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Skilled adult readers activate the meanings of high-frequency words using phonology: Evidence from eye tracking.

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Skilled adult readers activate the meanings of high-frequency words using phonology: Evidence from eye tracking

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Abstract We examined whether highly skilled adult readers activate the meanings of high-frequency words using phonology when reading sentences for meaning. A homophone-error paradigm was used. Sentences were written to fit 1 member of a homophone pair, and then 2 other versions were created in which the homophone was replaced by its mate or a spelling-control word. The error words were all high-frequency words, and the correct homophones were either higher-frequency words or low-frequency words—that is, the homophone errors were either the subordinate or dominant member of the pair. Participants read sentences as their eye movements were tracked. When the high-frequency homophone error words were the subordinate member of the homophone pair, participants had shorter immediate eye-fixation latencies on these words than on matched spelling-control words. In contrast, when the high-frequency homophone error words were the dominant member of the homophone pair, a difference between these words and spelling controls was delayed. These findings provide clear evidence that the meanings of high-frequency words are activated by phonological representations when skilled readers read sentences for meaning. Explanations of the differing patterns of results depending on homophone dominance are discussed.

Keywords Reading · Phonology · Homophones · High-frequency words · Eye tracking

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In alphabetic languages, the letters of a word encode the spoken form of the word. For more than a century, researchers have investigated the role of this phonological information in silent reading (for a review, see Leinenger, 2014). Some think that knowledge of letter–sound correspondences plays a critical role in initially learning to read (e.g., Share, 1995), and phonology has been shown to contribute to the activation of word meanings when elementary school-age children silently read sentences for comprehension (e.g., Blythe, Pagán, & Dodd, 2015; Jared, Ashby, Agauas, & Levy, 2016). Here our focus is on skilled adult readers. There is evidence that skilled adult readers can very quickly activate the phonological representation associated with a printed letter string. For example, in masked priming studies, a prime that is presented for 50 ms and then masked facilitates the reading of a phonologically related target word (see Rastle & Brysbaert, 2006, for a review). The issue that we address here concerns the contribution of this phonological information to the activation of a word's meaning.

A common view is that phonological activation of meaning is important early in reading development, but then is replaced by faster direct activation of meaning from print (Share, 1995; M. Coltheart, 2000). For example, in M. Coltheart's (2000) influential dual-route model, processing along the direct lexical route to meaning gets faster with each encounter with a word, such that the meanings of more frequent words are activated by the direct route before the slower phonological route has finished processing the word. In contrast, others have argued that word meanings are always activated by phonological representations (Frost, 1998; Van Orden, 1987). Alternatively, Harm and Seidenberg (2004) proposed that there is a cooperative division of labor between phonological and orthographic pathways to meaning activation, with the relative contribution of phonology depending on a variety of factors, such as the skill of the reader and the frequency of the word. Phonology is expected to contribute more to the activation of meanings for less-skilled readers than for more-skilled readers, and more to low-frequency words than to high-frequency words. An important question relevant to all of these theories, then, is whether phonology makes any contribution to the activation of meaning when highly skilled readers read high-frequency words.

There is abundant evidence that phonology contributes to the activation of meaning when skilled readers read low-frequency words, but it is not yet clear whether phonology still plays a role in the activation of meanings when they read high-frequency words (for reviews, see Jared, Levy, & Rayner, 1999; Newman, Jared, & Haigh, 2012). After many thousands of exposures to such words, it is possible that their meanings are activated quickly based on orthographic information before much activation from phonology is available. In this investigation, our aim was to determine whether phonology continues to be a source of activation for high-frequency word meanings when skilled readers read sentences for comprehension.

The homophone error paradigm

Studies of phonological influences on the activation of word meaning often use homophones. Homophones are two words with identical pronunciations, but which differ in spelling and meaning (e.g., *here/hear*). The rationale for using homophones is that if word meanings are activated only from orthographic representations, then just the meaning of a presented homophone should be activated. In contrast, if phonology activates the meanings of words, then presentation of a homophone will result in activation of semantic representations associated both with the presented homophone and of its homophone mate. If it can be shown that the meaning of the unseen homophone mate has been activated, then we can infer that phonology has influenced the computation of meaning.

Studies that use homophones often employ a homophone-error paradigm. In this paradigm, a context is created that is appropriate for one member of a homophone pair (e.g., *The conference delegates flew here from all over North America*), and then in some instances the correct homophone is replaced by its mate (e.g., *The conference delegates flew hear from all over North America*). If participants fail to notice the homophone error, then the inference is made that the phonological representation of the homophone error resulted in activation of the meaning of the unseen correct homophone. Because of the high degree of orthographic similarity that usually exists between homophones in English, it is critical that performance on homophone errors be compared to nonhomophonic control words that are also incorrect in the sentence context (*The conference delegates flew heat from all over North America*). These spelling-control words are selected to be as orthographically similar to correct homophones as are the homophone errors. Thus, if participants are more likely to fail to notice the homophone error than the spelling-control error, then the effect can be attributed to the shared phonological representations between the correct homophone and the homophone error, and not to their orthographic similarity.

Before presenting our own research that uses this homophone-error paradigm, we first briefly review the few studies that have investigated whether skilled readers activate word meanings using phonology when silently reading high-frequency words in connected text. The majority of these studies have used eye tracking, as this technique allows the participant to engage in fairly natural reading.

Previous studies

Daneman, Reingold, and Davidson (1995) asked participants to read two stories for comprehension as their eye movements were monitored. Each story originally had 30 homophones. In Experiment 1B, three version of each story were made such that each version contained 10 correct homophones, 10 homophone errors, and 10 spelling-control errors. In one of the stories (*The Desjardins*) the higher-frequency member of the homophone pair was the homophone error, and therefore it is the results from this story that are of particular interest here. Daneman et al. observed that high-frequency homophone errors and spelling-control errors had similar first-fixation durations and similar gaze durations (the sum of all fixations on a word before leaving it), and both word types had significantly longer fixation durations than correct homophones. Daneman et al. interpreted their data as providing evidence against the view that phonological codes play an important and early role in activating the meanings of high-frequency words. However, total repair time (which included all fixations made on the word before moving to the next word as well as fixations made on any prior text as a result of regressive eye movement from the target word; also known as go-past time) was significantly shorter for homophone errors than for spelling controls. Daneman et al. concluded from this finding that homophony facilitates the error-recovery process. In a subsequent study (Daneman & Reingold, 2000), they replicated their findings with an additional group of participants.

Jared et al. (1999) conducted three eye-tracking experiments using the homophone-error paradigm. We focus here on their findings for skilled readers (participants who scored in the top third on a reading comprehension test according to the test norms) and high-frequency error words. In one experiment, critical words were placed in a long story. Thirty-six of the homophone errors in the study were high-frequency words (half had high-frequency mates and half had low-frequency mates). There were three versions of the story, such that each participant saw 12 correct homophones, 12 high-frequency homophone errors, and 12 high-frequency spelling controls. Like Daneman and colleagues (Daneman & Reingold, 2000; Daneman et al., 1995), Jared et al. found that high-frequency homophone errors and spelling-control errors had similar gaze durations, and both had significantly longer gaze durations than correct homophones had. Consistent with the claim of Daneman and colleagues that homophony facilitates the error-recovery process, total fixation times (the sum of all fixations on a word, including those made following regressions from subsequent text) for homophone errors were shorter than for spelling-control errors. In the next experiment, the same stimuli were placed in single-sentence contexts where it was easier to ensure that the error words were semantically anomalous as soon as they were encountered, and the same results were obtained. The final experiment also used sentence contexts and increased the number of stimuli so that each participant saw 18 of each of the three types of words. The correct homophones were all low in frequency. The skilled readers again showed no difference between homophone errors and spelling controls in gaze durations, or even between homophone errors and correct homophones, although total fixation times did differ. Therefore, these experiments did not provide evidence that very skilled readers activate the meanings of high-frequency words from phonological representations when silently reading connected text, although their less-skilled counterparts did.

Feng, Miller, Shu, and Zhang (2001) had participants read 30 short texts for meaning while their eye movements were tracked. Each original text contained one target homophone. Four different versions of each text were created, such that the target word was either a correct homophone, a homophone error, a spelling control, or an unrelated control. There were 30 homophone pairs, and 16 of these were pairs in which both members were high in frequency. Each participant would, therefore, have seen only four texts with each high-frequency word type. As in the previous studies, Feng et al. observed that high-frequency homophone errors and spelling-control errors had similar first-fixation durations and similar gaze durations, and both had significantly longer fixation durations than did correct homophones. However, there was some evidence from a distributional analysis of fixation latencies of a difference between high-frequency homophone errors and spelling controls on short gaze durations (see their Figure 4), providing just a hint of an effect of phonology on the reading high-frequency words for meaning. The total fixation time was significantly shorter for homophone errors than for spelling controls, again suggesting that homophony facilitates the error-recovery process. A complication in the interpretation of Feng et al.'s data is that the orthographic similarity of the two members of the homophone pairs and the predictability of the correct homophone from the prior context were also manipulated, and results for high-frequency words were collapsed across these variables. Dissimilarity between the spellings of two members of a homophone pair has been shown to make a homophone error easy to detect (Jared & Seidenberg, 1991). Furthermore, highly predictable conditions make homophone errors harder to detect (Rayner, Pollatsek, & Binder, 1998), and likely reflect top-down activation of phonology from meaning (Daneman & Reingold, 2000; Jared & Seidenberg, 1991). To better focus on the bottom-up role of phonology in activating word meanings, Daneman and colleagues used a low-constraint text (Daneman & Reingold, 2000), and they also used orthographically similar homophone pairs, as did Jared et al. (1999).

A reason that stronger evidence for the role of phonology in activating the meanings of high-frequency words has not been observed in eye-tracking studies so far is that homophone dominance may be an important variable. Rubenstein, Lewis, and Rubenstein (1971), in one of the earliest studies on homophone effects, predicted that homophone effects would be more likely to be observed when a homophone mate was higher in frequency than the presented homophone than when it was lower in frequency, and they provided a post hoc analysis of the high-frequency homophones in their lexical decision data that supports their prediction. However, the analysis was based on very few stimuli and decision latencies were very long, likely because pseudohomophones were included in the experiment. In the aforementioned eye-tracking studies that included high-frequency homophones with high-frequency mates (Feng, 2001; Jared et al., 1999), dominance was not taken into account.

Both meaning dominance and frequency were manipulated in an eye-tracking study by Folk (1999) that used homophones, although she did not use a homophone-error paradigm. Participants read sentences containing homophones or matched control words, both of which were correct in the sentence (e.g., *Tara said that the son/wife of the millionaire would inherit everything*). Six of the high-frequency homophones were the dominant member of their homophone pair, and the other six were from balanced pairs where both members were high-frequency words. The mean gaze duration on high-frequency balanced homophones was significantly longer (15 ms) than on matched control words, and the homophone effect was not significant when homophones were the dominant member of the pair. The results of this study are consistent with the predictions of Rubenstein et al. (1971), but that view suggests that a larger homophone effect might have been observed had Folk included a group of high-frequency homophones that were the subordinate member of the pair. Furthermore, given the very small number of stimuli in each group, more convincing evidence is needed.

In a previous study in our lab (Newman et al., 2012), we used the homophone-error paradigm to investigate whether dominance influences the size of the homophone effect. High-frequency homophone errors had either higher-frequency mates (error homophones were the subordinate member) or low-frequency mates (error homophones were the dominant member). The two sets of high-frequency homophone errors were matched for frequency so that the influence of the mate frequency could be examined. The study collected event-related potential (ERP) data rather than eye fixations. Critical words were embedded in sentences, which were presented one word at a time. Differences in the ERP waveforms between homophone errors and matched spelling controls were first evident in a 150–200 ms time window in posterior electrodes, which Newman et al. interpreted as indicating that the two word types differed in the early activation of orthographic and phonological representations (see Barber & Kutas, 2007, and Grainger & Holcomb, 2009, for proposals of how ERP components map to word recognition processes). By the 250–300 time window, the homophone errors with higher-frequency mates differed from spelling controls in anterior electrodes, but no differences were observed in the N400 (an index of semantic fit). These findings were interpreted as indicating that the meanings associated with both members of the homophone pair were briefly activated, but the meaning associated with the presented homophone quickly won out. In contrast, homophone errors with low-frequency mates continued to differ in posterior electrodes from spelling controls until 300 ms after stimulus presentation, then the differences between the two disappeared, before arising again in the N400, with spelling controls producing a greater negative response. Newman et al. interpreted the smaller N400 for these homophones errors compared to spelling controls as providing evidence that the representations of the mates were not suppressed and went on to activate their meanings.

Although ERP methodology has the advantage of providing precise information about the timing of participants' processing when reading silently, the presentation of words one at a time in each sentence is unlike natural reading, and consequently, results from such studies may not reflect normal reading processes. For example, Ditman, Holcomb, and Kuperberg (2007) cited evidence suggesting that sentence level influences on word recognition are greater with slower presentation rates, such as the one used in Newman et al. (2012). A 750 ms stimulus onset asynchrony (SOA) was used in that experiment to ensure that most of the processing of target words, and especially the N400 response, was captured prior to the presentation of the next word. However, it is possible with this unnatural delay between words that participants rehearsed each incoming word in phonological working memory, which may exaggerate effects of phonology.

This study

The experiment presented here is an extension of the Newman et al. (2012) ERP experiment to an eye-tracking task. Sereno and Rayner (2003) noted that both ERP and eye-tracking methodologies have limitations, but together they can produce a clearer picture of the processes involved in reading. The goal of the experiment, then, was to gain a firmer understanding of the role of phonological information when skilled readers silently read high-frequency words in connected text.

In our introduction we suggested that there has been little evidence from eye-tracking studies that phonology influences the activation of the meanings of high-frequency words when skilled readers silently read connected text because no eye-tracking study has used high-frequency homophones that were all the subordinate member of the homophone pair, as in our ERP study. Therefore, the same stimuli were used as in that study (Newman et al., 2012)—that is, high-frequency homophone errors were either the subordinate or dominate member of the homophone pair. Another issue with the eye-tracking studies in our review is that participants typically saw only a small number of stimuli in each condition. There are not many high-frequency homophones, and these stimuli have been distributed across lists so that a participant typically saw only one member of each triple (correct homophone, homophone error, spelling control). In our review of the eye-tracking studies, we specifically mentioned the number of stimuli seen by each participant in each condition to draw the reader's attention to this limitation. When constructing the stimuli for our ERP study, we were particularly concerned about this problem. Because of the signal-to-noise issue with ERP data, more items were needed than have typically been used in eye-tracking studies. Our solution was to write three sentence frames for each correct homophone, and to have participants see the correct homophone in one sentence frame, the homophone error in a second sentence frame, and the spelling control in a third sentence frame, with each member of a triple in a different experimental block. That way each participant had data for 24 stimuli in each condition. These stimuli were used here to provide the most sensitive test of the influence of phonology as possible.

In the homophone-error paradigm, evidence concerning the role of phonology in the activation of word meanings comes primarily from a comparison of homophone errors and spelling controls. If the meanings of high-frequency words are activated by phonology, then reading times should be faster on homophone errors than on spelling controls because the meaning associated with the correct homophone should receive some activation from the phonological representation activated by the presented mate. Our hypothesis was that the difference in reading times between homophone errors and spelling controls would be most likely to be immediately evident when homophone errors had higher-frequency mates (i.e., they were the subordinate member) because of strong connections between the phonological representation of the homophone and the meaning associated with a higher-frequency mate. Indeed, a hint of such a difference was seen in the Feng et al. (2001) eye-tracking study where both members of the homophone pair were high-frequency words, and also in Folk's (1999) study. We also expected to find a difference between homophone errors and spelling controls when homophone errors had lower-frequency mates, but thought that the effect might be delayed because of weaker connections between the phonological representation of the homophone and the meaning associated with a lower-frequency mate. Such a result would be consistent with the findings of Jared et al. (1999). A comparison of reading times on homophone errors and correct homophones is less informative regarding the role of phonology. Reading times on the two should be similar if meanings are activated primarily by phonology, but of course interpretation of null effects is problematic. Furthermore, because the frequency of the correct homophone was purposely manipulated to examine the impact of homophone dominance, the two members of the homophone pair are not matched for frequency. A finding of a significant difference between reading times on homophone errors and correct homophones would provide some evidence for direct activation of meaning by orthography.

Typical measures of word reading time in eye-movement studies include first-fixation duration (the duration of the first fixation regardless of the number of fixations on a word) and gaze duration (the sum of all fixations on a word prior to leaving the word). Rayner (1998) has pointed out that these measures do not completely capture the first-pass processing time for a word because readers do get some information about a word on the previous fixation (there are preview effects), and processing is not always completed prior to the eyes moving on to the next word (there are spillover effects). However, first fixation and gaze duration measures have been shown to be sensitive to word meaning, as evidenced by the large literature on the processing of ambiguous words, such as *bank*. For example, Sereno, O'Donnell, and Rayner (2006) observed lexical ambiguity effects in first fixation and gaze duration measures as well as in total fixation time (the sum of all fixations made on a word, including regressions back to the word), although not in spillover (fixation time on the next word). In addition, Juhasz and Rayner (2003) demonstrated that the concreteness of a word predicted first-fixation durations, gaze durations, and total-fixation times. In summary, first-fixation and gaze-duration measures obtained from eye tracking, although not perfect measures of times to activate word meanings, are sensitive to meaning variables and do have the potential to provide evidence on our question of interest here. We used these measures as indices of immediate processing on target words, and we used total fixation time as a measure of later processing (i.e., integration of the word into the sentence meaning). We also analyzed the first-fixation duration on the region after the target word (spillover) as a measure of delayed processing of the target word.

Our participants were particularly skilled readers on the basis of a reading comprehension test. The extensive contact that these participants have had with high-frequency words would produce fast processing along the orthographic-to-meaning pathway. Of interest is whether processing along the orthographic-phonological-semantic pathway also becomes more rapid with experience such that it still contributes to the activation of the meanings of high-frequency words in these readers.

Method

Participants

Thirty-six English-speaking University of Western Ontario undergraduates participated in the experiment (M_{age} = 20.5 years). To ensure that participants were all highly skilled readers, pretesting was done, and only those students with a reading comprehension score above the 80th percentile on the Comprehension subtest of *the Nelson-Denny Reading Test,* Form G (Brown, Fishco, & Hanna, 1993), were invited to participate in this study. Participants received either course credit or monetary compensation.

Materials

The stimuli were the same as in Newman et al. (2012). There were 48 English homophone pairs and matched spelling controls. One member of each homophone pair was selected as the homophone to be correct in the sentence contexts and its mate was designated as the homophone error. All of the homophone error words were high-frequency words (Newman et al. selected homophone error words that had a frequency of 23/million or more according to the Kučera & Francis, 1967, word count, which comprises approximately the most frequent 15 % of words). The homophones were divided into two sets of 24 pairs. In one set, the correct homophones were higher in frequency than their homophone-error mates, and in the other group the correct homophones were lower in frequency than their homophone-error mates. The homophone-error words from the two groups were matched in frequency and length. A spelling-control word was matched to each homophone-error word for frequency, length, and orthographic similarity to the corresponding correct homophone (see Table 1 for means). Log frequencies were obtained from CELEX (Baayen, Piepenbrock, & Gulikers, 1995) and SUBTL (Brysbaert & New, 2009) databases. Orthographic similarity was calculated using Weber's graphemic-similarity index (Weber 1970); the formula appears in Van Orden

Table 1 Characteristics of the words

Word group	Letter length	Phoneme length	Log CELEX frequency	Log SUBTL frequency	OLD20	OS to correct homophone
VH-H						
Correct	4.4	3.1	2.59	4.21	1.59	
Homophone error	4.3	3.1	1.88	3.35	1.44	.58
Spelling control	4.6	3.5	1.95	3.59	1.53	.55
L-H						
Correct	4.7	3.4	0.75	2.18	1.58	
Homophone error	4.5	3.4	1.96	3.50	1.48	.64
Spelling control	4.7	3.5	1.78	3.42	1.58	.60

Note OLD20 = orthographic Levenshtein distance; OS = orthographic similarity; VH-H = very high-frequency correct word and high-frequency error word; L-H = low-frequency correct word and high-frequency error word.

(1987). A measure of orthographic familiarity, OLD20, is also reported. OLD20 is the mean orthographic Levenshtein distance between a word and its 20 closest neighbors, and values were taken from the English lexicon project (Balota et al., 2007).

Each of the 48 correct homophones appeared in three different sentence frames (see Table 2). The target homophones appeared at least three words from the start of the sentence and no further than the second to last word of the sentence. Correct homophones were not predictable given the preceding sentence context, and the homophone error words and spelling-control words were clearly anomalous when encountered (see Newman et al., 2012, for norming data). Three stimulus lists were created. Each list contained all 144 critical sentence frames, and none were repeated. For one third of the sentences, the target word was a correct homophone, one third contained a homophone error, and one third contained a spelling-control word. The pairing of sentence frames and target words was counterbalanced across lists. Each block consisted of 16 sentences with homophone errors, 16 sentences with correct homophones, and 16 sentences with spelling-control words. Each list contained the same number of stimuli from the two frequency conditions.

In addition to these critical sentences, each stimulus block contained 80 filler sentences. The filler sentences contained no errors. Therefore, of the 128 sentences presented in each block, 75 % contained no errors, 12.5 % contained a homophone error, and 12.5 % contained a spelling-control error. Because each list contained three blocks, the total number of sentences per list was 384. To ensure that participants were carefully reading the sentences, comprehension questions were written for 25 % of the sentences containing critical words (i.e., 12 per block) and for 25 % of the filler sentences (i.e., 20 per block). Half of these questions required a YES response and half required a NO response.

A spelling test was created to determine whether participants knew the correct spelling of the homophones used in the study. V. Coltheart, Patterson, and Leahy (1994) pointed out that homophone effects may be exaggerated by lack of knowledge of the correct spellings. Printed on a piece of standard paper in boldface font were words related to each of the 48 correct homophone members, and to the right of this word was one of three alternatives presented in random order: the homophone error, the correct homophone, the spelling control (e.g., **Animal**: *bare bear beer*). Instructions printed at the top of the page asked participants to circle the alternative that was related to the word printed in bold. An example was provided.

Apparatus

The eye-movement data were acquired using an Eye-Link 1000 tower mounted system (SR-Research, Ontario, Canada) with a sampling rate of 1 kHz. Viewing was

Table 2 Example of the distribution of a stimulus triple across sentences, blocks, and lists

List 1
A *David's antique rug was* ***made*** *in a different country*
B *Last night I* ***maid*** *pasta for dinner*
C *Steve was willing to bet anyone that his mother* ***mate*** *the best lasagna*
List 2
A *David's antique rug was* ***maid*** *in a different country*
B *Last night I* ***mate*** *pasta for dinner*
C *Steve was willing to bet anyone that his mother* ***made*** *the best lasagna*
List 3
A *David's antique rug was* ***mate*** *in a different country*
B *Last night I* ***made*** *pasta for dinner*
C *Steve was willing to bet anyone that his mother* ***maid*** *the best lasagna*

binocular, but eye movements were recorded from the right eye only. Sentences were presented on a 21-inch CRT monitor positioned 60 cm from participants' eyes. A chin and forehead rest was used to minimize head movements.

Procedure

The *Nelson-Denny Reading Comprehension Test* was administered in small groups. The test consists of seven passages, each of which is accompanied by multiple-choice questions (total = 38). As per test instructions, participants were given 20 minutes to complete as much of the test as they could in that time. Participants who scored above the 80th percentile were invited back for a second session in which the completed the eye-tracking task.

Participants were told that they would read sentences on a computer screen for comprehension while their eye movements were monitored. Sentences were displayed in a single line in the center row of the monitor, and appeared in black 18-point Courier New font type on a light-gray background. Before each trial, a box appeared on the left side of the screen in the center row. Once participants fixated on the box, it was replaced by the sentence. They were asked to read each sentence at their normal speed and to press the mouse when finished. They were told that after many of the sentences, a question would appear on the computer screen and they were to indicate their answer (YES or NO) by using the mouse to click on the appropriate box on the screen. They were not told about the presence of errors. Calibration consisted of a nine-point grid. After initial calibration, participants were given one list of 384 experimental trials. Trials with a block were in a random order. They were given a short break every 64 trials. Participants were recalibrated after every 12 trials, or more often if the experimenter noted a drift in eye movements. Twelve participants were assigned to each of the three lists, with the order of blocks within a list counterbalanced across participants. After participants had finished the experiment, they were given the spelling test.

Results

Participants clearly knew the spellings of the correct homophones. The mean score on the spelling test was 98.2 % (*SD* = 1.9). Furthermore, they answered 93.9 % (*SD* = 3.4) of the questions on the stimulus sentences correctly, indicating that they were trying to read the sentences for understanding.

Analyses were performed on three eye-tracking measures from target words. The region used for computing these measures was the target word and the space before it. First fixation (FF) is the duration of the first fixation on a word regardless of how many other fixations were made. Gaze duration (GD) is the sum of all fixations made on a word before moving to another word. Total Time (TT) is the sum of all fixations on a word, including those made on subsequent passes through the sentence. Data from 22.2 % of trials on first-pass measures (FF, GD) were lost due to skipping (TT = 12.5 %), and data from 0.7 % of trials had no data due to track loss. Data from trials with fixations less than 80 ms were discarded (FF = 12, GD = 12, TT = 23). Furthermore, approximately 20 trials with the longest fixation times were discarded from the data for each measure to help normalize the distribution (FF: 19 > 600 ms, GD: 21 > 800 ms, TT: 21 > 1,800 ms; all 0.6 % of the data). Analyses were also performed on the first fixation made in the next region after the target word (spillover). The next region was the remainder of the sentence. On 43 trials, there was no fixation after the target word. Data from 46 trials with first fixation times less than 80 ms and 20 trials with fixations greater than 750 ms were discarded. The means in each experimental condition are presented in Table 3.

Linear mixed-effects models were run on the eye-tracking data using the *lmer* function of the *lme4* package in R (Bates, Maechler, Bolker, & Walker, 2015). Fixation latencies were log transformed. A $|t|$ of 1.96 is assumed to indicate $p = .05$. The mixed-effects models included Word Type and Frequency Condition (deviation coded) as the fixed effects of interest as well as log subtitle word frequency, and the random effects were the intercepts for participants and items as well as by-participant random slopes for Word Type and Frequency Condition (very high-frequency mate, high-frequency error: VH-H, low-frequency mate, high-frequency error: L-H). Analyses were first conducted with homophone errors and spelling controls as the two word types, and then with homophone errors and correct homophones as the two word types. Specifically, the formula used was: eye-tracking measure ~ Word Type * Frequency Condition + scale(LogSubtitle Frequency) + (1 + Word Type + Frequency Condition | Participant) + (1| Item). In the slopes term for participants, Word Type + Frequency Condition was used instead of Word Type * Frequency Condition because some models would not converge with the latter term.

Homophone errors versus spelling controls

First fixation The difference in first fixation durations between words that were homophone errors and spelling controls was not significant, $\beta = .017$, $SE = 0.013$, $|t| = 1.30$, nor was there was a significant effect of Frequency Condition, $\beta = .019$, $SE = 0.013$, $|t| = 1.40$, or an interaction between the two, $\beta = -.045$, $SE = 0.026$, $|t| = 1.70$. However, analyses on each Frequency Condition separately showed that the difference between homophone errors and spelling controls in the VH-H condition was marginally significant, $\beta = .038$, $SE = 0.019$, $|t| = 1.95$, but the difference was not significant in the L-H condition, $\beta = -.005$, $SE = 0.19$, $|t| = 0.29$.

Table 3 Eye-tracking data (fixation times are in ms)

Measure	Very high, high frequency			Low high frequency		
	Correct homophone	Homophone error	Spelling control	Correct homophone	Homophone error	Spelling control
First fixation						
M	222	229	240	242	240	238
SD	26.0	29.0	27.6	27.4	29.8	25.1
Gaze duration						
M	238	255	271	265	264	262
SD	35.8	40.9	41.5	37.7	37.1	34.3
Spillover						
M	226	241	238	230	236	246
SD	27.9	33.1	28.0	27.2	31.8	36.1
Total time						
M	281	405	503	325	399	489
SD	54.7	110.0	150.8	65.1	107.1	162.3
Skipping (%)						
	28.8	26.3	23.8	17.1	20.5	17.0

Gaze duration The difference between words that were homophone errors and spelling controls was again not significant, $\beta = .026$, $SE = 0.017$, $|t| = 1.59$, nor was the effect of Frequency Condition, $\beta = .007$, $SE = 0.017$, $|t| = 0.39$. The interaction between the two was marginally significant, $\beta = -.064$, $SE = 0.033$, $|t| = 1.95$. Analyses on each Frequency Condition separately showed that the difference between homophone errors and spelling controls was significant in the VH-H condition, $\beta = .051$, $SE = 0.026$, $|t| = 1.98$, but not in the L-H condition, $\beta = -.004$, $SE = 0.021$, $|t| = 0.21$.

Total time Homophone errors had significantly shorter total-fixation times than spelling controls, $\beta = .190$, $SE = 0.028$, $|t| = 6.87$, but the effect of Frequency Condition was not significant, $\beta = -.005$, $SE = 0.025$, $|t| = 0.20$, nor was the interaction between the two, $\beta = .004$, $SE = 0.051$, $|t| = 0.08$. Analyses on each Frequency Condition separately confirmed that the difference between homophone errors and spelling controls was very robust in both the words in the VH-H condition, $\beta = .197$, $SE = 0.04$, $|t| = 5.08$, and in the L-H condition, $\beta = .189$, $SE = 0.037$, $|t| = 5.17$.

Spillover The difference in first-fixation durations in the region following homophone errors and spelling controls was not significant, $\beta = .011$, $SE = 0.013$, $|t| = 0.90$, nor was the effect of Frequency Condition, $\beta = .002$, $SE = 0.013$, $|t| = 0.16$. The interaction between the two approached significance, $\beta = .045$, $SE = 0.025$, $|t| = 1.80$. Analyses on each Frequency Condition separately showed that the difference in first-fixation durations following homophone errors and spelling controls was not significant in the VH-H condition, $\beta = -.012$, $SE = 0.017$, $|t| = 0.68$, but approached significance in the L-H condition, $\beta = .034$, $SE = 0.019$, $|t| = 1.83$.

Homophone errors versus correct homophones

First fixation The difference between words that were homophone errors and correct homophones was not significant, $\beta = -.019$, $SE = 0.014$, $|t| = 1.35$, there was an effect of Frequency Condition, $\beta = .054$, $SE = 0.017$, $|t| = 3.16$, but no interaction between the two, $\beta = .027$, $SE = 0.036$, $|t| = 0.76$. Separate analyses on each Frequency Condition indicated that the difference between homophone errors and correct homophones approached significance in the VH-H condition, $\beta = -.036$, $SE = 0.020$, $|t| = 1.87$, and was not significant in the L-H condition, $\beta = .002$, $SE = 0.020$, $|t| = 0.08$.

Gaze duration Homophone errors had significantly longer gaze durations than correct homophones, $\beta = -.038$, $SE = 0.016$, $|t| = 2.36$, and there was a significant effect of Frequency Condition, $\beta = .049$, $SE = 0.020$, $|t| = 2.47$, but no interaction between the two, $\beta = .021$, $SE = 0.041$, $|t| = 0.51$. Separate analyses on each Frequency Condition indicated that the difference between homophone errors and correct homophones was significant in the VH-H condition, $\beta = -.067$, $SE = 0.024$, $|t| = 2.77$, but not in the L-H condition, $\beta = .003$, $SE = 0.022$, $|t| = 0.01$.

Total time Homophone errors had significantly longer total-fixation times than correct homophones, $\beta = -.251$, $SE = 0.032$, $|t| = 7.95$, the effect of Frequency Condition was not significant, $\beta = .044$, $SE = 0.031$, $|t| = 1.42$, and the interaction between the two was also not significant, $\beta = .086$, $SE = 0.064$, $|t| = 1.35$. Separate analyses on each Frequency Condition confirmed that the difference between homophone errors and correct homophones was very robust in both the words in the VH-H mate condition, $\beta = -.316$, $SE = 0.045$, $|t| = 7.09$, and in the L-H condition, $\beta = -.174$, $SE = 0.035$, $|t| = 4.99$.

Spillover First fixation durations on the region after the target word were longer following homophone errors than correct homophones, $\beta = -.035$, $SE = 0.013$, $|t| = 2.67$. There was no significant effect of Frequency Condition, $\beta = -.006$, $SE = 0.014$, $|t| = 0.47$, and no interaction between the two, $\beta = .029$, $SE = 0.026$, $|t| = 1.13$. Separate analyses on each Frequency Condition indicated that the difference in first-fixation durations following homophone errors and correct homophones was significant in the VH-H condition, $\beta = -.050$, $SE = 0.017$, $|t| = 2.96$, but not in the L-H condition, $\beta = -.021$, $SE = 0.020$, $|t| = 1.05$.

Discussion

The goal of this study was to determine whether the meanings of high-frequency words are activated by phonological representations when skilled readers read silently for meaning. A homophone-error paradigm was used in which faster reading times on homophone errors than on spelling controls is taken as evidence that word meanings are activated by phonology. Reading times are expected to be faster on homophone errors than on spelling controls when phonological representations are involved because the meaning associated with the correct homophone for the sentence should also receive some activation from the phonological representation that is activated by the homophone error. Previous eye-tracking studies using this paradigm have not found clear evidence that phonology plays a role in activating the meanings of high-frequency words in skilled readers. Our hypothesis was that the difference in reading times between high-frequency homophone errors and spelling controls would most likely be immediately evident in eye-tracking measures when homophone error words had even higher frequency homophone mates. Very strong connections between the phonological representation activated by the homophone error and the meaning associated with a higher-frequency mate would allow the meaning that fit the sentence to become available more quickly than when homophone mates were low-frequency words.

First-fixation durations and gaze durations, both measures of immediate word processing, were indeed shorter for high-frequency homophone errors than for spelling controls when the high-frequency homophone errors had even higher frequency homophone mates. This finding for homophones with higher-frequency mates provides clear evidence that phonological codes play an early role in activating the meanings of high-frequency words. No difference between high-frequency homophone errors and spelling controls was observed in either first-fixation duration or gaze duration measures when the homophones had low-frequency mates, suggesting that the meaning associated with the low-frequency mate had not yet received sufficient activation from the phonological representation before the decision to move the eyes was made, likely because of weak connections between the phonological representation and the meaning of the mate. However, the spillover analysis provides some evidence that the meaning associated with the low-frequency mate was activated by phonology, just more slowly. The first fixation made on the part of the sentence after the homophone showed a trend towards shorter fixations following homophone errors than spelling controls. In summary, evidence for phonological activation of meaning from the homophone-error paradigm depends on being able to detect activation of the mate of the homophone that was presented, and our findings show that a mate's frequency needs to be quite high for its meaning to be activated quickly enough to be detectable in first fixation and gaze duration measures.

Both groups of homophone errors had shorter total-fixation times than spelling controls, indicating that homophone errors were more easily integrated into the sentence than spelling controls. The integration was very likely easier because the meanings associated with the homophone mates, which did fit the sentence, were available, having been activated by their phonological representations. These data are consistent with Daneman et al.'s (1995) conclusion that homophony facilitates the error-recovery process.

We also compared reading times on homophone errors and correct homophones, although we noted previously that there are interpretation difficulties with this comparison. No difference between high-frequency homophone errors and correct homophones was found in either first-fixation duration or gaze-duration measures when the correct homophones were low in frequency. Although this is what one would expect if word meanings are activated primarily by phonology, it is a null effect and therefore is weak evidence. When correct homophones were higher in frequency, the difference between homophone errors and correct homophones approached significance in the first-fixation data and was significant in the gaze-duration data. This finding provides some evidence of direct activation of word meanings from orthography. However, differences in frequency between correct and error homophones in each condition (the frequency of the correct homophone was purposely manipulated to examine the impact of homophone dominance) complicate the interpretation of these comparisons.

Relation to previous studies

The results of this study help us understand why it has been difficult to observe differences between high-frequency homophone errors and spelling controls in first-fixation and gaze-duration measures. No previous eye-tracking study has used high-frequency homophones with higher-frequency mates—that is, high-frequency but subordinate homophones. Feng et al. (2001), using high-frequency homophones with high-frequency mates (but not necessarily the subordinate member), did see a small difference between high-frequency homophone errors and spelling controls in short fixations in their distributional analysis, although not in their first-fixation or gaze-duration data generally. Folk (1999) also found a homophone effect for balanced high-frequency homophones. Here we saw such a difference when all high-frequency homophones were the subordinate member of the pair and a larger number of stimuli were used.

In some previous studies, the difference between homophone errors and correct homophones was significant (e.g., Daneman et al., 1995; Jared et al., 1999, Experiments 4 & 5), and in one other it was not (Jared et al., 1999, Experiment 6). In each of these studies, the frequency of the two word types differed, as it did here. Therefore, the variation in results across studies is likely at least partially dependent on the extent of the frequency difference between correct homophones and homophone errors.

The data from this eye-tracking study are consistent with Newman et al.'s (2012) ERP data on the same stimuli. To recap, in that study the homophone errors with higher frequency mates differed from spelling controls in anterior electrodes in a 250–300 ms time window, but no such difference was found in the N400. Here, the same stimuli differed in first-fixation and gaze durations, but not in the spillover measure. The eye-tracking findings are therefore consistent with the interpretation given for the ERP results that the meanings associated with both members of the homophone pair were briefly activated, but the meaning associated with the presented homophone quickly won out. In the ERP study, homophone errors with lower frequency mates did not differ from spelling controls in the 250–300 ms time window, but the two word types did differ in the N400. Here, the same stimuli did not differ in either first-fixation or gaze durations, but showed a trend to differing in the spillover measure. These findings are consistent with the interpretation given for the ERP results that there was a delay in the activation of the meaning of the mate for these words. The word-by-word presentation with a 750-ms SOA used in the ERP study appears not, therefore, to have unduly affected the results. Here, total reading times for homophone errors were shorter for homophone errors than spelling controls in both frequency groups. An ERP counterpart of the advantage in error recovery for homophones errors compared to spelling controls was not explored in the Newman et al. (2012) study. However, an inspection of the ERP waveforms in that article shows a larger P600 for homophone errors than for spelling controls. Although the P600 is often considered to be a marker of syntactic processing, Van Herten, Kolk, and Chwilla (2005) showed that it is also sensitive to semantic violations. They suggested that the P600 reflects a monitoring component that checks on the accuracy of sentence comprehension. Such an interpretation is consistent with Daneman et al.'s (1995) proposal of an error-recovery process.

Theoretical implications

Our finding that phonology plays an early role in activating the meanings of high-frequency words, even in highly skilled readers, has important theoretical implications. This finding provides evidence against the view that phonological activation of meaning early in reading development is later replaced by faster direct activation of meaning from print (e.g., M. Coltheart, 2000; Share, 1995), instead supporting the view that word meanings are always activated by phonological representations (Frost, 1998, Van Orden, 1997). With respect to Harm and Seidenberg's (2004) proposal that there is a cooperative division of labor between phonological and orthographic pathways to meaning activation, our results suggest that although factors such as frequency and reader skill may alter the relative contribution of the two pathways, the phonological pathway continues to provide at least some activation of word meanings when reader skill and word frequency are high.

How does the frequency of the unseen homophone mate influence processing?

The two groups of homophone errors were matched for frequency, yet they did not produce the same pattern of results. That the unseen homophone mate had an impact on processing the presented homophone is evidence that its representations were activated. One might have expected that the mates that were very high in frequency would have provided strong competition for the presented high-frequency homophones, and that their effects would be more obvious and long-lasting than high-frequency homophones with low-frequency mates. There are several theoretical ideas as to why the very high-frequency mates are not more disruptive.

One idea is that greater familiarity with the spelling of the homophone mate makes it easier to determine that it does not match the word that was presented. This view was proposed by Van Orden (1987) to explain findings from category decision experiments using homophone errors (*FLOWER-rows*). He claimed that the meanings of all words are activated by phonology, and a subsequent spell-check procedure is used to disambiguate homophones. The spelling that is associated with the meaning that fits the context is retrieved and compared with the orthographic representation of the presented word. Homophone errors are easier to detect when the correct homophone is a high-frequency word than when it is a low-frequency word because the spellings of high-frequency words are more familiar and less likely to inadvertently pass the spelling check. This account is consistent with our pattern of findings for the two groups of homophone errors. However, although the spell-check procedure may have been a plausible account of participants' performance in a category-verification task, which it was designed to explain, it is less clear whether participants would perform such a check in the sentence-reading task used here and in Newman et al. (2012) because participants were not required to make a decision about the fit of the homophone errors in the context. Furthermore, the spell-check as described by Van Orden appears to be a process that happens somewhat later in processing, but our data suggest that the meaning associated with a very high-frequency mate is suppressed very quickly.

Perfetti's (1992; Perfetti & Hart, 2001) lexical quality hypothesis can also provide an account of homophone-mate frequency effects. In this view, with experience, readers come to develop high-quality lexical representations in which the constituents (orthography, phonology, and semantics) each have precise representations and are bound tightly together so that all constituents are activated simultaneously. Perfetti and Hart (2001) claimed that homophones threaten lexical quality because there is a competition between the two semantic representations, as well as a competition between the two orthographic patterns. They proposed that relative to individuals with low-quality lexical representations, those with high-quality lexical representations would more quickly activate a homophone mate but also more quickly resolve any confusion between the homophone and its mate. Similarly, within skilled readers, some lexical representations would be of higher quality than others depending on exposure. When a homophone and its mate both have high-quality lexical representations, the presentation of one member would quickly activate the mate, but the confusion would be resolved more quickly than when the lexical representations of one or both members of a homophone pair are of lower quality. This view is consistent with the pattern of findings reported here, although one might like more details about how the resolution process is assumed to work.

A specific mechanism to disambiguate homophone meanings was proposed by Harm and Seidenberg (2004), who suggested that readers develop inhibitory connections between orthographic representations of homophones and the semantic representation associated with their mate, particularly when the mate is a higher-frequency word. They provided a demonstration of this mechanism using a connectionist model of word recognition that had two pathways to meaning: one from orthography to semantics and the second from orthography to phonology to semantics. Their simulations revealed that the orthographic-phonological-semantic pathway activated the semantics of a dominant homophone much more strongly than a subordinate one. They then examined the input from each pathway to a semantic feature related to the homophone mate when the model was presented with a homophone. They observed that the orthographic-semantic pathway produced strong inhibition of the semantic feature related to its homophone mate when the mate was a high-frequency word. Their explanation of this finding was that model training is error-driven, and when one pathway produced incorrect activation, the other was pressured to overcome that error (see also Rueckl & Seidenberg, 2009). Thus, for high-frequency homophones with higher-frequency mates, there is some activation of both meanings associated with the homophone from the orthographic-phonological-semantic pathway (more for the dominant than the subordinate meaning), but strong suppression of the inappropriate meaning by the orthographic-semantic pathway.

In the case of high-frequency homophones with lower-frequency mates, Harm and Seidenberg (2004) showed that the orthographic-semantic pathway does not develop strong inhibition of the semantic feature related to the low-frequency homophone mate because that semantic feature is not highly activated from phonology and therefore there is little error for the orthographic-semantic pathway to correct. No homophone effect was observed in their simulation for high-frequency homophones with low-frequency mates based on the activation level of a semantic feature of the mate. However, here and in Newman et al. (2012), such homophones did differ from spelling controls in later measures. This difference might arise in the human data from the influence of sentence context, which was not considered in the Harm and Seidenberg simulations. The meaning associated with the unseen mate may get a boost because it fits into the sentence context, whereas the meaning associated with the presented homophone might be inhibited because it does not fit the context. The sentence frames in this study were written so that the target words could not be predicted from the prior context, but error words were obviously wrong when encountered. If the meaning of the unseen homophone mate (which has been activated by phonology) gets a boost in activation from context, and there is little inhibition of its representations because infrequent exposure has given little opportunity for error correction, then perhaps even high-frequency homophone errors might be difficult to detect.

In their simulations, Harm and Seidenberg (2004) explored the impact of error correction on the activation of semantic representations, but Newman et al. (2012) speculated about a similar process happening in other parts of the model. For example, phonological representations feed activation back to two orthographic representations in the case of homophones. Feedback from semantic to orthographic representations may be pressured to correct that error, and this error correction should have a greater impact on connection weights in the case of a high-frequency mate than for a low-frequency mate.

The Harm and Seidenberg (2004) model is a model of single word recognition, and therefore is an incomplete model of silent reading of texts. The most relevant eye-tracking measures for this model are first fixation times and gaze durations, as measures of early and slightly later word reading times. A more complete model of reading will need to combine the detailed account of activation of orthographic, phonological, and semantic codes in word recognition with a model of oculomotor control in reading, such as the E-Z reader model (e.g., Pollatsek, Reichle, & Rayner, 2006; Rayner, Pollasek, & Reichle, 2003).

Conclusion

Newman et al. (2012) provided evidence from an ERP study suggesting that phonology plays a role in activating the meanings of high-frequency words when skilled readers silently read sentences. The aim of this research was to provide converging evidence from eye-tracking measures to support this claim. A limitation of the ERP methodology was that the words of the sentences had to be presented one at a time with a fairly long delay between presentations. Here, participants were able to read words in the sentences more naturally, and the data were consistent with the ERP findings. ERP and eye tracking both have their weaknesses, but together these experiments provide converging evidence that phonology still contributes to the activation of word meanings in the silent reading of connected text, even for the highly skilled readers that we tested here (readers above the 80th percentile on a reading comprehension test) and for words that they have read many thousands of times. Although these readers would have had strong links between the spellings and meanings of the high-frequency words, their links between spelling and sound, and between sound and meaning, must also have been very strong.

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