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Brief article

The effect of phonological neighborhood density on eye movements during reading

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Abstract

Recent research has indicated that phonological neighbors speed processing in a variety of isolated word recognition tasks. Nevertheless, as these tasks do not represent how we normally read, it is not clear if phonological neighborhood has an effect on the reading of sentences for meaning. In the research reported here, we evaluated whether phonological neighborhood density influences reading of target words embedded in sentences. The eye movement data clearly revealed that phonological neighborhood facilitated reading. This was evidenced by shorter fixations for words with large neighborhoods relative to words with small neighborhoods. These results are important in indicating that phonology is a crucial component of reading and that it affects early lexical processing.

Keywords: Phonology; Eye movement control; Reading; Phonological neighborhood

1. Introduction

The role that phonology plays in reading is one of the most researched and heavily debated topics in the area of psycholinguistics. This topic has been of interest in

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the areas of isolated word recognition and sentence reading. In both areas, there are two general ways that the impact of phonology is usually studied. One way is to assess the influence of spelling sound typicality (i.e., regularity and consistency) and the other is to gauge the effect of homophony. In isolated word recognition, researchers have shown that both homophony (Pexman, Lupker, & Jared, 2001) and spelling sound inconsistency (Cortese & Simpson, 2000) slow processing.

In the study of eye movements while reading, the variables of spelling sound typicality and homophony have also been employed, but the results are mixed. Sereno and Rayner (2000) found an effect of regularity on eye movements, but Inhoff and Topolski (1994) failed to find an effect on some of their eye movement measures (e.g., gaze duration). Although spelling sound typicality has not received much attention in eye movement research, there have been many studies of homophony. One way that homophony is used is to measure eye movements to sentences that either contain the correct homophone of a homophone pair (e.g., the sentence contains *plain* where *plain* is contextually appropriate), the incorrect homophone mate (e.g., the sentence contains *plane* where *plain* is appropriate), or an orthographic control (e.g., the sentence contains *plant*). Using this method, some studies have found evidence that phonology is activated early in processing (Rayner, Pollatsek, & Binder, 1998), whereas others have failed to find that phonology is used early in reading (Daneman, Reingold, & Davidson, 1995). The effects of homophony on parafoveal processing have also been studied. This research indicates that parafoveal processing of a homophone mate facilitates subsequent processing of the contextually appropriate homophone (Pollatsek, Lesch, Morris, & Rayner, 1992). This indicates that phonology may be extracted before a word is fixated, demonstrating a quick acting role for phonology in reading.

Recently, there has been increased interest in a new phonological variable termed phonological neighborhood. Two words are said to be phonological neighbors if they have the same number of phonemes and differ by one phoneme substitution. For example, the word *gate* has *bait* and *get* as neighbors. The results of word recognition studies using phonological neighborhood have shown that words with many neighbors are processed more rapidly than are words with few neighbors (Yates, 2005).

The current research was designed to address the question of whether phonology plays a central role in reading for meaning by testing whether phonological neighborhood has an effect on the reading of words embedded in sentences. Specifically, it was predicted that fixations on words with large phonological neighborhoods would be shorter than fixations on words with small neighborhoods and that this effect would be evident in the earliest measures of processing. It is important to test this prediction for two reasons. First, this experiment provides an important test of the strong phonological theory of reading (Frost, 1998), which holds that phonological processing is a mandatory component of reading. Accordingly, the strong phonological theory of reading predicts a facilitative effect of phonological neighborhood. Second, for a variable to be useful in understanding the reading process it is necessary to conduct a careful investigation of its effect on both isolated word recognition and sentence reading and then relate these effects to the relevant models. Work along these lines has already been conducted in terms of the effect of phonological neighborhood on isolated word recognition (Mulatti, Reynolds, & Besner, 2006; Yates, 2005; Yates, Locker, & Simpson, 2004). However, there has been no attempt to understand how (or if) phonological neighborhood affects sentence reading and whether models of eye movement control during reading can account for the effect. Finding a facilitative effect of phonological neighborhood density would mean that these models would need to incorporate a word recognition system that allows phonological similarity to speed processing.

2. Methods

2.1. Participants

The participants were 32 undergraduates at the University of South Alabama who earned course credit for their participation. All participants reported English as their native language and having normal or corrected to normal vision.

2.2. Materials

The target words consisted of 30 words with large phonological neighborhoods ($M = 22$) and 30 words with small phonological neighborhoods ($M = 6$). The two groups of words were controlled on number of letters, number of phonemes, number of syllables, CELEX frequency (Baayen, Piepenbrock, & Gulikers, 1995), Kučera and Francis (1967) frequency, orthographic neighborhood size, average orthographic neighborhood frequency, and average phonological neighborhood frequency. The values for the orthographic and phonological variables were obtained using the Wordmine database (Buchanan & Westbury, 2000).[1] Separate t tests comparing the two groups on each of the control variables indicated that there were no significant differences, all $p\text{s} > .10$. See Table 1 for a list of the means and standard deviations of the control variables. Additionally, the two groups of words were also compared on age of acquisition (AoA) and imageability. The AoA and imageability values were obtained from the combined Bristol (Stadthagen-Gonzalez & Davis, 2006) and the MRC norms (Coltheart, 1981) using the N-Watch program (Davis, 2005). For AoA, the values for 70% of the stimuli were contained in N-Watch. For these stimuli, there was not a significant difference between the words with large phonological neighborhoods ($M = 324$) and words with small phonological neighborhoods ($M = 327$). There were imageability values for 87% of the stimuli, and for these, there was no significant difference between the words with large phonolog-

[1] As there are sometimes discrepancies between databases in terms of values for neighborhood characteristics, the neighborhood values were also calculated using the N-Watch program (Davis, 2005). Although somewhat different values were obtained from N-Watch, there were no significant differences between the two groups of words in terms of any of the orthographic or phonological neighborhood control variables.

Table 1
Means and (standard deviations) for the control variables

Control variables	Small neighborhood	Large neighborhood
Kučera–Francis frequency	19.3 (25.5)	14.7 (14.3)
CELEX frequency	12.0 (11.1)	14.2 (10.2)
Number of syllables	1.1 (0.3)	1.3 (0.5)
Number of phonemes	3.8 (0.4)	3.7 (0.7)
Number of letters	4.6 (0.7)	4.9 (0.7)
ON size	5.0 (3.4)	5.8 (3.7)
Average ON frequency	15.2 (21.9)	15.8 (15.4)
Average PN frequency	14.5 (50.0)	14.5 (17.1)

ON, orthographic neighborhood.
PN, phonological neighborhood.

ical neighborhoods ($M = 541$) and those with small phonological neighborhoods ($M = 544$). Finally, we also equated the two groups of words as closely as possible on spelling-to-sound regularity using the values in the N-Watch program. We only evaluated regularity in terms of the monosyllabic stimuli, as it is not clear what the rules for spelling-to-sound regularity are for disyllabic words. Of the total stimuli, 78% were monosyllabic. Of these, eight of the large phonological neighborhood words were irregular and eight of the small neighborhood words were irregular.

Each word with a small phonological neighborhood was paired with a word having a large phonological neighborhood, resulting in 30 word pairs. For each pair, a sentence was written that could accommodate both words. For example, for the pair of words *sting/punch,* the sentence frame was "*The painful* [*sting/punch*] *made the man wince*". Two lists were constructed that contained 15 sentences with small phonological neighborhood words and 15 sentences with large phonological neighborhood words. The target words were counterbalanced across lists such that only one of the words from each pair occurred in each list. In addition, to ensure that the predictability of the sentences did not differ between the two conditions, a separate group of participants ($N = 10$) was given the sentence frame up to but not including the target word. They were instructed to provide the next word in the sentence. The results show that the target word was provided 1.0% of the time for the sentences containing words with large phonological neighborhoods and 0.3% of the time for those with small phonological neighborhood words. This difference did not approach significance, $F < 1$. Finally, another group of participants ($N = 10$) was given each of the 60 experimental sentences up to and including the target word and were asked to rate the plausibility on a seven point scale from 1 (highly implausible) to 7 (highly plausible). The mean plausibility rating did not differ significantly ($F < 1$) between the sentences with large neighborhood words ($M = 5.33$) and those with small neighborhood words ($M = 5.36$).

2.3. Apparatus and procedure

Eye movements were recorded using an EyeLink II video-based pupil tracking system (SR research, Toronto, Canada) that has a high spatial resolution (noise $< 0.01°$) at a sampling rate of 500 Hz. Viewing was binocular, but eye movements were only recorded from the right eye. Sentences were displayed on a 21″ ViewSonic G225f CRT monitor running at a screen resolution of 1024×768. At a viewing distance of 81 cm, three characters equaled approximately 1° visual angle.

When participants arrived at the experiment, they were fitted with the headband containing the cameras of the eye tracking system. The eye tracker was then calibrated. Following calibration, a validation procedure was conducted. After this, the experiment began. Participants were told to read the sentences for comprehension and that after some of the sentences a yes/no question would appear to check their comprehension of the sentences. Before viewing the experimental sentences, each participant read 10 practice sentences. After reading the practice sentences, the participants read the 30 experimental sentences from either List 1 or List 2 along with 10 filler sentences. All sentences were displayed on a single line.

Each trial began with a fixation point where the first letter of the sentence would appear. Once the participant was looking at the fixation point, a drift correction was applied and the sentence was displayed. After reading the sentence, the participant pressed a button on the response pad to terminate the sentence display. After 25% of the trials, a yes/no comprehension question appeared to which the participant responded using the response pad. As participants correctly answered the questions over 93% of the time, it seems they had little trouble comprehending the sentences.

3. Results and discussion

Data were excluded from analyses if there was a track loss or readers skipped the target word. This resulted in the elimination of 15% of the data.[2] To assess the effect of phonological neighborhood on reading we examined the following measures (see Table 2): (a) single-fixation duration (the duration of the first forward fixation provided it was the only fixation), (b) first-fixation duration (the duration of the first forward fixation irrespective of whether there were other first pass fixations), (c) gaze duration (the sum of all forward fixations), (d) total time (total of all fixations on a target word), and (e) percentage of regressions back to the target word.

Phonological neighborhood size was treated as a within-participants factor for the participants analyses and a between-items factor for the items analyses. Although the two groups of words were controlled on many variables, they did differ in terms of bigram and trigram frequency based on the summed log bigram (token) frequency (SLBF) and summed log trigram (token) frequency (SLTF) values from N-Watch (Davis, 2005). Words with large phonological neighborhoods had larger SLBF and SLTF values than words with small phonological neighborhoods. To ensure that these differences did not have an effect on the results reported here both SLBF and SLTF were used as covariates in the items analyses. The analysis of the single-

[2] For sentences containing large phonological neighborhood words, the target word was skipped 5.2% of the time. The target word skipping rate was 5.6% for sentences containing small neighborhood words.

Table 2
Eye movement measures for the target words as a function of phonological neighborhood size

Reading measures	Small neighborhood	Large neighborhood	Difference
Single-fixation duration (ms)	256	238	18
First-fixation duration (ms)	253	240	13
Gaze duration (ms)	278	273	5
Total time (ms)	333	336	−3
Percentage of regressions (%)	18.0	15.4	2.6

fixation durations revealed that words with large phonological neighborhoods were fixated for less time than words with small phonological neighborhoods, $F_1(1,31) = 6.37$, $p = .017$, partial eta^2 ($\eta_p^2 = .171$); $F_2(1,56) = 5.05$, $p = .029$, $\eta_p^2 = .083$. The results for the first-fixation durations indicated that words with large phonological neighborhoods were fixated for less time than words with small phonological neighborhoods, $F_1(1,31) = 7.72$, $p = .009$, $\eta_p^2 = .199$; $F_2(1,56) = 5.49$, $p = .023$, $\eta_p^2 = .089$. In terms of gaze duration, words with many neighbors were fixated for less time than words with few neighbors. However, the effect was not significant in either the participants or items analyses $F_1 < 1$; $F_2(1,56) = 1.41$, ns. For total time, there was no effect of phonological neighborhood, both $F < 1$. Finally, there was no effect of neighborhood density on percentage of regressions $F_1 < 1$; $F_2(1,56) = 1.45$, ns.

Although the two groups of words did not differ significantly on the variables reported in Table 1, these variables might still have had an influence on the fixation data reported here. To evaluate this, we tested whether any of the control variables from Table 1 correlated with the single-fixation duration and first-fixation duration measures. The results of these correlations revealed that only three variables showed a trend toward significance (i.e., $p < .20$).These three measures are the two measures of frequency and the number of phonemes measure. None of the other correlations approached significance, all $p > .44$. To assess whether these variables were affecting the results we ran two additional ANCOVAs with the covariates reported above (i.e., SLBF and SLTF) plus the three variables that showed a trend toward significance with the fixation measures (i.e., Kučera and Francis frequency, CELEX frequency, and number of phonemes). The results showed that the effect of phonological neighborhood was still significant for both single-fixation durations $F(1,53) = 4.95$, $p = .030$, $\eta_p^2 = .085$ and for first-fixation durations $F(1,53) = 4.27$, $p = .044$, $\eta_p^2 = .075$. Finally, we note that none of these control variables proved to be significant covariates, all $F < 1$. As such, it seems that the effect reported here can be attributed to the differences in phonological neighborhood size between the two groups of words and not some other variable.[3]

[3] According to the N-Watch database (Davis, 2005), large neighborhood words had more higher frequency phonological neighbors ($M = 5.3$) than small neighborhood words ($M = 2.7$). This variable did not correlate significantly (both $p > .40$) with either single-fixation durations ($r = .101$) or first-fixation durations ($r = .092$). Including this variable as an additional covariate did not change the results for either single-fixation or first-fixation durations (i.e., the effect of phonological neighborhood density was still significant, both $p < .05$).

The analyses of the eye movement data support the argument that phonological neighborhood has an effect on silent reading. More importantly, this finding provides direct support for the strong phonological theory of reading (Frost, 1998). Interestingly, the effect of phonological neighborhood was only significant in fixation measures that are assumed to reflect early lexical processing (i.e., single-fixation and first-fixation durations). This agrees with previous studies that have found the effects of phonology to be evident in the early measures of reading. For example, Inhoff and Topolski (1994) found that regularity had a significant effect on first-fixation durations. Similarly, Pollatsek et al. (1992) found that a parafoveal preview of a homophone had an effect on first-fixation durations. Additionally, Rayner, Sereno, Lesch, and Pollatsek (1995) reported pseudohomophone priming at short durations. Thus, by demonstrating a phonological neighborhood effect early in processing, the current research provides converging evidence with previous research indicating that the phonological code is used in the earliest stages of reading.

Because phonological neighborhood influences fixation durations, models of eye movement control while reading will need to account for the effect. One model that has received considerable attention is the E-Z Reader model (Reichle, Pollatsek, & Rayner, 2006). In the E-Z Reader model, there are two stages of lexical processing referred to as L_1 and L_2. L_1 represents a familiarity check that allows the system to determine whether recognition is imminent and begin preparing a saccade. The completion of L_2 occurs once lexical access is complete, and at this point attention shifts to the next word. It has been suggested that L_1 is influenced by the phonological representation of the word (Reichle et al., 2006). With regard to phonological neighborhood, it has been argued that words with large neighborhoods receive more activation within the phonological system due to the activation of their neighbors (Yates, 2005). This increased activation within the phonological system may make words with large neighborhoods appear more familiar (Yates et al., 2004). Thus, one way for the E-Z Reader model to account for these results is to assume that words with large phonological neighborhoods complete the L_1 familiarity check more rapidly than do words with small neighborhoods. However, determining exactly how the E-Z Reader model and other models can best simulate the phonological neighborhood effect is an important topic of future research.

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