously ending in <dt>) and for the other half of the target verbs, we selected tweets incorrectly containing the homophonous counterpart of the third person singular present tense forms (i.e., erroneously ending in <d>). We then created correctly-spelled variants of these tweets. With these original and corrected tweets, we could test participants' reading of the first person singular present tense (either correctly spelled or incorrectly spelled as its homophone) of half of the target verbs, and participants' reading of the third person singular present tense (also either correctly or incorrectly spelled) of the other half of the target verbs. Finally, we selected 256 tweets as fillers, not containing any spelling errors.

The verb forms that were presented as first person singular present tense forms had an average lemma frequency of 5180 (with a standard deviation of 18,041), while those that were presented as third person singular present tense forms had an average lemma frequency of 3497 (standard deviation: 13,344). The average relative frequency for first person singulars was 2.56 (with a standard deviation of 4.39), and for third person singulars 2.95 (with a standard deviation of 6.30). These frequencies are based on SUBTLEX-NL (Keuleers et al., 2010).

Table 1 A tweet with a target verb form, exemplifying the structure of the experimental tweets. IA refers to Interest Area (see the text)

IA1 introductory part	IA2 subject	IA3 verb form	IA4 spillover 1	IA5 spillover 2	IA6 final part
Ik stel af en toe echt onmogelijk domme vragen aan mijn docent, maar	*hij*	*[beantwoord/ beantwoordt]*	*ze*	*altijd*	*lief en rustig*
'Sometimes I ask really stupid questions to my teacher, but	he	answers	them	always	nice and quietly'

All tweets with target verbs had the same structure, consisting of six Interest Areas (IAs). The structure is illustrated in Table 1, which also shows one tweet as an example. They started with an introductory part consisting of several words. This introductory part was followed by the subject of the sentence, which was directly followed by the verb form, and after the verb form two words followed to catch potential spillover effects. After the spillover region, a concluding part followed. Please note that participants saw only one version (either correct or incorrect) of the target verb form (both are indicated between square brackets in Table 1).

For all but two of the 32 tweets with the third person singular present tense as target form, the words preceding the target verb form announced the verb forms' grammatical function. For the two tweets for which this was not the case, the misspelling could be interpreted as a correctly-spelled past participle. This small number is not likely to have affected our results.

Apart from the structure, another important factor in the selection of the target tweets was that the tweets did not contain features such as hashtags and user-tags, which might attract the participants' attention and in this way influence the reading process. Tags in the filler tweets were removed (N = 17). Furthermore, the tweets contained no other spelling mistakes, nor did they contain emojis.

Twenty-five percent of the tweets in the experiment were followed by yes/no questions. The questions were more or less proportionally distributed over tweets containing target verbs and filler tweets: 16 of the 64 tweets containing target verb forms and 66 of the 256 filler tweets were followed by questions. These questions targeted the general content of the tweets, to encourage participants to pay attention to the contents of the tweets. Two examples of tweets containing target verb forms and their questions, to be answered with respectively *yes* and *no*, are given in (1) and (2).

(1) *Toiletten in de trein zijn altijd vies, dus ik* [*mijd/mijdt*] *ze als het maar even kan.*
Question: *Gaat deze persoon weleens met de trein?*
'Train toilets are always dirty, so I avoid them if it's remotely possible.'
Question: 'Does this person sometimes travel by train?'

(2) *Dit is de eerste avond dat m'n vader kookt en hij* [*verbrandt/verbrand*] *zich meteen aan de pan en heeft een brandblaar.*
Question: *Kookt de vader wel vaker?*
'This is my father's first evening cooking and he immediately burns himself on the pan and has a blister.'
Question: Does the father cook more often?

We created three pairs of lists. Each list contained 64 target tweets so that each target verb occurred exactly once. Each member of a pair contained all filler tweets and (1) 16 correctly-spelled first person singular present tense forms of the target words, (2) 16 correctly-spelled third person singular present tense forms of the target words, (3) 16 incorrectly-spelled first person singular present tense forms of the target words, and (4) 16 incorrectly-spelled third person singular present tense forms of the target words. The members of a list pair only differed in the correctness of the target verb forms: If the correct spelling of a target verb form was used in one member of a pair, the incorrect spelling was used in the other member, and vice versa. The list pairs differed in the positions of the target verb forms in the list (e.g., a verb form could appear as the sixth trial in one list, but as the twentieth in another). With these three pairs of lists, we could detect practice effects and effects of fatigue and thus decrease the variance in the data.

We determined the order of the tweets in the three pairs of lists with pseudo randomization, applying Mix (Van Casteren & Davis, 2006). We ensured that each tweet with a target verb form was followed by at least four filler tweets, that no more than two tweets with questions followed each other, that tweets with questions were separated by maximally seven tweets without questions, and that a tweet with a question was followed by minimally one filler tweet.

Each list started with a practice block with four tweets that appeared in a fixed order. Two practice tweets were followed by content questions. The practice tweets did not contain homophonous verb forms. Every participant was presented with one experimental list. Each list, without the practice tweets, was divided into three equally long parts, the experimental blocks.

2.1.3 Procedure

Participants' eye gazes were tracked while they read the tweets. They were told the aim of the experiment was to investigate how people read tweets and they were asked to read the tweets for comprehension. We can, however, not guarantee that the participants performed some type of proofreading, especially after having spotted several spelling errors.

The participants were separately tested at the Centre for Language Studies Lab at Radboud University. The experiment was programmed in Experiment Builder (version 2.1.140) and the eye-tracking system used was Eyelink 1000, combined with a fixed desk mount with adjustable chin rest. Participants were seated in front of a PC monitor in a dimly lit, sound-proof booth. After they read the study information document and signed the consent form, the chair and chin rest were adjusted to the appropriate heights, so that the participants were in a comfortable position and the camera could track their eyes. They were instructed not to move during the experiment as this would invalidate the calibration.

The experiment started with an instruction screen that explained that after a short practice block, tweets would be presented on the screen, one by one. The participants' task was to read – for comprehension – these tweets carefully and to answer the comprehension questions that followed some of the tweets. Hereafter, the first calibration and validation were performed, after which the practice block started. After completion of the practice block, participants had a final opportunity to ask questions before continuing the experiment. In the breaks, in between the three blocks, participants were allowed to move and it was checked whether they were still comfortable. At the beginning of each block, a new calibration and validation were performed. In total, the experiment took 35-55 minutes, depending on the participant's reading speed, durations of the breaks, and the ease with which calibration and validation could be performed.

The tweets were horizontally aligned to the left of the screen and vertically centered. Since none of the tweets exceeded one line on the screen, all tweets thus started at the same position on the screen, independently of their length. The font used was Calibri, size 22.

Before each tweet was presented, a fixation dot appeared at the position of the beginning of the tweet. Because it has been shown that readers typically need at least 50-70 ms to acquire the visual information necessary for reading (Rayner, 1998), this fixation dot contained a fixation trigger which ensured that the tweet was only presented after the participant had fixated on the dot for at least 80 milliseconds. In this way it was ensured that participants were looking at the position of the beginning of the tweet when it appeared. Participants were instructed to press the space bar when they had finished reading the tweet. After each five tweets, a drift correction was automatically performed before the fixation trigger appeared. At each drift correction, a recalibration could be performed if necessary.

When a tweet was followed by a content question, the word *vraag* 'question' and the question itself were presented on the screen, such that the question itself was horizontally and vertically centered on the screen and the word *vraag* 'question' was presented on the line above. The x-key on the keyboard corresponded to the answer 'no' and the period-key corresponded to 'yes'. This information was visible at the bottom of the screen for all questions, to prevent confusion. Additionally, 3D-foam stickers were applied to the corresponding keys, to make sure the participants would not lose track of the meanings of these keys.

2.1.4 Analysis

We restricted our analyses to the tweets with target verb forms. We manually checked the fixation data and, if necessary, corrected them for drift using Eyelink Dataviewer (version 3.1.97). During this process, we could only see the grid of the IAs and not the words themselves, so that we would not be influenced by the contents of the tweets. In the entire analysis, we focused on IAs 2 (subject), 3 (the verb form), and 4 and 5 (spillover regions). For these IAs, we removed fixations shorter than 80 ms (213 data points, 2.2%) because readers cannot reliably acquire visual input during these short fixations.

We analyzed the *Fixation Probability of all IAs* (*i.e.*, *IAs 2-5*), *First Fixation Durations on the IAs that had been fixated on*, and *Total Fixation Durations on the IAs that had been fixated on*. We used general linear mixed effects models with the binomial link function for the first dependent variable (fixation probability), and linear mixed effects regression models for the second and third dependent variables (duration of the first fixation and total duration of the fixations) in R version 4.1.2 (R Core Team, 2021), using the Car package (Fox & Weisberg, 2011).

Before we analyzed the fixation durations, we log-transformed the values in order to make the data better approximate normal distributions, and subsequently removed data points with values of more than 2.5 SD below/above the grand mean (175 data points, 1.8% of the data in the analysis of the first fixation duration; 230 data points, 2.4% of the data in the analysis of the total fixation duration).

In all models, as described in Section 1.7.2, our most important predictor is *Correctness*, which indicates whether the verb form was spelled correctly or replaced by its homophone. Two other predictors of interest are the *Grammatical function* of the verb form and the *Relative homophone frequency* of the presented verb form compared to its homophone counterpart (log-transformed).

We combine the data for the different *Interest Area* and included *Interest Area* (IA) as a predictor in our statistical analyses (with the levels IA2, IA3, IA4, and IA5). Because the effects of the misspellings may manifest themselves during the reading of the word itself and during the reading of the other words to different extents (see Sects. 1.6 and 1.7.2), we studied the interactions of IA with our main predictors. In our discussions of the results, we refrain from discussing simple effects of IA, as they very likely result from the types of words presented in the different IAs. For instance, while IA3 always contains a verb form, IA4 often contains a pronoun or a determiner, which are probably easier to process (see for an example Table 1).

Finally, we incorporated *Lemma frequency* of the verb (log-transformed) in order to reduce the variance in the data. Note that any effects from this predictor are lexical rather than morphological in nature. Frequencies were taken from SUBTLEX-NL (Keuleers et al., 2010). In order to account for differences among participants, target verbs, and the word presented in each IA, the model contained *Participant*, *Verb*, and *Current word* as crossed random effects.

Each fixed predictor was added individually to the model, and only remained in the model if it was statistically significant and improved the model's AIC value, or figured in statistically significant interactions. We included random slopes if they significantly improved the model fit, as revealed by likelihood ratio tests. After the fixed and random effects of the models were established, outliers were removed from the lmer-models by deleting all data points with absolute standardized residuals exceeding 2.5 standard deviations, after which we refitted the final models.

2.2 Results

Fixation Probability

In the first analysis, we studied the presence versus absence of fixations on IAs 2-5. Table 2 presents the final statistical model, specifying the size and direction of the effect for each predictor level.

Table 2 Experiment 1: Statistical model for the presence versus absence of a fixation. The intercept represents correctly-spelled first person singular verb forms and Interest Area 3. A positive β implies that the given level of the predictor resulted in a higher fixation probability than in the case represented by the intercept

Fixed effects		β	z	p
Intercept		2.38	10.57	<.001
Correctness (incorrect)		0.75	2.94	<.01
Grammatical function (3rd person)		0.47	1.83	0.07
Interest Area 2		−2.64	−3.23	<.01
Interest Area 4		−1.32	−6.14	<.001
Interest Area 5		−0.94	−4.37	<.001
Lemma frequency		−0.05	−2.67	<.01
Grammatical function (3rd person) * Correctness (incorrect)		−0.93	−2.53	<.05
Interest Area 2 * Correctness (incorrect)		−0.66	−2.41	<.05
Interest Area 4 * Correctness (incorrect)		−0.57	−2.09	<.05
Interest Area 5 * Correctness (incorrect)		−0.90	−3.23	<.01
Interest Area 2 * Grammatical function (3rd person)		0.86	1.00	0.32
Interest Area 4 * Grammatical function (3rd person)		−0.67	−2.39	<.05
Interest Area 5 * Grammatical function (3rd person)		−0.71	−2.48	<.05
Interest Area 2 * Grammatical function (3rd person) * Correctness (incorrect)		1.09	2.79	<.01
Interest Area 4 * Grammatical function (3rd person) * Correctness		0.81	2.06	<.05
Interest Area 5 * Grammatical function (3rd person) * Correctness		1.12	2.81	<.01
Random effects	*participant*	*current word*		*verb*
Intercept	0.49	0.80		0.17

Most importantly for our research question, Table 2 shows that an incorrect spelling of the first person singular present tense (i.e., with <dt> instead of <d>) increases the probability of a fixation on Interest Area 3, which contains the verb form (note that the intercept represents this function and this IA). In order to be able to interpret the two-way and three-way interactions of *Correctness* with *Grammatical function* and *Interest Area*, we releveled the model (see Tables B-E in the Appendix). These releveled models do not show simple effects of *Correctness*. This implies that the effect of the misspelling of the first person on the probability of a fixation was restricted to the reading of the word itself, and the misspelling of the third person did not affect the probability of a fixation, in any IA.

In addition, as expected, the model also shows an effect of *Lemma frequency*, which suggests a lower fixation probability for more familiar words. We also tested for the role of relative frequency and of several interactions with our predictors of interest that are not listed in the table, but no effects were found.

First Fixation Duration

Table 3 presents the final statistical model for the duration of the first fixation, specifying the size and direction of the effect for each predictor level. In addition

Table 3 Experiment 1: Statistical model for the duration of the first fixation. The intercept represents correctly-spelled verb forms and Interest Area 3. A positive β implies that the given level of the predictor resulted in a longer first fixation duration than in the case represented by the intercept

Fixed effects	β	t	p
Intercept	5.40	370.45	<.001
Correctness (incorrect)	−3.24	−0.28	0.78
Interest Area 2	−2.17	−1.16	0.25
Interest Area 4	−6.47	−4.77	<.001
Interest Area 5	−1.99	−0.16	0.87
Interest Area 2 * Correctness (incorrect)	8.27	0.42	0.67
Interest Area 4 * Correctness (incorrect)	3.91	2.16	<.05
Interest Area 5 * Correctness (incorrect)	−5.08	−0.30	0.77
Random effects	*current word*	*participant*	
Intercept	0.02	0.09	

to the predictors listed in Table 3, we also tested the role of *Relative homophone frequency* and *Lemma frequency*, but we found no significant main or interaction effects with other variables. The random intercept of *Verb* was dropped from the model, because the model failed to converge with this intercept.

Table 3 shows that there was an interaction of *Correctness* and *Interest Area*, which we further investigated by releveling the model (see Tables F-H in the Appendix). This interaction indicates that the first fixations were shorter on the first spillover region (IA4) than on all other IAs when the verb form, both the first and the third person singular, was correctly spelled.

Total Fixation Duration

In the third analysis, we tested the total fixation duration. Table 4 presents the final statistical model for the total duration of all fixations, specifying the size and direction of the effect for each predictor level. We not only checked for the predictors listed in Table 4, but also for effects of *Relative homophone frequency* and *Grammatical function*, but we found no significant main or interaction effects with other variables of interest.

The table shows an interaction of *Correctness* with *Interest Area*, which we further investigated by releveling the model (see Tables I-K in the Appendix). The interaction suggests that an incorrect verb form, both the first and the third person singular present tense, attracted longer total fixation durations. Interest Area 5 (the second spillover region) also attracted longer total fixation durations, while Interest Area 4 was not affected by the spelling of the verb form. Further, we found an effect of *Lemma frequency*, which shows that the total duration fixation was shorter when the verb was more frequent and thus more familiar.

In Experiment 2, we further investigated the effect of incorrectly-spelled homophones. In order to see to what extent the results from Experiment 1 generalize to other homophone pairs, we focused on the homophone pair consisting of third person singular present tense verb forms and past participles.

Table 4 Experiment 1: Statistical model for the total fixation duration. The intercept represents correctly-spelled verb forms and Interest Area 3. A positive β implies that the given level of the predictor resulted in longer total fixations than in the case represented by the intercept

Fixed effects		β	t	p
Intercept		5.86	119.75	<.001
Correctness (incorrect)		0.08	3.20	<.01
Interest Area 2		−0.18	−4.35	<.001
Interest Area 4		−0.19	−7.24	<.001
Interest Area 5		−0.14	−5.44	<.001
Lemma frequency		−0.02	−2.96	<.01
Interest Area 2 * Correctness (incorrect)		−0.07	−2.12	<.05
Interest Area 4 * Correctness (incorrect)		−0.04	−1.22	0.22
Interest Area 5 * Correctness (incorrect)		−0.04	−1.25	0.21
Random effects	*participant*	*current word*		*verb*
Intercept	0.15	0.10		0.07

3 Experiment 2

3.1 Method

3.1.1 Participants

As in Experiment 1, sixty participants took part in the experiment, of which none had participated in Experiment 1. They met the same requirements as the participants in Experiment 1. The mean age was 23 years (SD: 3.8; range: 18-33). Six participants received course credit instead of gift cards. This experiment was also approved by the Ethics Assessment Committee for the Humanities of Radboud University.

3.1.2 Materials

We selected 64 weak prefix verbs whose stems do not end in /d/ (see the Appendix). Thirty one verb forms are presented in the experiment with the third person singular present tense and thirty three with the past participle. The third person singular present tense forms had an average lemma frequency of 5465 (with a standard deviation of 8583), while the past participles had an average lemma frequency of 5426 (standard deviation: 12,879). The average relative frequency for the past participles was 3.56 (with a standard deviation of 12.24), and for third person singulars 3.27 (with a standard deviation of 6.98).

Following Experiment 1, we selected 64 real tweets, one for each target verb form, partially from TwiNL (Tjong Kim Sang & Van den Bosch, 2013), and partially via the Twitter search engine (https://twitter.com/search-advanced?lang=nl). The tweets did not contain features such as hashtags, user-tags, or emojis and did not contain other spelling mistakes than the homophone confusion that we tested.

For 33 of the target verbs, we selected tweets incorrectly containing the past participle instead of the homophonous third person singular present tense form and for

Table 5 Two examples of target tweets in Experiment 2, one with a third person singular present tense form and one with a past participle, showing the general structure of the target tweets

IA1 introductory part	IA2 word	IA3 verb form	IA4 spillover	IA5 final part
Een docent zegt altijd dat je als student tot de top 1% van het	*land*	*[behoort / behoord]*	*maar*	*sommige medestudenten zijn echt niet zo slim hoor*
'A lecturer always says that you as a student to the top 1% of the	country	belongs	but	some fellow students are really not that smart'
'A lecturer always says that as a student you belong to the top 1% of the country, but some fellow students are really not that smart'				
O ja. En als we dan toch willen muggenziften, waarom nog een bijeenkomst als er	*ook*	*[vergaderd / vergadert]*	*kan*	*worden via conference call?*
'Oh yeah. And if we still want to nitpick, why another meeting if	also	met	can	be via conference call'
'O yeah. And if we still want to nitpick, why another meeting if it can also be done via conference call?'				

the other 31 target verbs, we selected tweets incorrectly containing the third person singular present tense instead of the homophonous past participle. We then created correctly-spelled variants of these tweets. With these original and corrected tweets, we could test participants' reading of the third person singular present tense (either correctly spelled or incorrectly spelled as its homophone) for almost half of the target verbs, and participants' reading of the past participle (also either correctly or incorrectly spelled) for the other half of the target verbs.

All tweets with target verb forms had the same structure, consisting of five Interest Areas (IAs). The target verb forms occurred in subordinate clauses that occurred after the main clauses. Each tweet started with an introductory part consisting of several words, including the main clause (i.e., IA1). This introductory part was followed by an IA that contained only one word (i.e., IA2), which was directly followed by the area that contained the target verb form (i.e., IA3). After the verb form, one word followed to catch possible spillover effects (i.e., IA4). The fact that the target verb forms in Experiment 2 are located near the end of the sentence, made us decide to create only one spillover region in Experiment 2. After this spillover region, a concluding part ended the target tweet, where wrap up effects can be expected (i.e., IA5). The structure of the tweets is illustrated in Table 5, which also shows one tweet as an example. Please note that participants saw only one version (either correct or incorrect) of the target verb form (while they are both indicated between square brackets in Table 5). Four target verb forms were excluded from the analyses, because the selected tweets did not meet the criterion that the verb form could be positioned in IA3. As a consequence, the analyses were based on 28 third person singular present tense forms and 32 past participles.

Because our stimuli were drawn from actual tweets, we could not ensure that for all verb forms the spelling error could be detected just on the basis of the preceding words. In many cases, the word immediately following the target verb form was necessary to determine whether the verb form was spelled correctly or not. In fact, this was the case for approximately 65% of the present tense verb forms and approximately 30% of the past participles. This difference between the two types of verb forms may imply that, on average, a misspelling is noticed earlier for past participles than for present tense forms. We may therefore expect an interaction of *Correctness* with *Interest Area*. However, it may also be the case that such an interaction is absent, because, while readers are fixating on the verb form, they may already obtain sufficient information about the following word to disambiguate between the possible grammatical functions of the target verb form.

We mixed the target tweets with the same filler tweets as tested in Experiment 1. Twenty-eight percent of all tweets were followed by yes/no content questions. The questions were more or less proportionally distributed over tweets containing target verbs and filler tweets: 24 of the 64 target tweets were followed by questions as were 66 of the 256 filler tweets.

We created six experimental lists of the tweets using the same procedure as in Experiment 1. Each list contained all filler tweets and (1) the correctly-spelled third person singular present tense forms of 14 target verbs, (2) the correctly-spelled past participles of 16 different target words, (3) the incorrectly-spelled third person singular present tense forms of yet 14 different target words, and (4) the incorrectly-spelled past participles of the remaining 16 target words.

3.1.3 Procedure

We followed the same procedure as in Experiment 1.

3.1.4 Analysis

Following the procedure described for Experiment 1, we manually checked the fixation data and, if necessary, corrected them for drift, using Eyelink Dataviewer (version 3.1.97). One participant was excluded from the analyses due to poor performance of the eye-tracker, that is, we were unable to see the fixations on several IAs.

We restricted our analysis to Interest Areas 2-4, where we may expect effects of the spelling of the verb form. Again, we conducted separate analyses for our three dependent variables *Fixation Probability* (*i.e.*, *IAs 2-4*), *First Fixation Duration*, and *Total Fixation Duration*, following the fitting procedure described for Experiment 1. Our fixed and random predictors were the same as in the analysis of Experiment 1.

3.2 Results

Fixation Probability

In the first analysis, we studied the presence versus absence of fixations on IAs 2-4. Table 6 presents the final statistical model, specifying the size and direction of the effect for each predictor level. Most importantly, the effect of *Correctness* suggests that the probability of a fixation is higher for incorrectly-spelled than for correctly-spelled verb forms. We also tested for the role of *Relative homophone frequency*, *Grammatical function*, and of several interactions with our predictors of interest that are not listed in the table, but no effects were found.

Table 6 Experiment 2: Statistical model for the presence versus absence of a fixation. The intercept represents correctly-spelled verb forms and Interest Area 3. A positive β implies that the given level of the predictor resulted in a higher fixation probability than in the case represented by the intercept

Fixed effects		β	z	p
Intercept		2.53	20.04	<.001
Correctness (incorrect)		0.11	2.06	<.05
Interest Area 2		−1.65	−10.75	<.001
Interest Area 4		−2.56	−14.38	<.001
Random effects	*participant*	*current word*		*verb*
Intercept	0.50	0.82		0.24

Table 7 Experiment 2: Statistical model for the duration of the first fixation. The intercept represents Interest Area 3. A positive β implies that the given level of the predictor resulted in a longer first fixation than in the case represented by the intercept

Fixed effects		β	t	p
Intercept		5.35	457.76	<.001
Interest Area 2		−0.03	−3.48	<.001
Interest Area 4		−0.04	−3.51	<.001
Random effects	*participant*	*current word*		*verb*
Intercept	0.07	0.03		0.02

Table 8 Experiment 2: Statistical model for the duration of the total fixation. The intercept represents correctly-spelled verb forms and Interest Area 3. A positive β implies that the given level of the predictor resulted in longer total fixations than in the case represented by the intercept

Fixed effects		β	t	p
Intercept		5.67	240.69	<.001
Correctness (incorrect)		0.04	3.69	<.001
Interest Area 2		−0.15	−8.37	<.001
Interest Area 4		−0.21	−9.45	<.001
Random effects	*participant*	*current word*		*verb*
Intercept	0.13	0.08		0.09

First Fixation Duration

The final model for the duration of the first fixation on the Interest Areas can be found in Table 7. We only found an effect of *Interest Area*. We also tested for the other variables, but no significant effects or interactions were found.

Total Fixation Duration

In the third analysis, we tested the total fixation duration. Table 8 presents the final statistical model, specifying the size and direction of the effect for each predictor level. We also tested for the other variables, but no significant effects or interactions were found. Most importantly, the effect of *Correctness* indicates that incorrectly-spelled verb forms overall received longer total fixations than correctly-spelled verb forms.

4 General discussion

This study investigated the role of morphological information in a word's spelling – in the form of consistent morpheme spelling – on the reading process. This role is best investigated on the basis of morphological information that is only present in the word's spelling and not in the word's pronunciation as well. So far, the effect of silent morphological information has only been addressed in studies where participants could not show naturalistic reading behavior (e.g., Molinaro et al., 2011; Carrasco-Ortiz & Frenck-Mestre, 2014). We studied whether readers also rely on silent morphological information under conditions that encourage them to show naturalistic behavior.

We compared how participants read sentences with verb forms that were either correctly spelled or incorrectly as the homophonic verb forms with incorrect morphological information. They read these verb forms in real tweets, and participants were therefore presented with natural language use. Moreover, participants could read the words in the tweets in any order (and thus also show regression), and we encouraged them to read the tweets for comprehension. We conducted two eye-tracking experiments, with Experiment 1 focusing on the homophone pair consisting of the Dutch first and third person singular present tense, and with Experiment 2 focusing on the homophone pair consisting of the Dutch third person singular present tense and the past participle. This way, we investigated whether silent incorrect morphological information affects natural reading behavior both for homophones that only differ in their agreement and for homophones that differ in whether they are a finite verb form versus a past participle.

In general, the results show that the correctness of the morphological information in the verb forms affects the reading process. In both Experiments 1 and 2, the total fixation on the verb form was longer when it was incorrectly than when it was correctly spelled. Moreover, for three out of the four verb forms, we found that silent incorrect information led to a higher fixation probability. These results suggest that also during natural reading conditions, readers rely on morphological information that is not encoded in the verb form's pronunciation but that is present in its orthographic representation.

Our results extend the findings by, especially, Kempen et al. (1997), Carrasco-Ortiz and Frenck-Mestre (2014) and Verhaert (2016), who tested the role of silent morphological information under more constrained conditions. Although we cannot exclude that participants focused on misspellings once they had noticed one, the conditions in our experiment encouraged natural reading behavior more than experiments where participants are presented with sentences word by word and where the sentences were just composed for the experiment.

The effect of silent morphological information on reading in naturalistic conditions shows that, also under these conditions, readers do not only recognize morphologically complex words via phonological encoding. They may activate the orthographic representation of the whole word in their mental lexicons (e.g., Alegre & Gordon, 1999; Bertram et al., 2000), which includes information about the morphological structure of the word and the functions of the respective morphemes, or by first decomposing the word and then activate its morphemes (e.g., Taft and Forster 1975, 1976). Our study was not designed to distinguish between these two possibilities.

Since we found clear effects of silent morphological information for the homophone pairs in both experiments, we can conclude that incorrect morphological information in the orthography of verb forms hinders reading not only when it leads to agreement errors with the subject of the sentence (Experiment 1) but also when it encodes other types of (syntactic) information (Experiment 2). Early studies mostly documented evidence for a role of silent morphological information in subject-verb agreement (e.g., Carrasco-Ortiz & Frenck-Mestre, 2014; Verhaert, 2016).

Verhaert (2016) also investigated the effect of confusion of the Dutch third person singular present tense and the past participle of weak prefix verbs, as we did in Experiment 2, but she found no effects in a self-paced reading experiment. A likely reason is that, in her experiment, participants could not glance at following words when reading the verb form, and they could thus not determine whether the form's spelling was correct. Kempen et al. (1997) also did not find evidence that readers relied on the opposition between final <t> for the third person singular present tense and the <d> for past participles. The reason for their null result may be that they tested complex sentences, with several verb forms in a sequence.

Our data from Experiment 1 documented that the effect of incorrect morphological information differed between the first person and the third person singular present tense verb forms. When the third person was incorrectly written instead of the first person, the probability of a fixation on the verb form was higher (in addition to the total fixation duration), but when the first person was incorrectly written instead of the third person, no difference in fixation probability was found. In the set of homophone verbs we used in Experiment 1, first person verb forms are spelled with word-final <d>, whereas third person verb forms are spelled with <dt>. Many studies report a preference for <d> over other word-final segments, both in reading (e.g., Ernestus & Mak, 2005) and in writing (e.g., Bosman, 2005; Frisson & Sandra, 2002), possibly because <d> is much more frequent in the inflectional paradigms of Dutch verbs than other word-final segments. Hence, it is likely that readers are more triggered by incorrect spelling <dt> (i.e., stem-final /d/ plus the suffix /t/) than by incorrect <d> (i.e., just the stem-final /d/), which results in a larger effect of a misspelling resulting in <dt>, such that not only the total fixation duration is affected but also the fixation probability on the verb form.

Experiment 1 also showed an effect of lemma frequency on fixation probability, which suggests that verbs that are more frequent, and thus more familiar, are processed more easily. No effect was found of lemma frequency on the first fixation duration, whereas we did find an effect on the total fixation duration. These results suggest that, initially, readers do not take the familiarity of the verb into account but, later on in the reading process, they regress less and shorter for higher frequency verbs. This finding is in line with the literature that gaze durations are longer on low-frequency words than on high-frequency words (e.g., Rayner 1993, 1998; Rayner & Duffy, 1986).

Interestingly, an effect of lemma frequency was absent in Experiment 2. A possible reason for why we only found effects of lemma frequency in Experiment 1 is that its range was too small in Experiment 2. The range of lemma frequency only spanned 57,042 in Experiment 2 and 106,496 in Experiment 1.

Neither of the two experiments showed an effect of relative homophone frequency. We used a sampling rate of 1000 Hz, which has been demonstrated to be more than sufficient for eye-tracking on a reading task (e.g., Holmqvist et al., 2011). Hence, the sampling rate cannot explain the absence of effects of relative homophone frequency. Rather it can be explained by the finding that frequency effects are in general larger in proofreading than in reading for comprehension (Daneman et al., 1995; Kaakinen & Hyönä, 2010). This was also demonstrated for Dutch homophonous verb forms (Verhaert et al., 2016). Since the task of both Experiments 1 and 2 was reading for comprehension, this might explain the absence of effects of relative frequency.

Overall, the results show that readers rely on the morphological information that is present in the spelling of a morphologically complex word, even if this morphological information is silent, and even when participants read natural texts (tweets) for comprehension and can show natural reading behavior. Incorrect morphological information leads to delays in reading, both when its implies an agreement error of the verb form with the subject and when it indicates an incorrect function (a present tense form versus a past participle). This shows that, also during more naturalistic reading conditions, readers process words not only by phonological encoding, but also by directly extracting morphological information from the spelling. A proper orthographic representation of morphologically complex words is thus important for reading of natural texts.

Appendix

Verb forms used in Experiment 1 as first person singular present tense: *aanvaarden* 'to accept', *beantwoorden* 'to answer', *begeleiden* 'to supervise', *behoeden* 'to save', *beïnvloeden* 'to influence', *bekleden* 'to clothe', *belanden* 'to end up', *bespieden* 'to spy', *besteden* 'to spend', *bevreemden* 'to amaze', *bevrijden* 'to free', *doorgronden* 'to understand', *misleiden* 'to mislead', *ontbranden* 'to ignite', *onthouden* 'to remember', *ontleden* 'to dissect', *verantwoorden* 'to justify', *verblinden* 'to dazzle', *verbranden* 'to burn', *vergoeden* 'to reimburse', *verkleden* 'to dress', *verleiden* 'to seduce', *vermelden* 'to mention', *vermoeden* 'to suspect', *vermoorden* 'to murder', *verspreiden* 'to spread', *vervreemden* 'to alienate', *verwonden* 'to wound', *verwoorden* 'to articulate', *voorbereiden* 'to prepare', *wedden* 'to bet'.

Verb forms used in Experiment 1 as third person singular present tense: *afleiden* 'to distract', *antwoorden* 'to answer', *behouden* 'to keep', *bestrijden* 'to fight', *betreden* 'to enter', *bidden* 'to pray', *binden* 'to bind', *dulden* 'to tolerate', *glijden* 'to slide', *houden* 'to keep', *lijden* 'to suffer', *melden* 'to report', *mijden* 'to avoid', *ondervinden* 'to experience', *ontaarden* 'to degenerate', *redden* 'to rescue', *rijden* 'to drive', *schelden* 'to scold', *schudden* 'to shake', *smeden* 'to forge', *snijden* 'to cut', *spreiden* 'to spread', *strijden* 'to fight', *verbeelden* 'to imagine', *verbieden* 'to forbid', *verbinden* 'to connect', *vermijden* 'to avoid', *vinden* 'to find', *voeden* 'to feed', *volharden* 'to persevere', *wijden* 'to dedicate', *zenden* 'to send'.

Verb forms used in Experiment 2 as third person singular present tense: *bedoelen* 'to mean', *bedreigen* 'to threaten', *behandelen* 'to treat', *behoren* 'to belong', *bekennen* 'to confess', *beledigen* 'to offend', *beloven* 'to promise', *bemoeien* 'to interfere', *beoordelen* 'to judge', *bepalen* 'to determine', *beschadigen* 'to damage', *beschermen* 'to protect', *beschouwen* 'to consider', *beschuldigen* 'to blame', *besparen* 'to spare', *bespelen* 'to play', *bestellen* 'to order', *bestuderen* 'to study', *besturen* 'to control', *betalen* 'to pay', *betekenen* 'to mean', *bevestigen* 'to confirm', *bewaren* 'to keep', *beweren* 'to claim', *geloven* 'to believe', *herhalen* 'to repeat', *herinneren* 'to remember', *ontkennen* 'to deny'.

Verb forms used in Experiment 2 as past participle: *bezorgen* 'to deliver', *gebeuren* 'to happen', *herstellen* 'to recover', *ontwikkelen* 'to develop', *veranderen* 'to change', *verbazen* 'to amaze', *verbeteren* 'to improve', *verdedigen* 'to defend', *verdelen* 'to divide', *verdwalen* 'to get lost', *verergeren* 'to worsen', *vergaderen* 'to meet', *verhuizen* 'to move', *verklaren* 'to explain', *verlagen* 'to lower', *verlangen* 'to desire', *vernietigen* 'to destroy', *verontschuldigen* 'to apologize', *veroordelen* 'to condemn', *veroveren* 'to conquer', *verschillen* 'to differ', *verspillen* 'to waste', *vertalen* 'to translate', *vertellen* 'to tell', *vertonen* 'to show', *vertrouwen* 'to trust', *vervagen* 'to fade', *vervelen* 'to bore', *vervolgen* 'to prosecute', *verwarmen* 'to heat', *verwennen* 'to spoil', *verwijderen* 'to delete'.

Table A Experiment 1: Statistical model for the presence versus absence of a fixation. Instead of incorporating grammatical function as a predictor, we tested the effect of the length of the presented form (i.e., whether the verb form that we presented in the experiment ended in <d> or <dt>). The intercept represents correctly-spelled third person singular verb forms and Interest Area 3. A positive β implies that the given level of the predictor resulted in a higher fixation probability than in the case represented by the intercept

Fixed effects	β	z	p
Intercept	2.94	8.83	<.001
Correctness (incorrect)	0.48	2.39	<.05
Verb-form length (<d>)	−0.30	−0.79	0.43
Interest Area 2	−1.85	−5.20	<.001
Interest Area 4	−2.17	−6.43	<.001
Interest Area 5	−1.79	−4.94	<.001
Lemma frequency	−0.05	−2.63	<.01
Relative homophone frequency	−0.17	−0.73	0.47
Verb-form length (<d>) * Correctness	−0.34	−2.09	<.05
Verb-form length (<d>) * Relative homophone frequency	−0.00	−0.01	0.99
Interest Area 2 * Correctness	−0.14	−0.74	0.46
Interest Area 4 * Correctness	−0.20	−1.00	0.32
Interest Area 5 * Correctness	−0.36	−1.81	0.07
Interest Area 2 * Verb-form length (<d>)	0.43	1.07	0.29
Interest Area 4 * Verb-form length (<d>)	0.33	0.82	0.41
Interest Area 5 * Verb-form length (<d>)	0.61	1.47	0.14
Interest Area 2 * Relative homophone frequency	0.07	0.27	0.79
Interest Area 4 * Relative homophone frequency	0.29	1.17	0.24
Interest Area 5 * Relative homophone frequency	0.17	0.64	0.52
Interest Area 2 * Verb-form length (<d>) * Relative homophone frequency	0.11	0.35	0.73
Interest Area 4 * Verb-form length (<d>) * Relative homophone frequency	0.08	0.24	0.81
Interest Area 5 * Verb-form length (<d>) * Relative homophone frequency	−0.04	−0.11	0.92

Random effects	*participant*	*current word*	*verb*
Intercept	0.49	0.81	0.17

Table B Experiment 1: Releveled statistical model for the presence versus absence of a fixation. The intercept represents correctly-spelled third person singular verb forms and Interest Area 3. A positive β implies that the given level of the predictor resulted in a higher fixation probability than in the case represented by the intercept

Fixed effects		β	z	p
Intercept		2.85	12.15	<.001
Correctness (incorrect)		−0.18	−0.69	0.49
Grammatical function (1st person)		−0.47	−1.84	0.07
Interest Area 2		−1.79	−7.23	<.01
Interest Area 4		−1.98	−8.83	<.001
Interest Area 5		−1.65	−7.22	<.001
Lemma frequency		−0.05	−2.67	<.01
Grammatical function (1st person) * Correctness		0.93	2.54	<.05
Interest Area 2 * Correctness		0.43	1.59	0.11
Interest Area 4 * Correctness		0.24	0.87	0.39
Interest Area 5 * Correctness		0.22	0.80	0.43
Interest Area 2 * Grammatical function (1st person)		−0.86	−1.00	0.32
Interest Area 4 * Grammatical function (1st person)		0.67	2.39	<.05
Interest Area 5 * Grammatical function (1st person)		0.71	2.48	<.05
Interest Area 2 * Correctness * Grammatical function (1st person)		−1.09	−2.80	<.01
Interest Area 4 * Correctness * Grammatical function (1st person)		−0.81	−2.07	<.05
Interest Area 5 * Correctness * Grammatical function (1st person)		−1.12	−2.82	<.01
Random effects	*participant*	*current word*		*verb*
Intercept	0.49	0.80		0.17

Table C Experiment 1: Releveled statistical model for the presence versus absence of a fixation. The intercept represents correctly-spelled first person singular verb forms and Interest Area 2. A positive β implies that the given level of the predictor resulted in a higher fixation probability than in the case represented by the intercept

Fixed effects		β	z	p
Intercept		−0.26	−0.33	0.75
Correctness (incorrect)		0.09	0.98	0.33
Grammatical function (3rd person)		1.32	1.63	0.10
Interest Area 3		2.64	3.24	<.01
Interest Area 4		1.32	1.64	0.10
Interest Area 5		1.70	2.11	<.05
Lemma frequency		−0.05	−2.67	<.01
Grammatical function (3rd person) * Correctness		0.16	1.20	0.23
Interest Area 3 * Correctness		0.66	2.41	<.05
Interest Area 4 * Correctness		0.09	0.61	0.54
Interest Area 5 * Correctness		−0.24	−1.65	0.10
Interest Area 3 * Grammatical function (3rd person)		−0.85	−1.01	0.31
Interest Area 4 * Grammatical function (3rd person)		−1.52	−1.85	0.06
Interest Area 5 * Grammatical function (3rd person)		−1.56	−1.90	0.06
Interest Area 3 * Correctness * Grammatical function (3rd person)		−1.09	−2.79	<.01
Interest Area 4 * Correctness * Grammatical function (3rd person)		−0.28	−1.44	0.15
Interest Area 5 * Correctness * Grammatical function (3rd person)		0.02	0.12	0.90
Random effects	*participant*	*current word*		*verb*
Intercept	0.49	0.80		0.17

Table D Experiment 1: Releveled statistical model for the presence versus absence of a fixation. The intercept represents correctly-spelled first person singular verb forms and Interest Area 4. A positive β implies that the given level of the predictor resulted in a higher fixation probability than in the case represented by the intercept

Fixed effects		β	z	p
Intercept		1.06	5.41	<.001
Correctness (incorrect)		0.18	1.79	0.07
Grammatical function (3rd person)		−0.20	−1.55	0.12
Interest Area 2		−1.33	−1.63	0.10
Interest Area 3		1.32	6.14	<.001
Interest Area 5		0.38	3.00	<.01
Lemma frequency		−0.05	−2.67	<.01
Grammatical function (3rd person) * Correctness		−0.12	−0.84	0.40
Interest Area 2 * Correctness		−0.09	−0.61	0.54
Interest Area 3 * Correctness		0.57	2.09	<.05
Interest Area 5 * Correctness		−0.32	−2.20	<.05
Interest Area 2 * Grammatical function (3rd person)		1.52	1.83	0.07
Interest Area 3 * Grammatical function (3rd person)		0.67	2.39	<.05
Interest Area 5 * Grammatical function (3rd person)		−0.04	−0.24	0.81
Interest Area 2 * Correctness * Grammatical function (3rd person)		0.28	1.44	0.15
Interest Area 3 * Correctness * Grammatical function (3rd person)		−0.81	−2.07	<.05
Interest Area 5 * Correctness * Grammatical function (3rd person)		0.31	1.48	0.14
Random effects	*participant*	*current word*		*verb*
Intercept	0.49	0.80		0.17

Table E Experiment 1: Releveled statistical model for the presence versus absence of a fixation. The intercept represents correctly-spelled first person singular verb forms and Interest Area 5. A positive β implies that the given level of the predictor resulted in a higher fixation probability than in the case represented by the intercept

Fixed effects		β	z	p
Intercept		1.44	7.42	<.001
Correctness (incorrect)		−0.14	−1.34	0.18
Grammatical function (3rd person)		−0.24	−1.69	0.09
Interest Area 2		−1.70	−2.11	<.05
Interest Area 3		0.94	4.37	<.001
Interest Area 4		−0.38	−3.00	<.01
Lemma frequency		−0.05	−2.67	<.01
Grammatical function (3rd person) * Correctness		0.19	1.24	0.22
Interest Area 2 * Correctness		0.24	1.65	0.10
Interest Area 3 * Correctness		0.90	3.24	<.01
Interest Area 4 * Correctness		0.32	2.20	<.05
Interest Area 2 * Grammatical function (3rd person)		1.57	1.90	0.06
Interest Area 3 * Grammatical function (3rd person)		0.71	2.48	<.05
Interest Area 4 * Grammatical function (3rd person)		0.04	0.24	0.81
Interest Area 2 * Correctness * Grammatical function (3rd person)		−0.02	−0.12	0.90
Interest Area 3 * Correctness * Grammatical function (3rd person)		−1.12	−2.82	<.01
Interest Area 4 * Correctness * Grammatical function (3rd person)		−0.31	−1.48	0.14
Random effects	*participant*	*current word*		*verb*
Intercept	0.49	0.80		0.17

Table F Experiment 1: Releveled statistical model for the duration of the first fixation. The intercept represents correctly-spelled verb forms and Interest Area 2. A positive β implies that the given level of the predictor resulted in a longer first fixation duration than in the case represented by the intercept

Fixed effects	β	t	p
Intercept	5.37	261.19	<.001
Correctness (incorrect)	5.03	0.32	0.75
Interest Area 3	2.17	1.16	0.25
Interest Area 4	−4.30	−2.22	<.05
Interest Area 5	1.97	1.05	0.30
Interest Area 3 * Correctness (incorrect)	−8.27	−0.42	0.67
Interest Area 4 * Correctness (incorrect)	3.08	1.47	0.14
Interest Area 5 * Correctness (incorrect)	−1.34	−0.67	0.50
Random effects	*current word*	*participant*	
Intercept	0.02	0.09	

Table G Experiment 1: Releveled statistical model for the duration of the first fixation. The intercept represents correctly-spelled verb forms and Interest Area 4. A positive β implies that the given level of the predictor resulted in a longer first fixation duration than in the case represented by the intercept

Fixed effects	β	t	p
Intercept	5.33	331.77	<.001
Correctness (incorrect)	0.04	2.60	<.01
Interest Area 2	0.04	2.22	<.05
Interest Area 3	0.06	4.77	<.001
Interest Area 5	0.06	4.54	<.001
Interest Area 2 * Correctness (incorrect)	−0.03	−1.47	0.14
Interest Area 3 * Correctness (incorrect)	−0.04	−2.16	<.05
Interest Area 5 * Correctness (incorrect)	−0.04	−2.39	<.05
Random effects	*current word*	*participant*	
Intercept	0.02	0.09	

Table H Experiment 1: Releveled statistical model for the duration of the first fixation. The intercept represents correctly-spelled verb forms and Interest Area 5. A positive β implies that the given level of the predictor resulted in a longer first fixation duration than in the case represented by the intercept

Fixed effects	β	t	p
Intercept	5.39	354.32	<.001
Correctness (incorrect)	−8.32	−0.68	0.50
Interest Area 2	−1.97	−1.05	0.30
Interest Area 3	1.99	0.16	0.87
Interest Area 4	−6.27	−4.54	<.001
Interest Area 2 * Correctness (incorrect)	1.34	0.67	0.50
Interest Area 3 * Correctness (incorrect)	5.08	0.30	0.77
Interest Area 4 * Correctness (incorrect)	4.42	2.39	<.05
Random effects	*current word*	*participant*	
Intercept	0.02	0.09	

Table I Experiment 1: Releveled statistical model for the total fixation duration. The intercept represents correctly-spelled verb forms and Interest Area 2. A positive β implies that the given level of the predictor resulted in longer total fixations than in the case represented by the intercept

Fixed effects		β	t	p
Intercept		5.69	99.01	<.001
Correctness (incorrect)		5.96	0.26	0.80
Interest Area 3		1.77	4.35	<.001
Interest Area 4		−1.60	−0.42	0.68
Interest Area 5		4.04	1.05	0.29
Lemma frequency		−1.87	−2.96	<.01
Interest Area 3 * Correctness		7.03	2.12	<.05
Interest Area 4 * Correctness		3.22	1.05	0.29
Interest Area 5 * Correctness		3.31	1.13	0.26
Random effects	*participant*	*current word*		*verb*
Intercept	0.14	0.10		0.07

Table J Experiment 1: Releveled statistical model for the total fixation duration. The intercept represents correctly-spelled verb forms and Interest Area 4. A positive β implies that the given level of the predictor resulted in longer total fixations than in the case represented by the intercept

Fixed effects		β	t	p
Intercept		5.67	112.05	<.001
Correctness (incorrect)		3.82	1.89	0.06
Interest Area 2		1.60	0.42	0.68
Interest Area 3		1.93	7.24	<.001
Interest Area 5		5.64	2.42	<.05
Lemma frequency		−1.87	−2.96	<.01
Interest Area 2 * Correctness		−3.22	−1.05	0.29
Interest Area 3 * Correctness		3.81	1.22	0.22
Interest Area 5 * Correctness		8.65	0.03	0.97
Random effects	*participant*	*current word*		*verb*
Intercept	0.14	0.10		0.07

Table K Experiment 1: Releveled statistical model for the total fixation duration. The intercept represents correctly-spelled verb forms and Interest Area 5. A positive β implies that the given level of the predictor resulted in longer total fixations than in the case represented by the intercept

Fixed effects		β	t	p
Intercept		5.73	116.40	<.001
Correctness (incorrect)		3.90	2.17	<.05
Interest Area 2		−4.04	−1.05	0.29
Interest Area 3		1.37	5.44	<.001
Interest Area 4		−5.64	−2.42	<.05
Lemma frequency		−1.87	−2.96	<.01
Interest Area 2 * Correctness		−3.31	−1.13	0.26
Interest Area 3 * Correctness		3.72	1.25	0.21
Interest Area 4 * Correctness		−8.65	−0.03	0.97
Random effects	*participant*	*current word*		*verb*
Intercept	0.14	0.10		0.07

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Declarations

Competing interests We have no conflicts of interest to disclose.

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