Vowel Processing During Silent Reading: Evidence From Eye Movements

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Abstract

Two eye movement experiments examined whether skilled readers include vowels in the early phonological representations used in word recognition during silent reading. Target words were presented in sentences preceded by parafoveal previews in which the vowel phoneme was concordant or discordant with the vowel phoneme in the target word. In Experiment 1, the orthographic vowel differed from the target in both the concordant and discordant preview conditions. In Experiment 2, the vowel letters in the preview were identical to those in the target word. The phonological vowel was ambiguous, however, and the final consonants of the previews biased the vowel phoneme either toward or away from the target's vowel phoneme. In both experiments, we observed shorter reading times for targets preceded by concordant previews than discordant previews. Implications for models of word recognition are discussed.

Vowel Processing During Silent Reading: Evidence From Eye Movements

Word identification experiments using various paradigms have established that skilled readers activate phonological information when reading silently (Berent & Perfetti, 1995; Drieghe & Brysbaert, 2002; Folk, 1999; Lee, Binder, Kim, Pollatsek, & Rayner, 1999; Lukatela, Frost, & Turvey, 1998; Lukatela & Turvey, 1994; Niznikiewicz & Squires, 1996; Perfetti & Bell, 1991; Perfetti, Bell, & Delaney, 1988; Pollatsek, Lesch, Morris, & Rayner, 1992; Rayner, Pollatsek, & Binder, 1998; Van Orden, 1987; Van Orden, Johnston, & Hale, 1988; Ziegler, Benraiss, & Besson, 1999; Ziegler, Ferrand, Jacobs, Rey, & Grainger; 2000). These studies reveal the operation of phonological processes in word recognition, but they do not address fine-grained questions about the nature and time course of those processes (cf. Ashby & Clifton, 2005; Ashby & Rayner, 2004).

Phonological processing appears to begin parafoveally, before the eyes actually fixate on a word (Chace, Rayner, & Well, in press; Henderson, Dixon, Petersen, Twilley, & Ferreira, 1995; Lesch & Pollatsek, 1998; Pollatsek et al., 1992). Supporting this view, Pollatsek et al. (1992) found evidence that parafoveally processed homophone previews facilitated reading relative to orthographically similar control previews. In that study, a target word such as *rains* was read faster when it was preceded by a homophone preview (*reins*) than when it was preceded by an orthographically similar control preview (*ruins*). Words preceded by an identical preview were read most quickly of all, which suggests that the preview effect involved more than phonological coding alone. However, homophone previews facilitated word recognition even when orthographic overlap with the target was minimal (e.g., *shoot*–*chute*). The results of Pollatsek et al. (1992) thus suggest that readers begin to access the phonological forms of words parafoveally. Readers use this information in word recognition processes that continue during the following fixation.

Using a similar method, Miellet and Sparrow (2004) demonstrated parafoveal phonological effects with nonword previews in French. However, rather than using homophones, whose phonological representations can be accessed from memory, these researchers used novel letter strings (i.e., pseudohomophones), whose phonological representations must be constructed. Words were presented in sentence contexts preceded by a preview that was either the identical word (e.g., *rose* in English), a pseudohomophone (*roze*), or a visually similar control (*roke*). Miellet and Sparrow found similar reading times in the identical and pseudohomophone conditions, and longer reading times for targets preceded by visually similar controls. Although this single experiment suggests that nonwords can give rise to phonological preview effects, pseudohomophone preview effects have appeared inconsistently in the eye movement literature (Lee et al., 1999; Lee, Kambe, Pollatsek, & Rayner, in press). Therefore, the extent to which phonological processing occurs during the parafoveal processing of nonwords is not yet clear.

In alphabetic writing systems such as English or French, it can be difficult to determine whether homophone and pseudohomophone effects are truly phonological in nature. Because virtually all homophones have letters in common, the possibility that the effects are due to orthographic overlap is hard to rule out. In Chinese, however, a given syllable may be written with different characters that have few strokes in common. Recent eye movement studies have established that phonological information is processed parafoveally in Chinese (Liu, Inhoff, Ye, & Wu, 2002; Pollatsek, Tan, & Rayner, 2000; Tsai, Lee, Tzeng, Hung, & Yen, 2004). These results suggest that parafoveal phonological coding is a fundamental part of reading and is not limited to a particular writing system.

Given that phonological processing plays an important role in reading, one that begins even before the eyes actually fixate a word, the present experiments examined the nature of the early phonological processes. In particular, to what extent do early phonological representations include information about vowels? There are several reasons to believe that vowel information may play little or no role in early phonological processing, at least in English. One reason comes from consideration of the English spelling system. In English, a given vowel spelling can correspond to several potential phonemes (e.g., *a* as in *tack* and *spa*, *ou* as in *shout* and *soup*); vowels are more variable in their spelling–sound relationships than consonants (Kessler & Treiman, 2001). The inconsistency of vowels may affect their role in early word recognition, making them more difficult to process than consonants (Brown & Besner, 1987; Carr & Pollatsek, 1985; Perfetti & McCutchen, 1982). The two-cycles theory (Berent & Perfetti, 1995) asserts that consonants and vowels are processed in separate cycles during word recognition, with the assembly of consonants finishing before the assembly of vowels. Support for this theory comes from eye movement experiments indicating that consonant information contributes more heavily than vowel information to the early phases of word recognition during silent reading (Lee, Rayner, & Pollatsek, 2001; 2002). In addition, the minimality principle (Frost, 1998; Shimron, 1993) posits distinct roles for vowels and consonants. The minimality principle states that the representation used for lexical access contains the minimal amount of phonological information that is necessary to activate a unique lexical item. Ambiguous vowel phonemes, such as the vowel in *pint*, do not necessarily have to be resolved in order to activate a particular lexical item. As a result, the representations used to access words in reading may consist primarily of consonant information.

In the two experiments reported here, we investigated whether skilled readers of English use parafoveal input to gain information about the phonological forms of vowels when reading silently. To do this, we used the eye-contingent display change technique employed in the previously mentioned studies by Pollatsek et al. (1992) and Miellet and Sparrow (2004): the *boundary paradigm* (Rayner, 1975). In this paradigm, eye movements are monitored as participants read sentences displayed on a computer screen. Figure 1 illustrates the boundary technique using a sentence from the present Experiment 1. Initially, a preview stimulus appears in the sentence instead of the target word. While fixating on the word before the preview (*were* in the example), readers begin to process the preview stimulus (*floam*) parafoveally. When readers move their eyes to fixate the target word location, the eyes cross an invisible boundary and trigger a change that displays the target (*flown*). As the preview information is not processed consciously and is replaced by the target word during a saccade, when vision is suppressed, readers are not aware of the change in the display.

Lesch and Pollatsek (1998) used a variation of the boundary paradigm to manipulate the parafoveal phonological information available to readers in an experiment in which participants judged whether pairs of words had related meanings. Although this experiment did not measure reading times of words in sentences, the materials and findings are relevant to the present experiments and so will be described here. Lesch and Pollatsek presented pairs of words, with each word appearing on one side of the screen. Participants first fixated the word on the left side, during which time the parafoveal information available from the second word was manipulated.

As the eyes moved to the word on the right, the preview changed to the target word. In the main conditions of interest, the second word that the participant fixated was a false homophone or a visually similar control. A false homophone can be pronounced as a homophone of a word, given English spelling conventions. For example, *bead* could be pronounced like *bed* /bɛd/, as though it rhymed with *head*. (Phonetic transcriptions in this paper follow the conventions of the International Phonetic Association, 2005). On one trial, *pillow* appeared as the first word, and readers moved their eyes to fixate either *bead* (the false homophone) or *bend* (the control). Participants were slower to reject the false homophone (*bead*) as semantically related to the first word (*pillow*) than to reject the visually similar control (*bend*). The longer reaction time was attributed to participants' generating an alternative pronunciation of *bead* (/bɛd/) that competed as a possible semantic associate of *pillow*. This result suggests that several possible phonological vowels were computed parafoveally based on the preview of the false homophone. Because the false homophone previews affected semantic decisions, it appears that these preliminary phonological codes, which were later rejected, initiated semantic activation.

Although the results of Lesch and Pollatsek (1998) suggest that readers can process vowel information parafoveally, they do not indicate whether readers typically do so during silent reading of text. The present experiments used nonword previews to investigate the phonological representations formed prior to lexical access during sentence reading. In each experiment, one condition used a preview in which the vowel phoneme was biased toward the vowel of the target word in a sense to be described. This condition will be referred to as the *concordant condition*. In the *discordant condition,* in contrast, the vowel phoneme in the preview was biased away from the phonemic vowel of the target word. The experiments differed in the nature of the biasing. In Experiment 1, the preview vowels were orthographically different from the target vowels. The previews in the concordant condition had vowel spellings that, in the real words of English, generally encoded the same phoneme as in the target vowel. An example is *er* for the target *ir*. The previews in the discordant condition had vowel spellings that generally encoded a different phoneme from the target vowel, such as *or* for the target *ir*. We asked whether the target words were read more quickly in the concordant condition than the discordant condition. If so, this would suggest that readers computed phonological vowel information on the basis of the parafoveal input and that this information affected their later processing of the target word. In Experiment 2, we used vowel spellings such as *ea* and *oo*. The preview vowel and the target vowel had the same spelling. These spellings, unlike the majority of those in Experiment 1, encoded more than one possible phoneme. For example, *oo* is sometimes pronounced as /u/ as in *loon* and sometimes as / / as in *cook*, with /u/ being the more common pronunciation. The phonemic vowel of the preview was biased by its following consonant either toward or away from the target's phonemic vowel. For example, the target *drool* was preceded by the preview *droon* in the concordant condition or *drook* in the discordant condition. Based on the statistics of English, a following *k* conditions the vowel phoneme such that it is usually pronounced as / /. That is, the final consonant should bias the vowel phoneme in the preview away from the target's vowel phoneme. If the target words are read more quickly in the concordant condition than in the discordant condition, this would suggest that vowel information was included in the representation that was formed on the basis of parafoveal input and that this information was affected by the consonantal context in which the vowel appeared. Together, the results of the experiments should shed light on whether readers represent phonological vowel information based on parafoveal input, whether this information is affected by the consonantal context in which the vowel appears, and whether these early phonological representations facilitate word recognition during silent reading.

Experiment 1

In Experiment 1, targets (e.g., *chirp*) were preceded by nonword previews whose vowel letters most commonly encoded the same vowel phoneme (*cherg*) or a different vowel phoneme (*chorg*) from that of the target. In neither condition were the preview vowels spelled in the same way as the target vowels. Our dependent measure was fixation time on the target word. If skilled readers begin to assign phonological vowel information before the target is fixated, then targets should be read faster in the concordant preview condition than the discordant preview condition. It is possible, however, that orthographic processing mediates the facilitative effect of concordant previews, such that detection of an orthographic mismatch between the preview and the target results in rejecting the phonological code of the preview. In that case, the lack of full orthographic overlap between the target and the preview could prevent readers from using the phonological preview information to facilitate word recognition, and the fixation times in the two conditions should not differ.

Methods

Participants. Data were analyzed from 38 students at the University of Massachusetts. They were paid or received experimental credit to participate. All participants in this and the following experiment were native English speakers with normal vision who were naive about the purpose of the experiment.

Apparatus and procedure. The stimuli were presented on a NEC 4FG monitor through a VGA video board that was controlled by a personal computer with an Intel 486 processor. An analog-to-digital converter interfaced the computer with a Fourward Technologies Generation VI Dual Purkinje Eyetracker. The monitor displayed text at a 200Hz refresh rate, permitting display changes within 5 ms. The eye tracker monitored movements of the right eye, although viewing was binocular. Letters were formed from a 7 × 8 array of pixels, using the fixed-pitch Borland C default font. Participants sat 61 cm away from a computer screen and silently read single-line sentences while their head position was stabilized by a bite bar. At this viewing distance, 3.8 letters occupied one degree of visual angle. At the beginning of the experiment, the eye-tracking system was calibrated for the participant. At the start of each trial, a calibration screen appeared, and participants who showed a discrepancy between where their eye fixated and the location of the calibration squares were recalibrated before the next trial.

On each trial, the calibration screen appeared and the experimenter determined that the eye tracker was correctly calibrated. The participant was instructed to look at the calibration square on the far left of the screen, and then the experimenter presented the sentence. When the sentence appeared on the screen, a nonword preview appeared in the target region. As readers read the sentence and their eyes approached the target region, this preview appeared parafoveally in their field of vision. Presentation of the actual target word was triggered during reading by a saccade into the target region, as the eyes crossed an invisible boundary placed after the last letter of the preceding word (see Figure 1). When the participant finished reading the sentence, he or she clicked a response key to make it disappear. In 25% of the trials, a comprehension question appeared on the screen. The participant responded by pressing the response key that corresponded with the position of the correct answer. Then the calibration screen appeared before the next trial. The experiment was completed in one session of approximately 30 minutes.

Materials. Thirty-four target words were embedded in single-line sentences (see Appendix A). The target words were monosyllables between four and six letters in length with a mean standard frequency index (SFI) of 49.3 (Zeno, Ivens, Millard, & Duvvuri, 1995). Target words were preceded by a pronounceable nonword preview in which the vowel phoneme was either the same as or different from the vowel phoneme in the target. For example, the target *dawn* had one of two previews: *daik* (in the discordant condition) and *dauk* (in the concordant condition). The expected pronunciation of the discordant and concordant previews was supported by an analysis that determined what proportion of one-syllable words with that rime pattern are pronounced with the same phonemic vowel as the target. To compute the word frequencies for these proportions, SFIs were summed across all words that had the pattern in question. Because SFIs are a logarithmic measure, summing them across words is similar to taking the product of the raw frequencies. In practice that means that the number of different words that enter into the computation has a very large effect on the resultant sum, so that the measure reflects the number of word types more than it does word tokens. The proportions were .013 and .804, respectively. Thus, most of the vowel spellings used in this experiment had little ambiguity. The paired previews for each target had the same initial letter as the target word, whereas the last letter in both differed from the target. Previews were typically constructed by substituting two of the letters at the end of the target word. According to the Mayzner and Tresselt (1965) position-specific letter frequency ratings, the previews in the concordant and discordant conditions had similar vowel bigram frequencies (42.7 and 41.4 per million words, respectively) and roughly similar final trigram frequencies (0.7 and 1.1 per million words). The mean final trigram frequency for the target words was 6.8 occurrences per million words.

Design. Each participant read every target word once, with each target preceded by one of the two possible nonword previews. Experimental condition was defined by the type of preview (discordant or concordant). Each participant read the 34 experimental sentences randomly interspersed with 96 unrelated filler items that also included a parafoveal preview display change.

Results and Discussion

Fixation time on the target was the dependent variable, and preview type was treated as a within factor in both the participant and item analyses. First fixation duration, single fixation duration, and gaze duration are the three fixation time measures reported, since these are the most direct measures of parafoveal effects on foveal word recognition (Rayner, 1998). Fixation time measures included only the trials in which readers fixated the target word during the first-pass reading of the sentence. *First fixation duration* is a measure of the mean time spent reading the first time the eye lands on the target word. Although this is a complete measure of reading time for words read a single fixation, it is only a partial measure of reading time for words that received multiple fixations. *Single fixation duration* is the mean time spent reading targets that received only one fixation. *Gaze duration* is a cumulative measure of the mean time spent reading before the eyes move on to the right of the target, irrespective of the number of fixations on the word. Other measures such as probability of fixation, spillover, and proportion of regressions indicated no significant differences between conditions.

Consistent with most eye movement research (Rayner, 1998), we trimmed the data to eliminate overly short and long fixations. Fixations under 80 ms were eliminated since such short fixations do not seem to reflect cognitive processing of the target word (Rayner, 1998; Rayner & Pollatsek, 1987). Fixations over 550 ms were also eliminated, and approximately 6% of the full data set (i.e., target words and sentence contexts) was lost for these reasons. Trials were excluded from the analyses for three reasons: if no fixations were made on the target word before the eyes moved past it to the right, if the reader blinked while within the target region, or if the display change occurred before the eyes landed in the target region. Subjects for whom 75% of the data were retained after these exclusions and who answered more than 80% of the comprehension questions correctly were included in our data set. This data criterion is similar to that used in other display change experiments in which there are several reasons for data loss (Sereno & Rayner, 1992), and it resulted in the exclusion of three participants from the Experiment 1 analyses. Analyses of variance (ANOVA) by participants (F_1) and items (F_2) were restricted to trials in which the saccade into the target region was launched within seven characters from the initial letter of the target, which is the average length of saccades during reading (Rayner, 1998). This excluded trials in which the launch site of the saccade into the target region was far enough away to hinder parafoveal processing of the critical letters in the preview (Rayner, McConkie, & Zola, 1980; Rayner, Well, Pollatsek, & Bertera, 1982). A similar number of data points contributed to each condition in the participants and items analyses.

First fixation duration. Table 1 shows the mean first fixation times for target words preceded by previews with vowel phonemes that were discordant or concordant with the vowel phoneme in the target. First fixation durations were 7 ms shorter on average for targets preceded by concordant previews than by discordant previews, but this effect was not significant, $F_1(1, 37) = 3.19$, $p < .10$; $F_2(1, 33) = 3.40$, $p < .10$.

Single fixation duration. The mean single fixation times for target words preceded by discordant and concordant nonword previews appear in Table 1. Single fixation durations were 9 ms shorter on average for targets in the concordant condition than the discordant condition, $F_1(1, 37) = 5.23$, $p < .05$; $F_2(1, 33) = 5.71$, $p < .05$.

Gaze duration. The mean gaze durations for target words preceded by discordant and concordant previews appear in Table 1. Gaze durations were 15 ms shorter on average for targets preceded by concordant previews than for those preceded by discordant previews, $F_1(1, 37) = 6.15$, $p < .05$; $F_2(1, 33) = 5.25$, $p < .05$.

Participants spent less time reading target words preceded by concordant vowel previews than by discordant vowel previews. These results suggest that readers began activating the phonemic vowel in the next saccade target parafoveally and integrated this representation with the foveal information available during subsequent fixations to read the target word. Because the vowel letters in both preview conditions differed from those of the target, the data demonstrate a phonological effect of vowel concordance in the absence of complete orthographic overlap.

One could counter that the results we obtained are due to some type of low-level visual similarity effect. The letters in the concordant condition previews may have been more visually similar to the target than the letters in the different-vowel-bias condition previews. For example, the *e* in *cherg* could be more similar to the *i* in the target *chirp* than is the *o* in *chorg*. However, an influence of visual similarity seems unlikely. Previous eye movement research has found that changing letter case between parafoveal and foveal presentations of a word does not affect reading times, suggesting that visual letter forms are not integrated across saccades during reading (McConkie & Zola, 1979; Rayner et al., 1980). Nonetheless, Experiment 2 addressed the possible confound of visual letter similarity by using nonword previews with orthographic vowels that were identical to the target vowel.

Experiment 2

The results of Experiment 1 suggest that, by the time readers fixate a given word, some information about phonological vowels is already activated and included in the developing phonological representation. Experiment 2 investigates *how* readers process phonological vowels. Specifically, we asked whether the phonological representation of an ambiguous vowel is influenced by its following consonant. This question is of interest because studies of English spelling-to-sound relationships show that the pronunciations of vowels become more consistent when the vowel is considered in the context of the surrounding consonants (Kessler & Treiman, 2001; Treiman, Mullennix, Bijeljac-Babic, & Richmond-Welty, 1995). The consonant(s) that follow the vowel are particularly influential, consistent with the view that vowel + final consonant units or *rimes* have a special role in English (Treiman & Kessler, 1995). For example, the vowel *a* is somewhat inconsistent in terms of spelling-to-sound translation, as it can be pronounced as in *rack*, *spa*, or *hall*. However, this vowel is pronounced consistently as / / when followed by *ll*, as in *hall, call,* and *small*. Studies by Treiman, Kessler, and Bick (2002; 2003) have demonstrated that adults' nonword reading and spelling is influenced by the contextual dependencies documented in the Kessler and Treiman (2001) corpus analyses. Although adults do not always pronounce a vowel like *a* as / / when it occurs before *ll*, they are more likely to pronounce it this way before *ll* than before, for example, *ff*. The results of Andrews and Scarratt (1998) are consistent with this view.

Do readers use consonant information to bias the parafoveal processing of vowels in silent reading? To address this question, Experiment 2 used the identical vowel letters in the preview conditions and the target words. Targets (e.g., *rack*) were preceded by nonword previews in which consonantal context was expected to lead to relatively substantial activation of a vowel phoneme that differed from that of the target (e.g., *rall*), or previews (e.g., *raff*) in which the most highly activated vowel phoneme was expected to match that of the target, with little or no activation of an alternative vowel. If readers are sensitive to the conditional consistencies reported by Kessler and Treiman (2001) and if they use consonant information early in word recognition to guide their activation of vowels, then we would expect to find shorter fixation times on targets in the concordant condition than the discordant condition. If readers cannot integrate parafoveal consonant and vowel information or if they do not use conditional consistencies, no difference should appear between the two conditions in fixation times. In this scenario, word recognition might proceed in several ways. Readers could initially activate several competing vowel options, as in Lesch and Pollatsek (1998), or they could activate the vowel phoneme that is most commonly represented by the letter pattern. Alternatively, readers could use a placeholder until lexical access specifies the vowel phoneme, in line with the minimality hypothesis.

Methods

Participants. Data were analyzed from 42 students from the same population as those who participated in Experiment 1. None had taken part in Experiment 1.

Apparatus and procedure. These were the same as in Experiment 1.

Materials. Thirty-two target words were embedded in single-line sentences (see Appendix B). Target words had four different vowel spellings (*ea*, *oo*, *o*, and *a*), and ranged in length from four to six letters, with a mean SFI of 49.2 (Zeno et al., 1995). Targets were preceded by a preview in which the coda consonant conditioned the vowel pronunciation on the basis of English spelling-to-sound statistics. For example, the target *rack* had one of two previews: *rall* in the discordant condition and *raff* in the concordant condition. The stimuli were selected on the basis of an analysis that determined what proportion of one-syllable words with that rime pattern are pronounced with the same phonemic vowel as the target. The proportions in the discordant and concordant vowel conditions were .153 and 1.000, respectively.

Design. The design was the same as in Experiment 1 except that each participant read the 32 experimental sentences randomly interspersed with 160 unrelated filler items.

Results and Discussion

Fixation time on the target was the dependent variable, and preview type (discordant or concordant) was a within factor in both the participant and item analyses. The data were trimmed following the same procedures as in Experiment 1. Five participants, who did not meet the data criterion, were excluded from the analyses. As in Experiment 1, no significant differences were found between conditions on probability of fixation, spillover, and proportion of regressions, and so these variables are not discussed further.

First fixation duration. The mean first fixation times for targets preceded by concordant and discordant nonword previews appear in Table 2. First fixation durations were 19 ms shorter on average for targets in the concordant condition than for targets in the discordant condition, $F_1(1, 41) = 5.98$, $p < .05$; $F_2(1, 31) = 4.04$, $p = .053$.

Single fixation duration. Table 2 shows the mean single fixation times. Single fixation durations were 16 ms shorter on average for targets in the concordant condition than for those in the discordant condition; the effect was marginal in the participants analysis, $F_1(1, 41) = 3.42$, $p = .07$, and significant in the items analysis, $F_2(1, 31) = 4.46$, $p < .05$.

Gaze duration. The mean gaze durations for target words appear in Table 2. Gaze durations were 19 ms shorter on average for targets in the concordant condition than for targets in the discordant condition, $F_1(1, 41) = 5.26$, $p < .05$; $F_2(1, 31) = 4.94$, $p < .05$.

The advantage observed for the concordant preview over the discordant preview suggests that the consonant information in the preview biased readers' early representation of the vowel phoneme. In the case of *drook*, for example, activation of /u/ appeared weaker than in the case of *droon*. Less activation of /u/ in the discordant condition, and more activation of the context-conditioned pronunciation / /, would have led to the slower processing of targets preceded by discordant previews. Longer reading times in the discordant condition could indicate activation of a single vowel phoneme that differs from that in the target or the activation of multiple alternative phonemes. We cannot decide between these alternatives based on the present data. However, if the final consonant information had not biased vowel processing, then readers should have represented the dominant vowel, /u/, to an equal degree for both *drook* and *droon*. In this case, no differences in fixation time between the two conditions would have appeared. The observed fixation duration differences thus suggest that readers used the final consonant to guide vowel processing toward the typical phoneme in *droon* and toward the less common consonant-conditioned phoneme in *drook*. This result provides converging evidence for skilled readers' sensitivity to the conditional consistencies established in Kessler and Treiman (2001). Importantly, it provides the first evidence that skilled readers use parafoveal conditional consistencies to inform the early phonological representations that support word recognition during silent reading.

General Discussion

Two experiments investigated how skilled readers processed vowels when reading silently. Our central finding is that skilled readers represented phonological vowels presented in parafoveal previews and used that information in word recognition on the next fixation. The experiments manipulated the characteristics of the vowel phoneme in the preview and the extent to which it was the same as or different from the vowel phoneme in the target word. Whereas the goal of phonological manipulation was similar in the two experiments, the method of that manipulation differed. In Experiment 1, the vowel phoneme in the previews was manipulated by using different vowel letters than those that appeared in the target word. Here, the letter information from both previews mismatched the foveal letter information. In Experiment 2, the vowel phoneme in the previews was manipulated using the conditional consistencies reported in Kessler and Treiman (2001). Here, the vowel letters in both previews were identical to the vowels letters in the target. In both experiments, skilled readers processed targets faster in the concordant preview condition than in the discordant preview condition. These results suggest that readers begin to encode vowel phonemes based on parafoveal information and that activation of vowel phonemes is influenced by the consonant that follows the vowel.

One somewhat surprising finding was that the size of the preview effect was nearly as large in Experiment 1 as Experiment 2. That phonological preview benefits occurred even with conflicting orthographic information in Experiment 1 suggests that inconsistent letter information did not prevent an influence of parafoveal phonological representations on foveal reading times. Readers seem to have used parafoveal phonological representations to facilitate word recognition even when foveal letter codes replaced the initial parafoveal letter codes.

We take the present data as evidence that readers include vowel phonemes in the early phonological representations constructed on-line during silent reading. Alternatively, one could locate the observed vowel effect in the inconsistency of the mapping from orthography to phonology, rather than in the early phonological representation. Although the vowel letters in Experiment 2 encoded multiple vowel phonemes, this was not generally the case in the Experiment 1. Therefore, the simplest account of the observed vowel effects appears to be in the early phonological representations readers construct en route to lexical access.

Our results are inconsistent with minimality theory, which claims that readers use minimal representations to access lexical items—representations that are often lacking detail about vowels (Frost, 1998; Shimron, 1993). If vowel information were absent from access representations, we should not have observed differences between conditions that differ in the nature of the vowel information that they provide. The data from our two experiments suggest that readers of English typically use more elaborated phonological representations, which contain information about vowels as well as consonants, in lexical access.

The implications of our data for two-cycles theory (Berent & Perfetti, 1995) are unclear. Although it is possible that consonants were processed more quickly than vowels at an early point in parafoveal word recognition, it appears that readers integrate the two sources of information before the target word is fixated and use this representation in word recognition during the following fixation. If two-cycles theory did hold for parafoveal processing, the quick resolution of parafoveal consonant information might guide the representation of phonologically ambiguous vowels right from the start of word recognition. We expect that any such difference emerges from the relative inconsistency of vowels as compared to consonants in English, rather than from any universal property of linguistic structure per se.

The results of Experiment 2 offer some insight into the nature of the phonological representations that skilled readers use in lexical access. Accessing the context-conditioned phoneme in the discordant preview condition required readers to represent the vowel in the context of the following consonant. When readers fixated the target, however, the following consonant had changed. If the phonemic vowel were only represented in terms of its context, then the changed final consonant should signal readers to abandon that representation, and foveal word recognition could proceed without much interference. In that case, any reading time differences should have been confined to first fixation. The observation of substantially longer reading times in the discordant condition for targets that received multiple fixations suggests that context-based phoneme segment information was accessible even when the context had changed. As readers represented conditioned vowel phonemes with and without their consonant context, our data suggest that several levels of phonological information are used in word recognition. Alternatively, readers initially could use parafoveal consonant contexts to bias the activation of a specific vowel phoneme, which might preserve phoneme information across the saccade to the target.

Our observation that nonword previews affected word reading times suggests that skilled readers began to form phonological representations from novel orthographic patterns prior to lexical access, on the basis of parafoveally presented information. This result poses several problems for dual-route models of word recognition. The most popular of such models, the DRC, includes only a few grapheme-to-phoneme conversion rules for vowels that are biased by the consonant context (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). For most of the stimuli of Experiment 2, the DRC rules yield the typical context-free pronunciation of the vowel. Another problem for dual-route models relates to their claim that assembly of phonology proceeds serially, whereas addressed phonology involves parallel processing (Coltheart et al., 2001; Havelka & Rastle, 2005). Because dual-route models would consider our nonword previews to be processed along an assembled route, it is not clear how the models could account for the vowel effect observed in Experiment 2. As a serial mechanism would operate from left to right in English, it is difficult to imagine how a letter could bias the pronunciation of the letter to its left. Our data also challenge the claim that the assembled phonology route only influences word recognition when the word is sufficiently unfamiliar to prevent lexical access by the faster, addressed phonology route. In both of the present experiments, nonword previews influenced the time spent reading relatively common words, suggesting that readers use phonological information assembled from the parafoveal preview to begin recognizing familiar words.

The vowel effects observed here are more in line with parallel distributed processing (PDP) models of reading that involve cooperative orthographic and phonological processes (e.g., Harm & Seidenberg, 2004). From this perspective, a phonological representation consists of a pattern of phonological activation operating within a semantic space. Although Harm and

Seidenberg’s (2004) model does not deal with integration of information across fixations, it appears that the model could potentially account for two patterns in the present reading data. In Experiment 1, conflicting parafoveal and foveal letter information did not inhibit readers’ use of parafoveal phonological representations in word recognition. Harm and Seidenberg’s model is consistent with this result, as simulations indicated that whereas the phonological activation of semantic units appeared stable after masking a visual stimulus, orthographic activation decayed quickly. If the saccade intervening between the onset of parafoveal activation and the activation during target fixation acts as a brief mask, then the primary activation remaining when the target is fixated would be phonological in nature. Additional phonological activation during fixation would continue to drive the system toward the same semantic space, whereas activation from the foveal orthographic information would lag behind. Thus, the model could potentially explain the apparent lack of orthographic gating of the phonological vowel effect in Experiment 1. The major outcome of Experiment 2—that readers were sensitive to dependencies between vowels and final consonants that are relatively common in written English—is consistent with the PDP assumption of frequency-based learning. Readers’ acquired sensitivity to orthographic rime patterns could alter the weights of phonological activation so as to yield stronger activation of a vowel phoneme that is less frequent overall when a particular rime pattern is encountered (e.g., *all*). The reading time differences observed in Experiment 2, in particular, require a model that assumes cooperative orthographic and phonological processing.

In summary, our results indicate that skilled readers include vowel information in the early phonological representations used to begin identifying words during silent reading. Parafoveal phonological information facilitated foveal word recognition whether the vowel letters in the preview and target were identical or not. Moreover, when the preview's vowel phoneme was biased by the following consonant, this conditional consistency increased activation of the subordinate vowel phoneme. This is the first demonstration that skilled readers use conditional consistencies to recognize words during silent reading. Early, parafoveal phonological representations appear to include vowel as well as consonant information, at least in the skilled reading of English.

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Appendix A

Materials for Experiment 1

Previews		
Discordant	Concordant	Sentences
braum	*braim*	Molly enjoyed her short *break* in the afternoon.
braim	*braum*	The crane lifted a *broad* beam onto the ship.
blorm	*blerm*	Becky would often *blurt* out the wrong answer in class.
chorg	*cherg*	Beth listened to the birds *chirp* in the back yard.
clewm	*cleem*	Robert's house always looked *clean* after the maid came.
craid	*craud*	Kathy watched the baby *crawl* across the floor.
daik	*dauk*	Jim waited until *dawn* to begin fishing the river.
draim	*draum*	The model was quickly *drawn* by the art students.
doist	*dowst*	The final argument left little *doubt* in the minds of the jurors.
faib	*faub*	Ellen watched the young *fawn* eat the meadow grasses.
fewns	*feens*	Margaret cooked a huge *feast* for Thanksgiving last year.
flarn	*flurn*	Liza would sometimes *flirt* with the guys she met at the bar.
floim	*floam*	The exotic pets were *flown* in from South America.
ghoab	*ghoob*	Andrew dressed like a *ghoul* for the Halloween party.
graub	*graib*	Susan's new MP3 player had *great* sound and it was lightweight.
groab	*groob*	Corey helped start a support *group* for victims of crime.
lail	*laul*	The buyers replaced the large *lawn* with a rock garden.
lewm	*leem*	The grocery only sold *lean* cuts of meat.

laib	*loob*	Some photographers take *lewd* pictures of women.
paim	*paum*	Abbey took the last *pawn* in the chess game.
poid	*powd*	Most of the time, Elizabeth would *pout* if she lost the game.
proit	*prowt*	Sam's brother looked *proud* when he received the award.
shaib	*shaub*	Deborah knitted her first *shawl* this year.
sharg	*sherg*	Carmen kept every *shirt* that belonged to her father.
soab	*soob*	For the party, Alice made *soup* and a salad.
staub	*staib*	Benjamin tasted every *steak* on the table.
stewn	*steen*	The pictures showed *steam* rising from the hot springs.
storp	*stirp*	The sailor mopped the wide *stern* of the ship.
straim	*straum*	The waitress put *straws* in all of the sodas.
tharn	*thern*	Jason hoped to take *third* place at the track meet.
tharnt	*thernt*	The young lion's *thirst* called him to the river bank.
troid	*trowd*	Sally ordered the baked *trout* for dinner.
voit	*vait*	Emma chose a black *veil* for the funeral.
yaim	*yaum*	Carl would often *yawn* during his morning class.

Appendix B

Materials for Experiment 2

Previews

Discordant	Concordant	Sentences
blook	*bloon*	Cathy hoped the flowers would *bloom* before... vacation.
blort	*blomp*	Amy saw the reddish *blobs* of clay drying in the sun.
bort	*bomp*	Most mothers have a close *bond* with their children.
chead	*chean*	Anne went to the store to buy some *cheap* wine for the party.
chead	*chean*	Derek thought that he should *cheat* on the Spanish exam.
clall	*claff*	Betty found the best *class* available at that time.
clall	*claff*	Sue knew that the shoes would *clash* with her dress.
drook	*droon*	Beverly said that all babies *drool* when they are teething.
drook	*droon*	Jessica's hat feathers might *droop* in the heat from the stage lights.
fook	*foon*	Claire regularly tried to *fool* her teacher with a fake doctor's note.
gort	*gomp*	The tribe pleased their *gods* by sacrificing small animals.
jort	*jomp*	Dawn quit one of her several *jobs* in the middle of finals week.
jort	*jomp*	Every day, David *jogs* with his wife in the park downtown.
nort	*knomp*	The couple chose wooden *knobs* for their kitchen cabinets.
nort	*nomp*	The candidate's speech got several *nods* of approval.
pead	*pean*	Anna climbed to the highest *peak* of the mountain.
prook	*proon*	The lawyer wanted to find *proof* of his client's innocence.
rall	*raff*	Paul set the doughnuts on a long *rack* until they cooled.

rall	*raff*	The baby's latest *rash* kept her from sleeping.
schook	*schoon*	Unlike Charlene, Tom hated *school* when he was a child.
scook	*scoon*	Joe ordered a large *scoop* of chocolate ice cream in a sugar cone.
slall	*slaff*	Bob let the rope hang *slack* while he tied up the boat.
slort	*slomp*	The twins looked like *slobs* in their ragged sweat pants.
snall	*snaff*	Jessie ate her sweet *snack* early today.
spead	*spean*	Although Donald is nervous, he should *speak* clearly.
squead	*squean*	Sally wanted the loud *squeak* in the hardwood floor fixed.
squead	*squean*	William would always *squeal* when his sister tickled him.
stook	*stoon*	Aaron asked if he could move his *stool* closer to the fireplace.
stread	*strean*	Karl walked beside the cold *stream* for several miles.
stread	*strean*	Lenore wiped the purple *streak* of lipstick off the mirror.
thall	*thaff*	Amy hoped that she could *thank* her brother in person.
trall	*traff*	Andy ran around the paved *track* until he was out of breath.

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Table 1

Reading Times (ms) for Target Words in Experiment 1

	Discordant Preview	Concordant Preview
First Fixation	296	289
Single Fixation	305	296
Gaze Duration	324	309

Table 2

Reading Times (ms) for Target Words in Experiment 2

	Discordant Preview	Concordant Preview
First Fixation	304	285
Single Fixation	311	295
Gaze Duration	330	311

Figure Caption

Figure 1. The parafoveal preview technique. The fixation point is denoted by an asterisk (*). The invisible boundary that triggers the display change is marked with a vertical bar (|).

* |
The exotic pets were *floam* in from South America.

| *
The exotic pets were *flown* in from South America.