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What Eye Movements Reveal About Deaf Readers

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Abstract

Levels of illiteracy in deaf populations around the world have been extremely high for decades and much higher than the illiteracy levels found in the general population. Research has mostly focused on deaf readers' difficulties rather than on their strengths, but having a better grasp of deaf readers' strengths could inform reading education. Deaf readers are a unique population. They process language and the world surrounding them mostly via the visual channel, and this greatly affects how they read or might learn to read. The study of eye movements in reading provides highly sophisticated information about how words and sentences are processed, and our research with deaf readers reveals the importance of their uniqueness.

Keywords
deaf readers, eye movements, reading skill, perceptual span, word processing

Illiteracy levels in the deaf population have been consistently higher than in the general population. The mean reading level of young deaf adults graduating from high school in the United States has been well below that of their hearing peers for decades (Kelly & Barac-Cikoja, 2007). However, 5% of deaf individuals become excellent readers and read at or above a 12th-grade level. While deaf individuals' generally poor reading performance has generated much research, there is no general agreement concerning the factors underlying skilled reading in the deaf population (but see Mayberry, del Giudice, & Lieberman, 2011). Recent research in our lab suggests that skilled deaf readers have unique eye movement patterns and process words in foveal and parafoveal vision quite effectively. We review this evidence, but first provide background information on eye movements in reading.

Eye Movements in Reading

The study of eye movements has provided crucial information about visual, attentional, word-level, and sentence-level processing during reading and, importantly, has documented the interplay between cognitive and oculomotor control during written-language processing (Rayner, 1998, 2009). Readers move their eyes with a series of alternating *fixations* (through which the visual information from the text is obtained) and *saccades* (rapid movements in which visual-information uptake is suppressed because of the extreme speed at which the eyes move; Matin, 1974). Fixations last on average 200 to 250 milliseconds, and saccades are brief (20–40 ms) and generally span 7 to 9 letter spaces. Readers do not fixate all words and skip about 30% of the words in a text (mainly short and frequent words), and though most saccades travel in the direction of reading (left to right for English), 10% to 15% of saccades are *regressions* back to revisit text that was previously read. The time spent fixating a word is highly variable among readers but is largely determined by lexical factors (Rayner, 1998, 2009), such as a word's frequency (*year* is read faster than *cyst*), length (*year* is read faster than *university*, and *university* might require a second fixation—i.e., a *refixation*), and predictability (*horse* would be read faster in the sentence "The cowboy rode his horse" than in the sentence "The child found his horse").

Text difficulty and reading skill also influence fixation durations. Skilled readers have shorter fixations overall than less-skilled readers (Bélanger, Slattery, Mayberry, &

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Rayner, 2012; Rayner, 1986), and because eye movement measures are very sensitive to reading level, fixation durations can also distinguish between average college-level readers and skilled college-level readers (Ashby, Rayner, & Clifton, 2005). Finally, reading skill also affects other eye movement measures, such that beginning readers and less-skilled readers (even college-level readers) make fewer skips, shorter saccades, more fixations within a sentence, more regressions back in the text, and more within-word refixations (Blythe, 2014).

Notably, the study of eye movements during reading (as opposed to the study of single-word processing) takes into account a very important property of the visual system. The visual field is divided into three regions around the center of fixation determined by the anatomy of the retina: The foveal region corresponds to the central 2° around the center of fixation, the parafovea corresponds to the next 5°, and beyond that is the periphery. Visual acuity decreases dramatically and gradually from the fixation point as a function of retinal eccentricity, and the eyes move so that words are centered on the fovea, where acuity is the sharpest. Interestingly, research has shown that during reading, readers not only process words that are in the fovea but also begin to process words before they are fixated, while they are in the parafovea (see below).

Specificity of the Deaf Population

Deaf readers are an interesting population to examine for many reasons. They differ from hearing readers in that they do not have auditory access to any of the languages they know and process language via different sensory channels. Indeed, deaf individuals perceive languages visually. The most easily and naturally accessible languages for deaf individuals are signed languages, which are perceived visually, but deaf individuals also perceive the languages of surrounding hearing individuals (spoken languages) visually, by reading their lips (depending on their degree of hearing loss, deaf individuals may also perceive some language-based sounds). Crucially, for written-language processing, hearing readers of alphabetical languages rely heavily on the association of sounds (phonemes) with letters (graphemes) when learning to read (Ehri, 1991; Frith, 1985; Gough & Hillinger, 1980), and skilled written-language comprehension is achieved via understanding the underlying principle that words are connections among graphemes, phonemes, and meaning (Rayner, Foorman, Perfetti, Pesetsky, & Seidenberg, 2001). Deaf readers generally have little or no access to the sounds of the language they read and, at a young age, they also often have less than optimal knowledge of the actual language (vocabulary, syntax) they are learning to read (Goldin-Meadow & Mayberry, 2001).

In searching for solutions to the rampant illiteracy levels in the deaf population, much focus has been placed on the first of these two facts (little or no access to sounds) as the source of deaf readers' difficulties in becoming skilled readers because of (a) the great importance phonological codes have in the learning process for hearing children and (b) the notion that skilled reading is highly dependent on the capacity to grasp the sound structures of a language and their relationship to orthography and meaning. Yet a recent meta-analysis found that in the deaf population, phonological decoding/awareness accounts for less variance in reading proficiency (11%) than does general language ability in spoken or signed languages (35%; Mayberry et al., 2011), and evidence is accumulating for a high correlation between sign-language skills and reading skills (operationalized as overall reading comprehension in Chamberlain & Mayberry, 2008).

Finally, there is evidence that as a consequence of using vision to monitor the environment, deaf individuals experience changes in the distribution of visual attention and have enhanced attention allocation to the periphery, relative to hearing individuals, in low-level visual perception tasks (Bavelier, Dye, & Hauser, 2006; Proksch & Bavelier, 2002).

Because of these fundamental differences in language and the allocation of attention, deaf readers may face the tasks of reading and learning to read from different grounds than hearing readers do. Discovering these differences can provide insight not only on reading and reading education in the deaf population (where new solutions are needed), but also on the universal architecture of reading. Indeed, it seems that written-language processing is modulated not only by the orthographic nature of a language (e.g., alphabetic vs. logographic) but also by the "unavailability" of certain perceptual channels (e.g., for deaf or blind readers). Furthermore, as argued by Blythe (2014), "to fully understand how children progress to skilled adult reading, it is necessary to consider changes in both cognitive processing and eye movement behavior" (p. 201). Thus, eye movement research is crucial for developing our understanding of skilled reading in the deaf population to gain a better grasp of how young deaf children learn to read.

Eye Movements of Deaf Readers

Historically, research on the reading processes of deaf children and adults has focused on their difficulties rather than on their strengths. Few studies have specifically targeted skilled deaf readers and provided standardized measures of their reading levels (though see Bélanger, Baum, & Mayberry, 2012; Bélanger, Mayberry, & Rayner, 2013; Bélanger & Rayner, 2013; Chamberlain & Mayberry, 2008; Emmorey, Weisberg, McCullough, & Petrich, 2013;

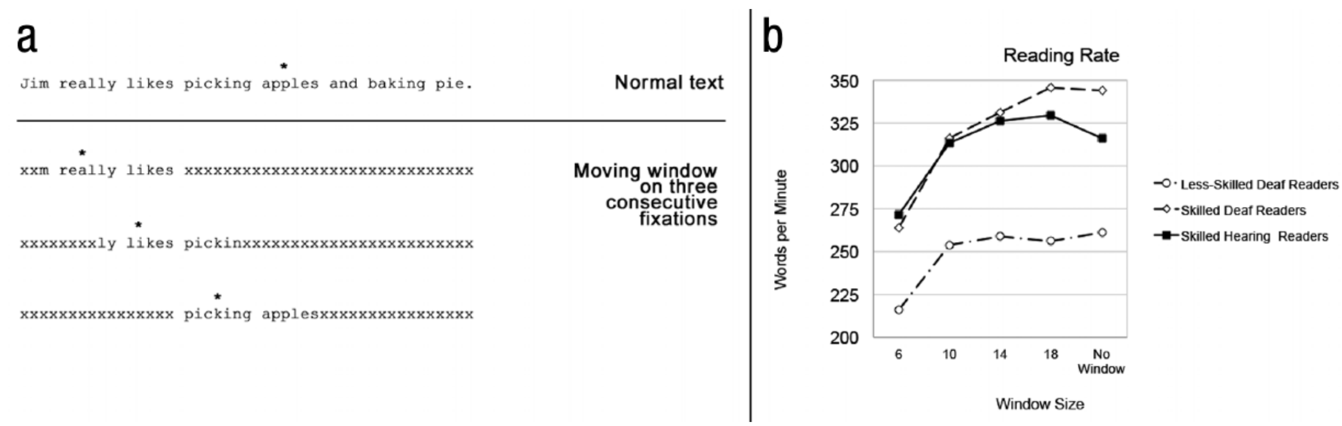

Fig. 1. Illustration of a moving window on three consecutive fixations (a) and results from Bélanger, Slattery, Mayberry, and Rayner (2012; b) showing reading rate as a function of window size (measured in number of letter spaces, including the spaces between words) among skilled hearing readers, skilled deaf readers, and less-skilled deaf readers. In the moving-window illustration, the asterisks represent the position of the eye. In this example, the window is asymmetrical and extends 4 letter spaces to the left and 10 letter spaces to the right of fixation. Adapted from "Skilled Deaf Readers Have an Enhanced Perceptual Span in Reading," by N. N. Bélanger, T. J. Slattery, R. I. Mayberry, and K. Rayner, *Psychological Science, 23*, p. 819.

Hirshorn, Dye, Hauser, Supalla, & Bavelier, 2014); rather, deaf readers of all reading levels have often been presented as a single group.

We used eye movements during reading to gain more insight into the attentional, visual, word-level, and sentence-level processes of skilled deaf readers. As mentioned earlier, eye movements in reading are mostly modulated by the properties of the text, and deaf readers do not differ from hearing readers on all aspects of the reading process or eye movement characteristics. Indeed, just like those of hearing readers, deaf readers' fixation durations are modulated by reading level, word frequency, and word predictability. Additionally, less-skilled deaf readers, like less-skilled hearing readers, rely more on context to aid word processing (Bélanger & Rayner, 2013). Crucially, however, we find that deafness itself influences certain eye movement patterns.

Visual attention and the perceptual span

The *perceptual span* is the region of effective vision around the fixation point where visual information is used to guide the eyes through the text. For readers of alphabetic left-to-right writing systems, this region extends 3 to 4 letter spaces to the left of fixation and 14 to 15 letter spaces to the right of fixation (McConkie & Rayner, 1975; Rayner & Bertera, 1979). The size of the span varies as a function of reading level (they are positively correlated; Rayner, 1986) and of the degree of processing difficulty of the currently fixated word (Henderson & Ferreira, 1990). Importantly, the size of the span is not simply a function of decreased visual acuity in the parafovea but is also under cognitive and attentional control (Miellet, O'Donnell, & Sereno, 2009).

Research using tasks tapping low-level visual attentional processing suggests, as mentioned earlier, that deaf individuals have enhanced allocation of attention to the periphery relative to hearing individuals. We examined whether this processing enhancement in the visual periphery in severely to profoundly deaf individuals would also be present during reading, a cognitively complex task, by using the moving-window paradigm (Bélanger, Slattery, et al., 2012; see Fig. 1a). Participants' reading speed was measured (in words per minute) at different window sizes extending 6, 10, 14, and 18 letter spaces to the right of fixation, respectively, and was compared to reading speed in a no-window control condition.

We found that severely to profoundly deaf adult readers have a wider perceptual span than hearing adult readers matched on reading level. Two groups of deaf readers were tested: skilled and less-skilled readers. The skilled deaf readers had a wider perceptual span (up to 18 letter spaces to the right of fixation; Fig. 1b) than did the skilled hearing readers matched on reading level (14 letter spaces to the right of fixation). The span of less-skilled deaf readers was as wide as that of hearing readers. This suggests that the size of the perceptual span in deaf readers is not determined solely by reading skill, but that it may be wider than expected because of the added influence of a differential spread of attention across the visual field that is specific to deafness. Indeed, because the less-skilled deaf readers read five grade levels below the skilled hearing readers, one would have expected their perceptual span to be smaller than that of the skilled hearing readers if its size were only a function of reading level.

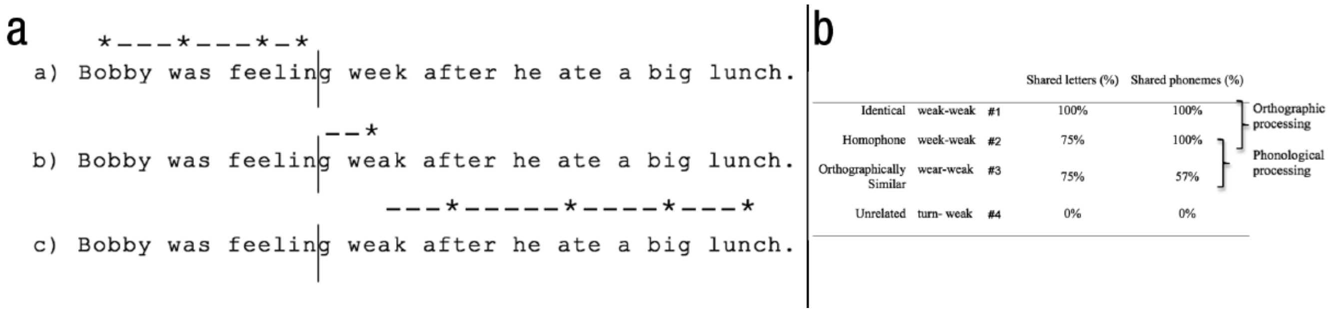

Fig. 2. An example of the trajectory of the eyes and related events in the gaze-contingent boundary paradigm (Rayner, 1975; a) and percentage of orthographic (letters) and phonological (phonemes) overlap between primes and targets across conditions in Bélanger, Mayberry, and Rayner (2013; b). The asterisks in panel (a) represent the locations of the eye fixations, and the dashed lines represent the saccades. The vertical lines indicate the location of an invisible boundary that is not seen by the participants but serves as the trigger for the display change. In line *a*, the word *feeling* (Word 3) is fixated and the word *week* (Word 4) begins to be processed in parafoveal vision. During the saccade from Word 3 to Word 4, the eyes cross the invisible boundary and trigger a display change so that when the eyes land on Word 4, the preview word has already changed to the correct target word, *weak* (line *b*). After the target word has been fixated, reading continues normally (line *c*).

Parafoveal processing of words

It has been shown that before a word is fixated, both orthographic and phonological information are activated while the word is still in parafoveal vision. This information then speeds the processing of the word when it is subsequently fixated (Pollatsek, Lesch, Morris, & Rayner, 1992; Schotter, Angele, & Rayner, 2012). Though historically there was no evidence of parafoveal semantic-information processing for readers of English, recent evidence suggests that semantic information is processed under certain conditions (Hohenstein & Kliegl, 2014; Rayner & Schotter, 2014; Schotter, 2013; Yan, Pan, Bélanger, & Shu, 2014).

Hearing children learn to read by associating orthographic representations (letters and letter patterns making up words) with phonological representations (sounds and sound patterns). They have lifelong access to spoken language in their environment and have built a large vocabulary of words they know and have heard. They have built-in phonological representations with which they can associate letter patterns. Phonological codes are a powerful link between written and spoken languages and remain useful during skilled reading. Because of the importance of phonological codes in reading acquisition and skilled reading in hearing individuals, much research on deaf readers has focused on whether they do activate phonological codes and whether this may be the source of their difficulties (Paul, Wang, Trezek, & Luckner, 2009). However, results are mostly inconclusive. Indeed, some studies suggest that deaf readers do not use phonological codes during word processing (Bélanger, Baum, & Mayberry, 2012; Waters & Doehring, 1990), while others suggest that they do (Kelly, 2003; Transler, Gombert, & Leybaert, 2001). Importantly, few studies with deaf readers have controlled for the reading level of their participants (Mayberry et al., 2011). Also, because deaf individuals mainly process language via the visual channel, it is possible that their reliance on phonological codes is not as central to the reading process as it is for hearing individuals, even in alphabetical languages, and that reading is qualitatively different in deaf readers.

It is thus essential to dissociate the effects of phonological coding from orthographic coding. Because both types of information are highly interrelated, this can result in important confounds in the case of deaf readers (i.e., effects of phonology could in fact be effects of orthography). Overall, the results are still unconvincing, as stated earlier, but our recent work suggests that deaf readers, skilled or less skilled, do not activate phonological codes during word processing (Bélanger, Baum, & Mayberry, 2012; Bélanger et al., 2013) across two different orthographies (French and English). Bélanger et al. (2013) used the *gaze-contingent boundary paradigm* (see Fig. 2a) to investigate the use of orthographic and phonological codes in parafoveal vision by deaf readers. Prior work using masked priming with a lexical decision task showed a clear dissociation between the effects of orthography and phonology in readers of French (Bélanger, Baum, & Mayberry, 2012), and though hearing readers activated both codes, deaf readers activated only orthographic codes and showed no effects at all of phonological processing.

Because of the inconclusive results on the use of phonological codes by deaf readers in the literature, Bélanger et al. (2013) attempted to replicate the results of Bélanger et al. (2012) with deaf readers of English, using eye movements, to determine whether orthographic and phonological codes are activated independently in parafoveal vision. Preview words were presented in the parafovea (see Fig. 2b for details about and results for the four different conditions), and targets replaced them after an invisible boundary was crossed (Fig. 2a). The preview either was identical to the target (e.g., *weak-weak*; Condition 1), was a homophone of the target (e.g., *week-weak*; Condition 2), or was orthographically related to the target (e.g., *wear-weak*; Condition 3). When comparing Conditions 1 and 2 (see Fig. 2b), the phonemes shared by the primes and the targets in both conditions were held constant (100% in each condition), but the amount of orthographic overlap (i.e., number of shared letters) was varied (100% in Condition 1 vs. 75% in Condition 2); thus, the comparison of fixation times on the targets between these two conditions reflected the unique contribution of orthography over and above the activation of phonological codes. The same logic applied for the comparison of Conditions 2 and 3, in which the amount of orthographic overlap was held constant (75%) and the amount of phonological overlap was varied (100% in Condition 2 vs. 57% in Condition 3), allowing for the unique influence of phonological codes to be determined. Bélanger et al.'s (2013) results replicated Bélanger, Baum, and Mayberry's (2012) results (using similar conditions in a masked priming lexical decision task): Hearing readers, as expected, showed early activation of both orthographic and phonological codes in parafoveal vision, but deaf readers again showed only effects of orthographic information and no effects of phonological information, regardless of their reading level (skilled or less skilled).

Word-processing efficiency

Finally, eye movements during reading reveal ongoing, fine-grained, on-line processes for written-word comprehension in context (relative to single-word tasks). Across experiments, eye movements of deaf readers have revealed a unique pattern during sentence reading. Indeed, when skilled deaf readers read connected text, they regressed back in the text (reread) less often than did skilled hearing readers, but they also skipped over words more often and refixated words less often than did skilled hearing readers.

Because deaf readers (skilled and less skilled) appear to bypass phonological codes (at least in our own very carefully controlled experiments in which we dissociated the effects of orthography and phonology) and because of these unique eye movement patterns, we propose the *word-processing efficiency* hypothesis—namely, that skilled deaf readers are more "efficient" than hearing readers at processing written words within a single fixation. We interpret these results as showing that deaf readers have tighter connections between orthography and semantics, but also that they are extremely attuned to the visual-orthographic makeup of words and quickly detect precise word form, within a single fixation (as shown by the reduced number of refixations) or even while words are still in the parafovea (as shown by the larger proportion of skipped words).

Interestingly, less-skilled deaf readers did not differ from skilled hearing readers on these measures (skipping, refixations, rereading), though their reading level was much lower (6th-grade vs. 11th-grade level), suggesting that they were also very efficient at processing words. In the experimental tasks, less-skilled deaf readers scored as high as the skilled hearing readers on comprehension questions (approximately 90% for both groups); thus, their eye movements accurately reflected text comprehension. As mentioned earlier, eye movement measures are extremely sensitive to small reading-level variations among college students; thus, less-skilled deaf readers, having a mean reading level equivalent to the last year of primary school, should have had a much lower skipping rate and a much higher refixation rate than the skilled hearing readers. This was not the case. The effects of efficiency appeared mostly in less-skilled deaf readers' skipping and refixation behavior, suggesting that they could quickly detect precise word form. However, their fixation durations were much longer than those of skilled hearing and skilled deaf readers, potentially suggesting a weaker semantic network and weaker, or slower, orthography-to-semantics connections overall.

Strikingly, this unique pattern of eye movements (word-processing efficiency) is visible very early on in young deaf readers (Bélanger, Schotter, & Rayner, 2014). While reading sentences, young deaf readers aged 8 to 12 years read significantly faster (more words per minute) than did young hearing readers matched on age and reading level. Young deaf readers also made significantly fewer fixations per sentence, indicating that they could process more visual information per fixation. Crucially, with equal comprehension levels in the reading task, young deaf readers made significantly fewer regressions back in the text relative to their hearing peers, indicating that despite reading fast and making fewer fixations per sentence, they did not need to reread as often to consolidate comprehension. If such eye movement patterns are due, as we suggest above, to a tighter connection between orthography and semantics (see also Yan et al., 2014, for a similar hypothesis with Chinese deaf readers, or Hirshorn et al., 2014, on the neural basis of written-language processing), then the fact that young deaf readers show this pattern extremely early would need to be taken into consideration in educational practices.

Summary

The results from studies on on-line reading and eye movement behavior suggest a high impact of visual modality and deafness on the reading act that should be investigated further. These results suggest that just as different orthographies place different emphases on which codes have more weight at certain times during the word-recognition process, deafness shifts the emphasis on which codes can be used more effectively in the recognition process. More importantly, these results raise more questions about how skilled comprehension is attained by deaf individuals. In other words, does skilled reading for deaf individuals necessarily involve the same processing stages as it does for skilled hearing readers? Ultimately, if skilled reading in the deaf population differs in several aspects from skilled reading in the hearing population, is there a need to rethink reading education for young deaf readers (since what is known about reading education emanates from research on young hearing readers and skilled hearing readers)? Indeed, in a context where reading education for deaf children is still based on phonology-centric models developed for hearing readers, it is essential to consider and further test the possibility of direct and stronger orthography-to-semantics connections in deaf readers (as suggested here by the results of our eye movements research; see also Hirshorn et al., 2014). This would be strong support for a greater focus on consolidating form-meaning connections (e.g., via American Sign Language) as the norm in deaf education, and not as the exception.

Recommended Reading

Bavelier, D., Dye, M. W. G., & Hauser, P. (2006). (See References). A review article on enhanced attention allocation in the periphery in deaf individuals.

Goldin-Meadow, S., & Mayberry, R. I. (2001). (See References). A review article on reading acquisition in deaf children.

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The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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