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Orthographic and Phonological Preview Benefits: Parafoveal Processing in Skilled and Less-skilled Deaf Readers

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Abstract

Many deaf individuals do not develop the high-level reading skills that will allow them to fully take part into society. To attempt to explain this widespread difficulty in the deaf population, much research has honed in on the use of phonological codes during reading. The hypothesis that the use of phonological codes is associated with good reading skills in deaf readers, though not well supported, still lingers in the literature. We investigated skilled and less-skilled adult deaf readers' processing of orthographic and phonological codes in parafoveal vision during reading by monitoring their eye movements and using the boundary paradigm. Orthographic preview benefits were found in early measures of reading for skilled hearing, skilled deaf, and less-skilled deaf readers, but only skilled hearing readers processed phonological codes in parafoveal vision. Crucially, skilled and less-skilled deaf readers showed a very similar pattern of preview benefits during reading. These results support the notion that reading difficulties in deaf adults are not linked to their failure to activate phonological codes during reading.

Keywords

deaf readers; orthographic code; phonological code; eye movements; preview benefits; word processing; reading level

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It is well known that for hearing individuals, phonological codes play an important part in learning to read (Booth, Perfetti, & MacWhinney, 1999; Rayner, Foorman, Perfetti, Pesetsky & Seidenberg, 2001) and in skilled reading as a cue to early word recognition (Ferrand & Grainger, 1994; Perfetti & Bell, 1991; Pollatsek, Lesch, Morris, & Rayner, 1992; Rastle & Brysbaert, 2006; Rayner, Pollatsek, & Binder, 1998). The role that these codes play in determining advanced reading skill in deaf readers, however, is a matter of debate (Mayberry, Del Giudice, & Lieberman, 2010). Because deaf children and adults only have degraded (or absent) access to the sounds of spoken language, they may only develop partial or underspecified phonological representations (Kelly & Barac-Cikoja, 2007) that support reading acquisition of an alphabetical language in readers who can hear (Rayner et al., 2001). Deaf individuals do have access to some levels of phonological information developed via nonauditory channels (i.e., visual lip reading and articulatory speech production; Kelly & Barac-Cikoja, 2007 for review).

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Some studies have suggested that deaf readers do not use phonological codes during word processing (Burden & Campbell, 1994; Cripps, McBride, & Forster, 2005; Waters & Doehring, 1990), whereas other studies suggested that they do use such a code (Daigle & Armand, 2007; Kelly, 2003; Transler, Gombert, & Leybaert, 2001). Importantly, few studies on deaf readers have controlled for the reading level of their participants (Mayberry et al., 2010). Despite the lack of control of this variable, there is still the lingering notion that the use of phonological information in reading is found only in older and better deaf readers (Daigle & Armand, 2007; Hanson & Fowler, 1987; Perfetti & Sandak, 2000). As Goldin-Meadow and Mayberry (2001) have suggested, phonological codes may play a different role for deaf readers than for hearing readers.

Previous research with skilled hearing readers has shown that orthographic and phonological information is extracted prior to a word being fixated and both types of information are used to initiate the processing of the word before it is fixated (Ashby, Treiman, Kessler & Rayner, 2006; Chace, Rayner & Well, 2005; Miellet & Sparrow, 2004; Pollatsek et al., 1992). In other words, before a word is fixated, both orthographic and phonological information are activated while the word is still in parafoveal vision. This information speeds reading of the word when it is subsequently fixated (see Schotter, Angele, & Rayner, 2012 for review). This facilitatory effect has been coined the *parafoveal preview benefit* (Rayner & Pollatsek, 1987). To study preview benefits, an *invisible boundary paradigm* has been used (Rayner, 1975, see Figure 1). In this paradigm, the phonological and orthographic relationship between a preview item (a prime) and a target word is manipulated. The preview word is initially inserted in the sentence at the same position as the target. While the eyes fixate the words preceding the preview word, the preview word is in the parafoveal region. The target replaces the preview word while the eyes move from the word preceding the target to the target location (i.e. during the saccade). An invisible boundary is inserted before the target to trigger the preview-to-target change when the eyes cross it. Participants generally do not perceive the change as vision is suppressed during saccades (which typically last between 25–40 ms in reading; Rayner, 1998).

A recent study with severely to profoundly deaf readers of French (Bélanger, Baum & Mayberry, 2012a), compared the use of orthographic and phonological codes in groups of adult skilled hearing readers (SKH), skilled deaf readers (SKD), and less-skilled deaf readers (LSKD) in a masked priming lexical decision task and in a recall task. Consistent with prior literature, in the masked priming lexical decision task, SKH readers first activated orthographic codes and phonological codes were activated shortly after (Grainger & Holcomb, 2008, for a review). Unsurprisingly, SKD and LSKD readers also activated orthographic codes during early word recognition, but neither the SKD *nor* the LSKD readers activated phonological codes. However, this task leaves open the possibility that SKD and/or LSKD readers activated phonological codes at a later processing stage during word recognition. As for the recall task, SKH readers used both orthographic and phonological codes to maintain information in short-term memory; by contrast both SKD *and* LSKD reader groups used orthographic codes to maintain words in short-term memory and did not use phonological codes at all. Because the SKD and LSKD readers showed no phonological activation in either task, these results suggest that reading difficulties in deaf adults may not be linked to the activation of phonological codes during reading. They also suggest that skilled deaf readers qualitatively differ from skilled hearing readers as they do not seem to use phonological codes at all. Other recent research by Bélanger, Slattery, Mayberry and Rayner (2012b) showed that qualitative differences between hearing and deaf readers are a distinct possibility: they found that SKD readers have a larger perceptual span (or region of effective vision) than do hearing readers, suggesting that they can process more information during one fixation than can their hearing peers.

The goal of the present study was to extend Bélanger et al.'s (2012a) work to (1) explore the use of phonological and orthographic codes in a different language (English), (2) with a different population (severely and profoundly deaf readers who use American Sign Language), (3) in a different task (eye movements during reading), while also controlling for reading level. Two groups of severely to profoundly deaf adult readers who mainly use ASL as a communication mode were tested: a group of SKD readers and a group of LSKD readers. To determine whether there are qualitative differences between skilled hearing and deaf readers, a group of SKH readers was also included in the experiment.

Consistent with previous research, we hypothesized that SKH readers would benefit from both orthographic and phonological information available in the parafovea and that these effects would be present early during word processing (Miellet & Sparrow, 2004; Pollatsek et al., 1992). Furthermore, we expected to replicate previous results and find that skilled and less-skilled readers who are deaf use orthographic codes and do not differ in their use of phonological codes (Bélanger et al., 2012a). Previous research with skilled and less-skilled adult hearing readers showed that they differed in their use of phonological codes in the parafovea (Chace et al., 2005): skilled readers computed these codes in the parafovea while less-skilled readers did not. If such a pattern of results were found for LSKD readers relative to SKD readers, it would provide support for the notion that only SKD readers use phonological codes during reading.

Methods

Participants

Forty severely to profoundly deaf adults (hearing loss > 71dB in the better ear) were recruited. They mostly were born deaf or became deaf before the age of two (though 3/40 participants became deaf between ages 3 and 10), used American Sign Language (ASL) as their main language and communication mode for more than 10 years, and were aged 20 to 45 years (M = 30 years). Twenty SKH readers, native speakers of English aged 21 to 43 years (M = 29 years) served as controls. All participants had normal or corrected-to-normal vision and received financial compensation for their participation.

Background Measures

To assess reading level, participants completed the *Peabody Individual Achievement Test-Revised* (PIAT-R; Markwardt, 1989). Deaf readers were split into two groups based on their standard PIAT-R score so that SKD readers (n=18) were well matched on reading level to the SKH readers (n = 20). The remaining deaf readers (n =22) were placed in the LSKD readers group[1]. An ANOVA, comparing the reading level of SKH (M = 85; SD = 6.8; Grade level equivalent = 11th grade), SKD (M = 82; SD = 5.5; Grade level equivalent = 10th grade), and LSKD readers (M = 68; SD = 4.1; Grade level equivalent = 6th grade), yielded an effect of group ($F(2, 57) = 52.13$, $p < .0001$, $\eta_p^2 = .65$). As expected, LSKD readers differed significantly from both SKH readers ($p < .0001$) and SKD readers ($p < .0001$), but because they were matched based on this variable, SKH and SKD readers did not differ ($p = .21$). Three subtests from the *Wechsler Adult Intelligence Scale—Revised* (picture completion, picture arrangement, and block design; Wechsler, 1981) confirmed the groups did not differ on non-verbal IQ ($p > .10$): no difference was found between the SKH readers (M = 11.4; SD = 1.7), SKD readers (M = 11.3; SD = 1.4) and the LSKD readers (M = 10.5;

[1]The groups were not quite matched on the number of participants as the important factor was to closely match the skilled deaf readers to the skilled hearing readers on their reading skill. Additionally, note that there is no control group for the less-skilled deaf readers as it would be highly unlikely to find a group of non-dyslexic hearing readers matched on age, reading level and non-verbal IQ.

SD = 1.5). The SKD and LSKD readers did not differ on degree of deafness in their better ear ($p > .48$), on age of deafness onset ($p > .17$) and on number of years of ASL use ($M > 22$ years; p > .20). Interestingly, SKD and LSKD readers did not differ in age of English acquisition ($M = 1.3$ years and $M = 2.7$ years, respectively; $p > .11$), but the SKD readers acquired ASL at a significantly younger age than did the LSKD readers ($M = 4.5$ years and $M = 8.2$ years, respectively; $F(1, 38) = 5.9$, $p = .02$, $\eta_p^2 = .14$).

Stimuli

Thirty-six preview/target pairs of homophones (*bored-board)* were used in the present experiment. They were largely taken from the stimuli used in Pollatsek et al. (1992), but a few more pairs were also added. All target and preview pairs were matched on number of letters, phonemes, and syllables, and were matched as closely as possible for number of orthographic neighbors and phonological neighbors across conditions (because of the constraint for orthographic and phonological overlap between some conditions, it was not possible to match on these variables perfectly).

A relative frequency manipulation was included in the experiment where a lower frequency (LF) homophone preceded a higher frequency (HF) target (*bored-board*) on half the trials (36 preview-target pairs). This order was reversed (*board-bored*) for the other half (36 preview-target pairs), thus creating 72 different target words with their matched homophone previews. For each of the 72 target words, three additional preview conditions were added: (1) an identical preview condition (*board-board*), (2) an orthographically similar and phonologically dissimilar condition (*beard-board*), and (3) an unrelated condition (*tight-board*). Preview words in the orthographically similar and in the unrelated conditions (*beard*, *tight*) were matched across conditions on frequency as closely as possible with their respective homophone preview (*bored*). These four conditions, when compared with one another, allowed for the dissociation of orthographic and phonological information as the percentage of orthographic and phonological overlap between preview and target words was manipulated differently across conditions. For effects of orthographic preview benefits, the identical condition was compared to the homophone condition. The percentage of overlapping letters and overlapping phonemes is shown in Table 1. Obviously, in the identical condition there was 100% phoneme and 100% letter overlap. In the homophone condition, there was 100% phoneme, but only 75% letter overlap. Thus, between the two conditions, phoneme overlap was held constant (100%) and orthographic overlap was manipulated. A difference in fixation times between these two conditions would be attributable to the unique effect of orthography. By the same logic, between the homophone and the orthographically similar conditions, the percentage of overlapping letters was held constant and the percentage of phoneme overlap was manipulated (see Table 1), determining the unique contribution of phonology in parafoveal vision. Finally, the 36 lower frequency targets (*weak*) were inserted in a neutral sentence context (e.g.: *Bobby was feeling weak after he ate a big lunch*.) and the 36 higher frequency targets (*week*) were inserted in a different, but still neutral context (e.g.: *Jason had an amazing week because he bought his first dog*.) The predictability of the targets was low and did not differ across the relative frequency conditions. To ensure that the contexts were neutral, sentences were normed in a cloze task by 20 undergraduates who did not take part in the experiment. Participants were provided with the first part of the sentence up to, but not including, the target. They were asked to provide the first word that came to mind to best continue the sentence. The mean probability of continuing the sentence with the low-frequency target words was 0.02 and was 0.01 for the high-frequency targets ($t < 1$) All sentences had a simple syntactic structure and were composed of frequent words to ensure that all participants would comprehend the sentences.

Apparatus

An EyeLink 1000 eyetracker (SR Research, Kanata, Ontario, Canada) was used to record eye movements during reading. The position of the eyes was sampled every millisecond. Participants sat 60 cm from a 22 inch NEC MultiSync FP1370 monitor (refresh rate of 150Hz) on which they read single-line sentences. Head movements were minimized with a chinrest and headrest.

Procedure

The UMass *Eye Track 0.7.10h* software (Stracuzzi & Kinsey, 2006) was used to present the sentences, which were presented in black 14pt *Courier New* font on a light grey background; 3.4 letters equaled 1° of visual angle. An invisible boundary was inserted before the target to initiate the preview-to-target change when the eyes crossed it (see Figure 1). The boundary was placed after the last letter of the word preceding the target. There was 1.8 ms delay (plus up to 6.7 ms to refresh the display monitor) for a display change to occur after the eye crossed the invisible boundary; thus the display change generally occurred during the saccade. Viewing was binocular, but eye movements were recorded from the right eye only. All sentences were displayed on a single line.

Upon arrival, participants completed the reading background tests. For the experimental task, participants were instructed to read silently for comprehension. Following a 3-point calibration procedure, the participants read the 72 experimental sentences, which were counterbalanced across the four preview conditions, so that each sentence was only seen once in one of the four conditions. The eyetracker was recalibrated when the experimenter deemed it necessary. There were also 128 filler sentences in which no display changes occurred. After 28% of the trials, yes/no comprehension questions were asked and participants responded by pressing buttons on a keypad. The comprehension questions were answered correctly 91%, 90% and 86% of the time by the SKH, SKD, and LSKD readers.

Analysis

We will present analyses for a number of standard eye movement measures (Rayner, 1998, 2009) including *first fixation duration* (the first fixation to land on a target word), *gaze duration* (the sum of fixations on the target word before the eyes move away from the target), and *refixations* on target words. These measures reflect early, first-pass processes. *Single fixation* data were also analyzed, but the pattern of results mirrored what was found for gaze duration, thus only the means are presented in Table 2.

Trials were excluded if (1) the display change occurred during a fixation (5.8%, 7%, and 6.7% for the SKH, SKD, and LSKD), (2) the boundary change was triggered by a saccade that landed to the left of the boundary (2.4%, 0.9%, and 2% for the SKH, SKD and LSKD), (3) a blink occurred just before, on, or just after the target word (2% of total data), or (4) fixation time was more than 2.5 standard deviations above the mean for each participant (Fist Fixations: 1.6%, 1.5% and 1.5% for SKH, SKD and LSKD; Gaze durations: 1.5%, 1.4% and 1.3% for SKH, SKD and LSKD). Finally, fixations shorter than 80 ms and within one letter of another fixation were combined with that fixation (3.4% of the total data).

Linear-mixed effects models (LMMs) were used to analyze the eye movement duration data and generalized linear mixed models (GLMM) were used to analyze refixations data (a binary variable). We used the lme4 package (Bates, Maechler & Dai, 2009), which is available in the R environment (R Development Core Team, 2008).

A model was specified for each of the dependent variables where participants and items were specified as crossed random effects (Baayen, 2008). Group, relative frequency, and preview were specified as fixed factors. Frequency and preview were within-subject variables. For each model, three successive difference contrasts (Venables & Ripley, 2002) were set up to analyze the independent preview effects of orthography (identical vs. homophone conditions), phonology (homophone vs. orthographically similar), and overall preview (identical vs. unrelated)[2]. To determine the similarities and differences between the SKH and SKD readers and between the SKD and LSKD readers, two successive difference contrasts were set up within the group factor (SKH vs. SKD and SKD vs. LSKD). Group, preview, and frequency, and their interactions were included in each model as random slopes, but these factors did not add significantly to any of the models. This was verified with gradual model reductions followed by a likelihood ratio test comparing the more complex model with the reduced model to verify the fit of each model. The models presented below were all reduced to random intercepts. Non-significant interactions were also dropped from complex models if they did not significantly increase the model's log-likelihood. Separate analyses were also performed for each group separately when interactions with group occurred in the full models. Regression coefficient estimates (b), standard errors (SE), and *t*-values (or *z*-values for binary data) are reported. A two-tailed criterion ($|t| \geq 1.96$; $|z| \geq 1.96$) was used to determine significance.

Finally, because the models were set up with successive difference contrasts for the group and for the preview conditions, two estimates were generated for group contrasts (SKH vs. SKD and SKD vs. LSKD), three estimates were generated for the preview condition contrast (Identical vs. Homophone, Homophone vs. Orthographically Similar, and Identical vs. Unrelated) and one for the frequency condition. The resulting models yielded six separate estimates for the three-way interaction, two estimates for the group x frequency interaction, six estimates for the group x preview interaction and three estimates for the frequency x preview interaction, along with separate estimates for each contrast for the factors alone. Recall that the frequency manipulation in the present experiment was based on the frequency of the prime relative to that of the target and that the main interest in including this factor was whether it would interact with preview benefit. For the sake of conciseness, we will not report a main effect of frequency or an interaction with this factor, unless it interacts with the preview factor (see Appendix for a table with the full LMM results for all variables).

Results

First Fixation Duration

The analyses for first fixations revealed that reading times were longer in the unrelated condition than in the identical condition ($b = -13.56$, SE = 4.09, $t = -3.31$), indicating an effect of overall preview benefit. The targets in the homophone condition were also fixated for a significantly longer time than in the identical condition (orthographic preview; $b = 9.08$, SE = 4.06, $t = 2.23$). The difference between reading times in the homophone and orthographically similar conditions (phonological preview) were not significant however ($b = 6.19$, SE = 4.03, $t = 1.54$). As may be expected, based on reading level, LSKD readers' first fixations ($M = 270$ ms) were longer overall than that of SKD readers ($M = 230$ ms; $b = 36.89$, SE = 14.46, $t = 2.55$), but SKD readers did not differ on this measure from SKH readers ($M = 238$ ms; $b = -8.82$, SE = 14.79, $t = -0.60$).

[2]The successive difference contrasts for type of preview were set up in the LME model, such that the measures for the identity condition were subtracted from the unrelated condition (to provide a measure of overall preview benefit effects), the measures from the homophone condition were subtracted from the identity condition (for the orthographic preview) and the measures from the orthographically similar condition were subtracted from the homophone condition (for the phonological preview effects).

Interestingly, there was a significant three-way interaction between the SKH and SKD readers and frequency for the contrast between the homophone and orthographically similar conditions (phonological preview benefit; b = 41.53, SE = 20.46, t = 2.03). All other three-way interactions were not significant (ts < 1.44), and neither were the frequency x preview interactions (ts < 1.07). The three-way interaction was unpacked with follow-up LMMs. Two separate analyses were conducted, one for each of the two groups, in order to assess the effects of phonological preview benefit at each frequency level. For the SKH readers, a significant interaction was found with frequency for the phonological preview contrast (homophone vs. orthographically similar conditions; b = −28.49, SE = 13.88, t = −2.05), revealing a phonological preview benefit effect (see Table 2 for means) only when the preview was of higher frequency than the target (24 ms; HFLF), and not when the preview word was of lower frequency than the target (−3ms; LFHF). The equivalent interaction was not significant for the SKD readers (b = 11.90, SE = 11.92, t = 0.99), despite the means suggesting a phonological preview benefit of - 1ms in the HFLF condition and of 17ms in the LFHF condition. These analyses suggest that SKH readers did benefit from phonological information in the parafovea, but this effect was modulated by the relative frequency between the preview and target words. Additionally, there was an indication that skilled deaf readers activated phonological codes when the preview was of lower frequency than the targets (but not in the reverse situation), but this interaction did not even approach significance[3].

Gaze Duration

Analyses for gaze durations mostly replicated the patterns found for first fixation durations. There was a significant difference between the unrelated and identical conditions (b = −23.42, SE = 5.08, t = −4.61), indicating an effect of overall preview benefit.[4] The difference between the identical and homophone conditions (orthographic preview) was also significant (b = 22,61, SE = 5.05, t = 4.48), but the difference between the homophone and orthographically similar conditions (phonological preview) was not significant (b = −0.61, SE = 4.99 , t = −0.12). Again, LSKD readers spent more time overall fixating targets (M = 306 ms) than SKD readers did (M = 245 ms; b = 57.45, SE = 18.04, t = 3.18). SKD readers, though they were 20 ms faster, did not significantly differ on this measure from SKH readers (M = 265 ms; b = −20.89, SE = 18.46, t = −1.13).

For gaze duration, none of the three-way interactions were significant (t < 1.13), though the means for the 3-way interaction for the SKH and SKD readers by frequency for the phonological preview contrast (t = 1.13) showed a similar pattern as what was found in the

[3]The SKD readers appear to show an effect of phonological preview benefit for the HFLF preview target pairs, but not for the LFHF preview-target pairs, whereas the SKH readers show the opposite pattern. However, this is true for first fixations only (not for gaze durations). In the separate analyses performed for each group, the interaction Frequency X Homophone-Ortho. Similar contrast (phonological preview) is significant for the SKH readers (t = −2.05) but does not even come close to significant for the SKD readers (t = 0.99). Interestingly, the pattern of means for the four conditions for the SKH readers is pretty stable across first fixations and gaze durations, but the interaction between interaction Frequency X Homophone-Ortho. Similar contrast only reached significance in the first fixation measures. For the SKD readers, however, the "reverse" pattern of phonological preview in first fixations is not present anymore in gaze durations. Examination of the pattern of refixations across frequency and preview conditions, which may explain the difference in effects of phonological preview across first fixations and gaze durations for the SKD readers, we find that between the homophone and orthographically similar conditions, refixations patterns are similar across both frequency conditions with 3% more refixations in the homophone condition than in the orthographically similar condition for the HFLF condition and also a 3% difference between those two preview conditions in the LFHF condition (see Table 2). Thus the different pattern in gaze durations for the SKD readers, relative to the pattern of result in first fixations, cannot be explained by different refixations rates across the different frequency conditions. It is hard to justify the presence of a phonological preview benefit in the LFHF condition for the skilled deaf readers in first fixations based on the present data.

[4]The overall preview benefit found in the present experiment is of smaller magnitude than what has been found in prior experiments (for example Pollatsek et al., 1992). We explain this difference by the fact that our hearing participants were drawn from the general population to be matched on age to our deaf participants, thus they may read at a slightly lower level than the undergraduates generally tested in reading experiments investigating skilled readers.

first fixation data, but only for the SKH readers. Indeed, for the SKH readers, there was a 16 ms difference between the homophone and orthographically similar conditions in the HFLF frequency condition, but this difference was -4 ms in the LFHF frequency condition. For the SKD readers, however, the difference between these two preview conditions was -4 ms and 4 ms for the HFLF and LFHF frequency conditions, respectively. None of the group x preview interactions were significant ($t < 0.92$), nor were any of the frequency x preview interactions ($t < 1.27$).

Refixations

There were more refixations in the unrelated condition than in the identical condition ($b = -0.52$, SE = 0.18, $z = -2.83$). Targets in the homophone condition were also refixated more often than targets in the identical condition (orthographic preview; $b = 0.66$, SE = 0.18, $z = 3.63$), but the difference in the proportion of refixations between the homophone and orthographically similar conditions just missed significance (phonological preview; $b = -0.31$, SE = 0.16, $z = -1.92$). LSKD readers ($M = 0.13$) refixated targets more often than SKD readers did ($M = 0.10$; $b = 1.12$, SE = 0.32, $t = 3.46$), and interestingly, SKD readers refixated targets significantly less often than SKH readers did ($M = 0.05$; $b = -0.74$ SE = 0.33, $t = -2.21$).

In the analyses for refixations, none of the three-way interactions were significant ($p > 0.42$), nor were any of the two-way interactions between frequency x preview ($p > 0.37$) and group x frequency ($p > 0.36$). There were significant interactions however between the SKH and SKD readers for the unrelated vs. identical condition ($b = -0.98$, SE = 0.49, $z = -1.99$), and for the identical vs. homophone conditions ($b = 1.01$, SE = 0.49, $z = 2.07$). The interactions between SKD and LSKD readers were not significant for any of the preview contrasts, indicating that the LSKD readers presented the same pattern of results as the SKD readers did ($p > 0.24$).

In order to break down the group x preview interactions, separate models were constructed for the SKH and SKD groups with the frequency and preview contrasts. There were no effects of preview on the refixation proportions for the SKH readers for any of the preview types: overall, orthographic, or phonological preview ($p > 0.44$). In contrast, SKD readers refixated target words more in the unrelated condition than in the identical condition ($b = -0.99$, SE = 0.42, $z = -2.40$). SKD readers also refixated targets more in the homophone condition than in the identical condition ($b = 1.09$, SE = 0.41, $z = 2.65$), indicating that when there was more orthographic overlap between preview and target words (identical condition), they found it less necessary to refixate the targets. This suggests that SKD readers are quite sensitive to orthographic information and can gather enough orthographic information in the parafovea so that they do not need to refixate a target word as frequently as hearing readers do. Again, no effect of phonological preview was found for the SKD readers ($b = -0.60$, SE = 0.36, $z = -1.70$). Thus, in contrast with the orthographic preview effect, SKD readers did not benefit from the phonological overlap between the homophone and orthographic conditions and refixated target words equally often in both conditions. This is also true for the LSKD. Recall that the group X preview interactions between the SKD and LSKD readers were not significant.

Discussion

The present experiment investigated the use of phonological and orthographic codes in parafoveal vision during normal reading in severely to profoundly deaf signers of ASL who were skilled or less-skilled readers. Previous research has put much emphasis on the unique role of phonological codes as a determinant of reading skills in deaf children and adults (Kelly & Barac-Cikoja, 2007), though recent work (Bélanger et al., 2012a) suggests that

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they may not play such a crucial role with respect to the reading difficulties many deaf people experience. The present results support this latter interpretation.

Several results are of note in the present experiment. First, the SKH readers replicated patterns found in previous research and used phonological codes from parafoveal vision during reading (Chace et al., 2005; Miellet & Sparrow, 2004; Pollatsek et al, 1992). An interaction was found in the first fixation measure, and phonological preview was only found in the HFLF preview/target condition (with the same pattern in gaze duration). Williams, Perea, Pollatsek, and Rayner (2006) found similar results and showed that when processing word neighbors, a higher frequency preview neighbor word presented in parafoveal vision before a lower frequency target (HFLF) has a different effect on target processing than the reverse situation (LFHF). In the first case, HF parafoveal neighbor words generated as much of a preview benefit as identical preview-target pairs, whereas in the latter case a LF parafoveal neighbor word did not. This finding suggests that the frequency of parafoveal words influences the activation of the letter identities (by providing more or less letter-level activation depending on the frequency of the preview). These processes are early enough (because they occur in the parafovea) that recognition of the target itself is not inhibited by lexical information (such as frequency), as might be predicted by the finding that higher frequency neighbors inhibit target processing (see Perea & Pollatsek, 1998). Our results extend Williams et al.’s results in that the frequency manipulation might specifically affect processing of phonological information in parafoveal vision.

More directly in line with our goals, SKD and LSKD readers showed consistent orthographic and overall preview benefits across early word processing measures (first fixations and gaze durations), suggesting that both groups were able to quickly generate orthographic codes from a preview word in parafoveal vision. This pattern of result is comparable to what was found for the SKH readers, although SKH readers also showed effects of phonological preview in first fixation durations. For both groups of deaf participants, however, there were no significant phonological preview benefits in the early processing measures. Strikingly, the present results replicated and extended those of Bélanger et al. (2012a) where skilled *and* less-skilled adult deaf readers showed the same pattern of phonological activation (none) in a primed masked lexical decision task as well as in a recall task. In the present experiment, using a different population (deaf adults who sign ASL rather than Quebec Sign Language), reading in a different language (English rather than French), measured with a different and more sensitive technique (eye movement measures during normal reading), SKD and LSKD readers showed no significant phonological activation across different measures of early word processing. This provides added support for the notion that the difference in reading skill between the groups of deaf readers is not related to their use (or not) of phonological codes.

Refixation probability data also revealed important patterns of results. Both groups of deaf readers’ probability of refixating a target word was influenced by the orthographic overlap between preview and targets. Indeed, when there was more orthographic overlap between preview and target words (identical condition relative to the homophone condition), both groups of deaf readers refixated the target less often. Interestingly, this was not the case for the SKH readers, whose probability of refixating a target word did not differ at all across the four preview conditions (see Table 2). This result suggests that deaf readers are quite sensitive to letter-based information, even if it is in parafoveal vision, and can gather enough orthographic information in the parafovea so that they do not need to refixate a target word as often before moving on to another word.

Finally, another important result was that SKD readers refixated the targets significantly less frequently than did SKH readers. This difference in proportion of refixations explains the shorter gaze durations for SKD relative to SKH readers (as refixations times are computed in gaze duration)[5], but also suggests that overall, SKD readers were very efficient[6] in reading target words in one fixation only before moving on to the next word. This result is in line with previous work showing that SKD readers have a slightly wider perceptual span than SKH readers (Bélanger et al., 2012b) and can process more information during a single fixation. SKD readers did not need to refixate words as often as SKH readers did before their eyes moved on to the next word because they were able to gather more information within only one fixation most of the time. This suggests that SKD readers are very efficient at processing words while they are foveated. However, the significantly higher skipping rate and low probability of regressing back to the targets for the SKD readers (relative to the SKH readers; see note 6) also supports this notion of "efficiency", which is apparent extremely early, as it begins when words are in the parafovea. It is interesting to note also that LSKD readers' percentage of word refixations and skipping is higher than might be expected relative to their reading level. Indeed, the LSKD readers' percentage of overall refixations and word skipping (13% and 20% respectively) was somewhat closer to the SKH readers' eye movement behavior (10% and 24%, respectively) than to SKD readers' eye movement behavior (5% and 29% respectively). This pattern of results suggests that although LSKD's reading level is much lower than that of SKH readers and their word reading is much slower, they are also, as observed for the SKD readers, very efficient at extracting orthographic information in the parafovea.

To conclude, the present research reveals several important similarities in eye movement characteristics and information processing between hearing and deaf readers, but also fascinating differences, such as the lack of (or weak) activation of phonological codes, the efficiency in gathering orthographic information in the parafovea and, for the skilled deaf readers, the increased amount of information processed within a single fixation relative to skilled hearing readers. The important point to be made here, however, is not whether deaf readers use phonological codes or not. The focus should rather be placed on proper assessment of reading level and on the similarities and differences between skilled and less-skilled deaf readers. Crucially, using a very sensitive measure of information processing, both SKD *and* LSKD readers showed no clear evidence of phonological code activation, replicating previous research (Bélanger et al., 2012a) conducted in a different language and in a different population. These results support the growing evidence that the use of phonological codes in reading is not a determinant of reading skills in the deaf population and that another, more lingering factor, might be at play in determining reading skill in deaf

[5]The probability of refixating a word is a function of the landing position of a saccade within a word, but also of the launch site of the saccade from the previous word (see Rayner, 2009). Rayner (1979) found that readers' eyes generally land in the middle of the first half of a word (*Preferred Viewing Location* - PVL). It has been shown that the proportion of refixations increases when the eyes do not land in an optimal position in a word (O'Regan, 1990; Rayner et al., 1996). To that effect, we conducted an analysis to investigate the launch sites and landing positions for the three groups of readers. SKD readers launched their saccade prior to the target word farther away (M = 5.8 characters away from the landing position in the target word) than SKH (M = 5.1) or LSKD readers (M = 4.9; $p < .03$). A farther launch site for the SKD readers, relative to the SKH readers, is consistent with a landing site closer to the beginning of the target word and farther away from the PVL, thus increasing the probability of refixations. However, surprisingly, the SKH and SKD readers did not differ in the landing position within targets (M = 2.3 vs. 2.2 characters into the word: $p = .16$). That the SKH and SKD readers did not differ in landing positions cannot explain the lower probability of refixations found for the SKD readers. Rather we suggest (see also Bélanger et al., 2012b) that SKD readers are extremely efficient when reading and processing words/text. This is also consistent with the higher skipping rate (see Note #6) and lower refixations rate found for the SKD readers.

[6]Across conditions, the target word was skipped 24% of the time, with the identical condition skipped 27% of the time, and the other three conditions skipped roughly 23% of the time (with no significant differences). Interestingly, the SKD skipped the target words significantly more often (29% of the time) than did the SKH (24%: $p = .001$) and the LSKD readers (20%: $p < .0001$). Similarly, the probability of regressing back to the target in the identical condition was 14%, whereas the other conditions were regressed to about 17% of the time (no significant differences were found between conditions). The SKD readers regressed back to the targets significantly less often (14%) than did the SKH readers (17%: $p = .05$) and the LSKD readers (19%: $p = .03$).

readers. In light of the pervasiveness of reading difficulties in the deaf population, the present results shed an important light on issues that would need to be addressed in educational settings for reading acquisition by deaf children.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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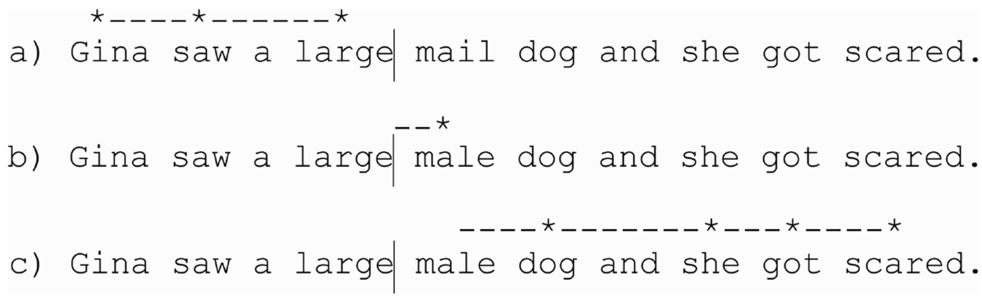

Figure 1.

An example of the trajectory of the eyes and the related events in the invisible boundary paradigm[a].

[a]The stars represent the location of the eye fixations and the dashed lines represent the saccades. The vertical lines indicate the location of the invisible boundary and are not seen by the participants. In line *a*, the word *large* ($word_4$) is fixated and the word *mail* ($word_5$) begins to be processed in parafoveal vision. During the saccade from $word_4$ (*large*) to $word_5$ (*mail*), the eyes cross the boundary and trigger the display change so that the preview word *mail* (line *a*) is replaced by the target word *male* (line *b*). When the eyes land on $word_5$ (*male*), the preview word (*mail*) is already changed for the target word (*male*). After the target word has been fixated, reading continues normally (line *c*).

Table 1

Percentage of orthographic and phonological overlap between primes and targets in each experimental condition (these overlap percentages were the same for both frequency conditions).

	Shared letters (%)	Shared phonemes (%)
Identical	100%	100%
Homophone	75%	100%
Orthographically Similar	75%	57%
Unrelated	0%	0%

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Table 2

Means (and standard deviations) for single fixations, first fixations, gaze durations and probability of refixations per condition and per group.

	Higher Frequency Preview/Lower Frequency Target				Lower Frequency Preview/Higher Frequency Target			
	Identical	**Homophone**	**Ortho. Similar**	**Unrelated**	**Identical**	**Homophone**	**Ortho. Similar**	**Unrelated**
Single Fixation								
SKH	237 (77)	238 (69)	257 (94)	248 (103)	225 (71)	250 (86)	246 (87)	240 (99)
SKD	236 (66)	251 (96)	246 (78)	233 (88)	208 (58)	212 (60)	229 (72)	234 (74)
LSKD	273 (100)	280 (126)	283 (108)	279 (113)	263 (90)	291 (113)	293 (105)	282 (115)
First Fixation								
SKH	232 (76)	231 (69)	255 (94)	243 (99)	219 (72)	241 (84)	238 (88)	241 (101)
SKD	233 (66)	247 (93)	245 (77)	233 (84)	208 (57)	210 (60)	227 (73)	231 (74)
LSKD	263 (100)	264 (115)	270 (105)	274 (109)	262 (89)	280 (112)	277 (105)	269 (111)
Gaze								
SKH	263 (114)	266 (101)	282 (118)	274 (125)	246 (92)	266 (101)	262 (107)	267 (128)
SKD	244 (76)	269 (108)	265 (123)	253 (102)	214 (64)	231 (88)	235 (81)	248 (87)
LSKD	291 (108)	323 (148)	314 (131)	314 (149)	276 (106)	313 (132)	311 (119)	303 (131)
Refixation								
SKH	0.11	0.12	0.10	0.11	0.10	0.09	0.09	0.09
SKD	0.04	0.09	0.06	0.08	0.02	0.06	0.03	0.06
LSKD	0.12	0.20	0.16	0.15	0.05	0.11	0.13	0.12