Skilled Deaf Readers have an Enhanced Perceptual Span in Reading

Journal:	*Psychological Science*
Manuscript ID:	PSCI-11-0958.R2
Manuscript Type:	Research article
Date Submitted by the Author:	n/a

Complete List of Authors:	Bélanger, Nathalie; University of California, San Diego, Psychology Slattery, Timothy; University of California, San Diego, Department of Psychology Mayberry, Rachel; University of California, San Diego, Linguistics, 0108 Rayner, Keith; University of California, San Diego, Psychology;

Keywords:	Reading, Deaf, Eye Movements, Individual Differences, Literacy

Running head: Deaf Readers' Perceptual Span

Skilled Deaf Readers have an Enhanced Perceptual Span in Reading

Nathalie N. Bélanger

Department of Psychology, University of California, San Diego

Timothy J. Slattery

Department of Psychology, University of California, San Diego

Rachel I. Mayberry

Department of Linguistics, University of California, San Diego

Keith Rayner

Department of Psychology, University of California, San Diego

Corresponding Author

Nathalie N. Bélanger

University of California, San Diego

Department of Psychology

9500 Gilman Drive #0109

La Jolla, CA 92093-0109

Phone: 858-822-7813 Fax: 858-534-7190

Email: nbelanger@ucsd.edu

Word count = 4,068

Abstract

Recent evidence suggests that deaf people have enhanced visual attention to simple stimuli in the parafovea in comparison to hearing people. Although a large part of reading involves processing the fixated words in foveal vision, readers also utilize information in parafoveal vision to pre-process upcoming words and decide where to look next. We investigated whether auditory deprivation affects low-level visual processing during reading, and compared the perceptual span of deaf signers who were skilled and less skilled readers to that of skilled hearing readers. Compared to hearing readers, deaf readers had a larger perceptual span than would be expected by their reading ability. These results provide the first evidence that deaf readers' enhanced attentional allocation to the parafovea is used during a complex cognitive task such as reading.

Keywords: Deaf readers, eye movements, reading skill, perceptual span, visual processing in the parafovea.

Illiteracy is a serious problem in the deaf population. The median reading level of young deaf adults graduating from high school is 8 years below the average of their hearing peers (Kelly & Barac-Cikoja, 2007). Although the reasons for this problem are unclear (Bélanger, Baum & Mayberry, in press; Mayberry, del Giudice & Lieberman, 2011), one intriguing hypothesis is that enhancements in visual cognition engendered by deafness may cause reading difficulties. Recent research has found that individuals who experience early severe to profound deafness are more efficient at processing information in extrafoveal (i.e., parafoveal/peripheral) vision compared to hearing individuals. This has been shown in studies investigating low-level visual perception of motion, orientation and brightness discrimination, and detection performed under attentionally demanding conditions. These effects are thought to arise from increased allocation of attention to stimuli in extrafoveal vision as a consequence of early deafness (Bavelier, Dye & Hauser, 2006; Dye & Bavelier, 2010). Based on such results, Dye, Hauser, and Bavelier (2008) speculated that "greater availability of parafoveal information may slow down foveal processing, resulting in longer fixations and slowing down the reading process" (p. 77). It is crucial to investigate how this unique aspect of visual cognition may influence reading in the deaf population.

Although there has been considerable research conducted with deaf people on various cognitive processing tasks related to reading (Kelly & Barac-Cikoja, 2007; Musselman, 2000), little research has examined reading *per se* in this population. Research using a self-paced moving window in which participants read sentences one word at a time and push a button to advance the movement of the window of text across a sentence, found that skilled deaf readers spent less time viewing each word than less skilled deaf readers (Kelly, 1995, 2003), a result consistent with the literature on hearing readers (Rayner, 1998, 2009). However, the self-paced reading paradigm is not very diagnostic of normal reading as it denies access to parafoveal information which is clearly used during normal reading

(Rayner, 1998).

Prior research with English hearing readers has demonstrated that, in addition to the word(s) processed in the fovea, information from up to 14-15 letter spaces to the right of fixation is used during reading (McConkie & Rayner, 1975; Rayner & Bertera, 1979). This region of effective vision, the *perceptual span*, is asymmetric because only information from 3-4 letters to the left is used (Rayner, Well, & Pollatsek, 1980). Evidence regarding the size of the perceptual span comes from the use of the gaze contingent moving window paradigm (McConkie & Rayner, 1975) in which text is displayed normally in a window around the fixation point, but beyond the window, words are replaced by a mask (see Figure 1). The size of the window is manipulated to provide increasing levels of information in the parafovea. The assumption is that if the window is wide enough, reading will not be disrupted compared to a condition in which all the text is visible (a no window control condition). Crucially, the size of the perceptual span is not simply a function of decreased visual acuity in the parafovea. A parafoveal magnification technique with a moving window (in which letters were larger on each fixation outside of the center of vision) found that the span was about 14-15 letter spaces to the right of fixation (Miellet, O'Donnell, & Sereno, 2009), confirming that the span is under cognitive/attentional control.

The size and asymmetry of the perceptual span does however vary with online processing constraints. The directionality of reading (e.g., Hebrew vs. English) influences the asymmetry of the span (Pollatsek, Bolozky, Well, & Rayner, 1981). Importantly, research has shown that the size of the perceptual span is sensitive to reading level (Häikiö, Bertram, Hyönä, & Neimi, 2009; Rayner, 1986), reading speed (Rayner, Slattery, & Bélanger, 2010), and the properties of the writing system (Inhoff & Liu, 1998). In fact, eye movement measures in general are very sensitive to reading level: less skilled and dyslexic readers are slower readers, have a smaller perceptual span, make shorter saccades, and more regressions than skilled readers (see Rayner, 1998). These measures can also distinguish highly skilled from average college-level readers (Ashby, Rayner, & Clifton, 2005).

[Insert Figure 1 about here]

The goal of the present experiment was to examine whether the perceptual span varied as a function of hearing status (deaf vs hearing readers), as well as how skilled deaf readers, less skilled deaf readers, and skilled hearing readers compared on reading speed (words read per minute - wpm), mean length of forward saccades, and mean fixation durations. As previously mentioned, when 14-15 letters to the right of fixation are visible, and the text beyond the window is masked, reading proceeds at a normal rate in skilled hearing readers. The enhanced extrafoveal visual/attention processing abilities reported for deaf individuals would predict a larger perceptual span in deaf readers than in hearing readers (matched on reading level). Additionally, given that saccades are planned with information gleaned from parafoveal vision, and are intimately connected with the distribution of visual attention, longer forward saccades would be predicted for deaf individuals (unless reading level also modulates this effect) compared to hearing controls. Recall, however, that Dye et al (2008) suggested that greater availability of parafoveal information (a larger perceptual span), could slow down foveal processing resulting in longer fixation durations in deaf readers. Finally, less skilled deaf readers would be expected to have a smaller perceptual span than skilled deaf readers, because their reading level is much lower. We also expected that they would have longer fixation durations and regress back into the text (reread) more than both skilled reader groups (Rayner, 2009). An additional question of interest is whether less skilled deaf readers have a significantly smaller perceptual span than skilled *hearing* readers. Such an effect would be predicted based on the reading ability of these two groups.

Method

Participants

Forty adults from San Diego's Deaf community participated. They were aged 20 to 45 years (*M* = 30 years), severely to profoundly deaf (hearing loss > 71dB in the better ear), born deaf or became deaf before the age of two (3/40 participants became deaf at age 3, 4, and 10), and used American Sign Language (ASL) as their main communication mode for more than 10 years. Twenty skilled hearing readers (SKH), 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

All participants completed the *Peabody Individual Achievement Test-Revised* (Markwardt & Markwardt, 1989), which provided an assessment of their reading level. This was crucial since reading level has been shown to influence the size of the perceptual span during reading. The deaf readers were split into two groups based on their PIAT-R score: skilled deaf readers (SKD), who were well matched on reading level to the SKH readers, and less skilled deaf (LSKD) readers[1]. A one-way ANOVA, comparing the reading level of skilled hearing readers (SKH, n = 20; *M* = 85; *SD* = 6.8), SKD (n = 18; *M* = 82; *SD* = 5.5) and LSKD readers (n = 22; *M* = 68; *SD* = 4.1), resulted in a significant effect of group ($F(2, 57) = 52.13$, $p < .0001$, $\eta_p^2 = .65$). SKH and SKD readers did not differ in reading level ($p = .21$), but LSKD readers differed significantly from both SKH readers ($p < .0001$) and SKD readers ($p < .0001$)[2]. Non-verbal IQ was also assessed for all participants with three subtests of the performance scale of the *Wechsler Adult Intelligence Scale—Revised* (Wechsler, 1981): picture completion, picture arrangement, and block design. Performance of the SKH readers (*M* = 11.4; *SD* = 1.7), SKD readers (*M* = 11.3; *SD* = 1.4) and LSKD readers (*M* = 10.5; *SD* = 1.5) was not different on this measure ($F(2, 57) = 2.4$, $p > .10$, $\eta_p^2 = .08$). Finally, although SKD and LSKD readers did not significantly differ in age of English acquisition (*M* = 1.3 and *M* = 2.7; $F(1, 38) = 2.7$, $p = 0.11$, $\eta_p^2 = .07$), SKD readers acquired

ASL at a younger age than LSKD readers (*M* = 4.5 and *M* = 8.2; $F(1, 38) = 5.9$, $p = .02$, $\eta_p^2 = .14$). The SKD and LSKD readers did not differ on degree of deafness in their better ear ($p = .48$), or on age of deafness onset ($p = .17$). Both groups had used ASL for over 22 years and did not differ on this measure ($p > .20$).

Stimuli

165 sentences containing 10 to 17 words were created; they all had simple syntactic structures in order to avoid reading difficulties that could be brought on by complex syntax for LSKD readers (Kelly, 1998).

Apparatus

Eye movements were monitored via an EyeLink 1000 eyetracker (SR Research Ltd.; spatial resolution less than 0.04°). Eye position was sampled every half millisecond. Participants were seated 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 the use of a chin and headrest. Eye movements from the right eye were recorded, but viewing was binocular.

Design and Procedure

There were four different window sizes. In each, 4 letter spaces were visible to the left of fixation and 6, 10, 14 or 18 letter spaces were visible to the right of fixation. The baseline was a full-line, no window (NW), condition where all words in the sentence were visible. In the experimental conditions, text outside the window was replaced by lowercase *x*'s (including the spaces between words, see Figure 1).

The testing session started with the completion of the reading and non-verbal IQ tests, followed by the participants' performing a 3-point calibration procedure on the eyetracker. Then they read 15 practice sentences prior to the experimental sentences. Sentences were presented in black 14 pt *Courier*

New font on a light grey background. One degree of visual angle comprised 3.4 letters. All sentences were displayed on a single line with a maximum of 78 characters (including spaces). Participants were instructed to read silently for comprehension and to press a keypad when they finished reading. Sentences were counterbalanced across participants and conditions. Order of presentation was randomized for each participant. Comprehension questions were asked after 22% of the trials. The SKH, SKD and LSKD readers scored 93%, 91%, and 88% respectively. An ANOVA revealed a significant group effect ($F(2, 57) = 6.15$, $p < .004$, $\eta_p^2 = .18$) with significant differences between LSKD and SKH readers ($p < .01$), and between LSKD and SKD readers ($p < .01$).

Analysis

In order to determine whether deaf readers have a larger perceptual span, we report their reading rate (in words read per minute, wpm) for each window size (WS), including the baseline NW condition. Reading rate is a composite measure that incorporates the number and durations of fixations across the sentence and is typically used to assess reading performance in moving window experiments. Forward saccades were also analyzed given that they are tightly linked with the distribution of visual attention in the parafovea. Finally, we analyzed average fixation duration in order to determine whether deaf readers' foveal processing of words is slowed down (relative to SKH readers). For completeness, the mean number of forward fixations per sentence and mean number of regressive fixations are presented (see Figure 3), but our focus here is on the other three measures.

Fixations shorter than 80 ms and within one letter of another fixation were combined with that fixation (0.3% of fixations for each group), but other fixations shorter than 80 ms were excluded (3.4 %, 2.4% and 2.4% of fixations for SKH, SKD and LSKD readers). Trials with two or more blinks were excluded (1.8%, 3%, and 2.4% of trials for SKH, SKD, and LSKD readers) along with trials in which there were fewer than 5 fixations for the whole sentence (1.4%, 1.9%, and 1.3% of trials for SKH, SKD, and LSKD readers).

Data were analyzed using linear-mixed effects models where participants and items were specified as crossed random effects (Baayen, 2008), using the lme4 package (Bates, Maechler & Dai, 2009) available in the R environment (R Development Core Team, 2008). The p-values were computed with Markov-Chain Monte Carlo sampling (with the pvals.fcn function from the languageR package). To compare the effect of increasing window size for each measure, four contrasts were set up (18 vs. NW, 14 vs. 18, 10 vs. 14, and 6 vs. 10) using successive difference contrasts (Venables & Ripley, 2002)[3]. Regression coefficient estimates (*b*), standard errors (SE), and *p*-values are reported.

Results

Reading Rate

As in prior moving window experiments, for each group our goal was to ascertain when they reached asymptote in reading rate (see Figure 2). For SKH readers, reading rate significantly increased from WS6 to WS10 (b = -40.21, SE = 3.56, $p < .0001$) and from WS10 to WS14 (b = -14.52, SE = 3.56, $p < .0001$), with no further increases in reading rate for larger window sizes[4]. Thus, SKH readers reached asymptote in reading rate with a window of 14 characters to the right of fixation, which replicates much prior research (Rayner, 2009). For LSKD readers, we found a similar pattern despite their significantly lower reading level. Reading rate increased from WS6 to WS10 (b = -38.73, SE = 3.94, $p < .0001$), and from WS10 to WS14 (b = -8.20, SE = 3.94, $p < .04$), with no further increases in reading rate for larger window sizes. Most interestingly, SKD readers did not reach asymptote until there were 18 characters available to the right of fixation. For these readers, reading rate increased from WS6 to WS10 (b = -50.86, SE = 4.53, $p < .0001$), WS10 to WS14 (b = -16.58, SE = 4.53, $p = .0003$), and WS14 to WS18 (b = -13.86, SE = 4.55, $p = .002$) with no additional increase from WS18 to NW.

Thus, SKD readers were faster in the WS18 condition than in the WS14 condition (344 vs. 329 wpm), whereas the other groups did not show this increase in reading speed (SKH: 329 vs 326 wpm; and LSKD: 268 vs. 266 wpm).

Overall reading rate did not significantly differ between SKH and SKD readers, ($b = 5.55$, SE = 24.09, $p = .82$). Not surprisingly, the LSKD read slower than SKH readers ($b = -51.63$, SE = 22.91, $p < .05$), and SKD readers ($b = -57.14$, SE = 23.37, $p < .01$). Additionally, the increase in reading rate from WS6 to WS10 was significantly greater for SKD than for LSKD readers ($b = 12.67$, SE = 5.94, $p < .05$), and marginally greater for SKD relative to SKH readers ($b = -10.05$, SE = 5.73, $p = .08$). Similarly, SKD readers' change in reading rate from WS14 to WS18 was significantly greater than for LSKD readers ($b = 14.44$, SE = 5.96, $p < .05$), and marginally greater than SKH readers ($b = -9.75$, SE = 5.76, $p = .09$). These interactions indicate that the SKD readers were more negatively impacted by the loss of parafoveal information (between 6 and 10 characters to the right of fixation) than LSKD and SKH readers, and that they were better able to extract information from farther away.

[Insert Figure 2 about here]

Forward Saccade Length

Mean forward saccade length reliably increased between each WS contrast for SKH readers (WS6 to WS10: $b = -0.98$, SE = 0.07, $p < .0001$; WS10 and WS14, $b = -0.63$, SE = 0.07, $p < .0001$; WS14 and WS18, $b = -0.19$, SE = 0.07, $p < .01$), for LSKD readers (WS6 to WS10: $b = -.98$, SE = 0.06, $p < .0001$; WS10 and WS14, $b = -0.76$, SE = 0.06, $p < .0001$; WS14 and WS18, $b = -0.25$, SE = 0.06, $p < .0001$), and for SKD readers (WS6 to WS10: $b = -1.24$, SE = 0.07, $p < .0001$; WS10 to WS14: $b = -0.84$, SE = 0.07, $p < .0001$; WS14 to WS18: $b = -0.53$, SE = 0.07, $p < .0001$), except for the WS18 and NW conditions, where all groups had a slight decrease in the length of forward saccades (SKH readers:

b = 0.20, SE = 0.07, $p < .01$; LSKD readers, *b* = 0.18, SE = 0.06, $p < .01$; SKD readers: *b* = 0.19, SE = 0.07, $p < .01$). Thus, the overall length of forward saccades was similar for all three groups (all *p*s > .19).

Importantly, the increases in forward saccade length that accompanied increases in window size were significantly larger for SKD than for SKH readers (WS6 to WS10: *b* = -0.28, SE = 0.10, $p < .01$; WS10 to WS14: *b* = -0.19, SE = 0.10, $p < .05$; WS14 to WS18: *b* = -0.33, SE = 0.10, $p < .001$ – see Figure 3). The SKD readers also made longer forward saccades than the LSKD readers in the WS6 to WS10 conditions (*b* = 0.26, SE = 0.07, $p < .01$) and the WS14 to WS18 conditions (*b* = 0.28, SE = 0.09, $p < .01$). There were no significant differences in forward saccade lengths between the LSKD and the SKH readers. As noted above, saccade planning is assumed to make use of attentional resources for the purpose of targeting areas of text that have yet to be adequately encoded. That SKD readers plan and execute longer forward saccades than SKH and LSKD readers strongly suggests they were better able to encode more of the intervening text.

[Insert Figure 3 about here]

Fixation Duration

Mean fixation durations for the SKH, SKD and LSKD groups were longer in the WS6 condition than in the WS10 condition (*b* = 5.42, SE = 1.45, $p < .001$; *b* = 5.54, SE = 1.83, $p < .01$; *b* = 5.48, SE = 1.63, $p < .001$), and longer in the WS18 condition than in the NW condition (*b* = 6.50, SE = 1.47, $p < .0001$; *b* = 8.44, SE = 1.86, $p < .0001$; *b* = 7.48, SE = 1.64, $p < .0001$). None of the other successive contrasts for window size were significant (*p*s > .06). Across all window sizes, mean fixation duration was 215 ms for SKH readers, 217 ms for SKD readers, and 227 ms for LSKD readers. Crucially, the SKD readers did not differ from SKH readers ($p = .85$). The LSKD made longer fixation durations than SKH readers (*b* = 16.74, SE = 8.53, $p < .05$) and SKD readers, but this latter difference did not quite reach significance ($p = .07$).

The pattern for mean fixation duration over the window size conditions was very similar (see Figure 3) for SKH, SKD, and LSKD readers. None of the interactions were significant (all *p*s > .18). This indicates that, relative to hearing readers, SKD readers' ability to effectively utilize parafoveal information, as evidenced by their reading rates, did not slow foveal processing and lead to longer eye fixations as suggested by Dye et al. (2008).

Discussion

The present experiment investigated the perceptual span of readers who were severely to profoundly deaf and communicate mainly via ASL. We were particularly interested in determining whether differential distribution of attentional resources across the visual field found in deaf individuals with early onset deafness (Bavelier et al., 2006) would translate into a larger perceptual span during reading. Our primary finding was that skilled deaf readers had an enhanced perceptual span in comparison to the matched hearing control group: reading rate for the SKD group reached asymptote with a larger window (18 letter spaces to the right of fixation) than for the SKH readers. We also replicated the general pattern of results for hearing readers: they processed useful information up to 14 letter spaces to the right of fixation (McConkie & Rayner, 1975).

Dye et al. (2008) suggested that an extended perceptual span for deaf readers might detract from foveal processing of words and result in slower reading. This was not the pattern of results found here. Interestingly, SKD readers' mean fixation durations at all window sizes matched that of SKH readers almost perfectly. Furthermore, not only did SKD readers read equally fast as SKH readers, they also regressed less than did SKH readers, making them very efficient readers. Unsurprisingly, the LSKD readers read at a slower rate than the other two groups. They also made more fixations (forward and regressive) than the skilled readers, in line with research showing that eye movements are highly sensitive to reading level (Ashby et al., 2005; Rayner, 1986).

Is the larger perceptual span in skilled deaf readers a function of their deafness and associated with a wider distribution of visual attention extrafoveally? The tight match on multiple characteristics (reading level, age, non-verbal IQ, and accuracy on the experimental tasks' comprehension questions) between the SKD and SKH readers suggests that is the case. In terms of grade-level equivalence, SKD readers (10^{th} grade level) were slightly lower than SKH readers (11^{th} grade). Thus, it could be expected that the perceptual span of SKD readers might be, if anything, smaller. This was not the case. Additionally, SKD readers had longer forward saccade lengths than SKH readers. Much research has shown that attention shifts to the parafovea prior to a saccade being targeted to a specific location (Rayner, 2009), thus supporting our claim that SKD readers have a wider distribution of attention.

Finally, we replicated the effects of reading skill on the size of the perceptual span; the SKD readers had a larger span than the LSKD readers. These two groups were formed based on PIAT-R scores but also matched on age, non-verbal IQ, degree of hearing loss, age of onset of deafness, and age of acquisition of English. However, they differed in age of ASL acquisition. This factor is tightly linked to reading skills in the deaf population (Chamberlain & Mayberry, 2008; Mayberry, Lock & Kazmi, 2002) and it is unsurprising that it was predictive of reading level in the current study. Additionally, despite significantly lower reading proficiency (6^{th} grade reading equivalence) and a significantly slower reading rate (factors known to reduce the perceptual span; see Rayner, 1986, 2009), the perceptual span of LSKD readers did not differ from that of SKH readers. The lack of difference in the size of the perceptual span between LSKD and SKH readers suggests that, relative to their reading level, LSKD readers have a wider perceptual span than hearing readers.

Overall our results have at least three major implications. First, they show that enhanced attention to the parafovea in deaf readers is not restricted to low-level visual perception but can also be recruited for a complex cognitive process such as reading. Second, they indicate that enhanced attention to the parafovea is not accompanied by reduced foveal processing as has been previously suggested. Third, they show that high levels of reading ability can be achieved by deaf readers and that the way in which they process written language varies somewhat from that of hearing readers; they take in more visual information within a fixation than do hearing readers matched on reading level. These results are especially noteworthy against the backdrop of illiteracy that is prevalent in the deaf population.

References

Ashby, J., Rayner, K., & Clifton, C. (2005). Eye movements of highly skilled and average readers: Differential effects of frequency and predictability. *Quarterly Journal of Experimental Psychology*, *58A*, 1065-1086.

Baayen, R. H. (2008). *Analyzing linguistic data: A practical introduction to statistics*. Cambridge, United Kingdom: Cambridge University Press.

Bates, D., Maechler, M., & Dai, B. (2009). lme4: Linear mixed-effects models using S4 classes. R package version 0.999375-28. http://lme4.r-forge.r-project.org/

Bavelier, D., Dye, M.W.G., & Hauser, P.C. (2006). Do deaf individuals see better? *Trends in Cognitive Sciences, 10*(11), 512-518.

Bélanger, N.N., Baum, S.R., & Mayberry, R.I. (in press). Reading difficulties in adult deaf readers of French: Phonological codes, not guilty! *Scientific Studies of Reading.*

Chamberlain, C., & Mayberry, R. I. (2008). ASL syntactic and narrative comprehension in skilled and less skilled deaf readers: Bilingual-bimodal evidence for the linguistic basis of reading. *Applied Psycholinguistics, 29*, 367-388.

Dye, M.W.G., & Bavelier, D. (2010). Attentional enhancements and deficits in deaf populations: An integrative review. *Restorative Neurology and Neuroscience, 28*, 181-192.

Dye, M.W.G., Hauser, P.C. & Bavelier, D. (2008). Visual skills and cross-modal plasticity in deaf readers: Possible implications for acquiring meaning from print. *Annals of the New York Academy of Sciences*, *1145*, 71-82.

Häikiö, T., Bertram, R., Hyönä, J., & Neimi, P. (2009). Development of the letter identity span in reading: Evidence from the eye movement moving window paradigm. *Journal of Experimental Child Psychology, 102*, 167-181.

Inhoff, A. W., & Liu, W. (1998). The perceptual span and oculomotor activity during the reading of Chinese sentences. *Journal of Experimental Psychology: Human Perception and Performance, 24*, 20–34.

Kelly, L. (1995). Processing of bottom-up and top-down information by skilled and average deaf readers and implications for whole language instruction. *Exceptional Children*, *61*(4), 318–334.

Kelly, L. (1998). Using silent motion pictures to teach complex syntax to adult deaf readers. *Journal of Deaf Studies and Deaf Education, 3*(3), 217–230.

Kelly, L. (2003). The importance of processing automaticity and temporary storage capacity to the differences in comprehension between skilled and less skilled college-age deaf readers. *Journal of Deaf Studies and Deaf Education*, *8*(3), 230-249.

Kelly, L. & Barac-Cikoja, D. (2007). The comprehension of skilled deaf readers: The roles of word recognition and other potentially critical aspects of competence. In K. Cain, & J. Oakhill (Eds). *Children's comprehension problems in oral and written language: A cognitive perspective* (pp. 244-279). Guilford Press.

Markwardt, F.C. (1989) Manual. In: *Peabody Individual Achievement Test-Revised*, American Guidance Service, Circle Pines, MN.

Mayberry, R. I., del Giudice, A. A., & Lieberman, A. M. (2011). Reading achievement in relation to phonological coding and awareness in deaf readers: A meta-analysis. *Journal of Deaf Studies and Deaf Education, 16*, 164-188.

Mayberry, R. I., Lock, E., & Kazmi, H. (2002). Linguistic ability and early language exposure. *Nature, 417*, 38.

McConkie, G. W., & Rayner, K. (1975). The span of the effective stimulus during a fixation in reading. *Perception & Psychophysics, 17,* 578-586.

Miellet S., O'Donnell P.J., & Sereno S.C. (2009). Parafoveal magnification: Visual acuity does not modulate the perceptual span in reading. *Psychological Science, 20*,721-728.

Musselman, C. (2000). How do children who can't hear learn to read an alphabetic script? : A review of the literature on reading and deafness. *Journal of Deaf Studies and Deaf Education*, *5*, 9 – 31.

Pollatsek, A., Bolozky, S., Well, A.D., & Rayner, K. (1981). Asymmetries in the perceptual span for Israeli readers. Brain and Language, *14*, 174-180.

R Development Core Team (2008). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing.

Rayner, K. (1986). Eye movements and the perceptual span in beginning and skilled readers. *Journal of Experimental Child Psychology, 41*, 211–36.

Rayner, K. (1998). Eye movements in reading and information processing: Twenty years of research. *Psychological Bulletin 124*, 372–422.

Rayner, K. (2009). The Thirty Fifth Sir Frederick Bartlett Lecture: Eye movements and attention during reading, scene perception, and visual search. *Quarterly Journal of Experimental Psychology*, *62*, 1457-1506.

Rayner, K., & Bertera, J. H. (1979). Reading without a fovea. *Science*, *206*, 468-469.

Rayner, K., Slattery, T.J., & Bélanger, N.N. (2010). Eye movements, the perceptual span, and reading speed. *Psychonomic Bulletin & Review, 17(6), 834-839.*

Rayner, K., Well, A.D., & Pollatsek, A. (1980). Asymmetry of the effective visual field in reading. *Perception & Psychophysics*, 27, 537-544.

Venables, W. N., & Ripley, B. D. (2002) *Modern Applied Statistics with S.* Fourth Edition, Springer.

Wechsler, D. (1981). *Wechsler Adult Intelligence Scale—Revised*. New York: Harcourt Brace Jovanovich.

Acknowledgments

The research was supported by NIH grant HD26765 and an ARRA supplement, and by FQRSC (125964) Postdoctoral Fellowship to N. N. Bélanger. Tim Slattery is now at the University of South Alabama. We thank the participants, and Jesse “Rupert” Dubler, Jullian Zlatarev, Bernhard Angele and Klinton Bicknell for help with data collection and analysis. A portion of these results was presented at the *52nd Annual Meeting of the Psychonomic Society*.

Footnotes

[1] Note that it would be highly unlikely to find a group of non-dyslexic hearing readers matched on age, reading level and non-verbal IQ, to the less skilled deaf readers.

[2] Grade level equivalents: SKH = 11th grade; SKD = 10th grade; LSKD = 6th grade.

[3] The successive difference contrasts for window size were set up, such that the measures for the smaller windows were subtracted from those of the larger windows.

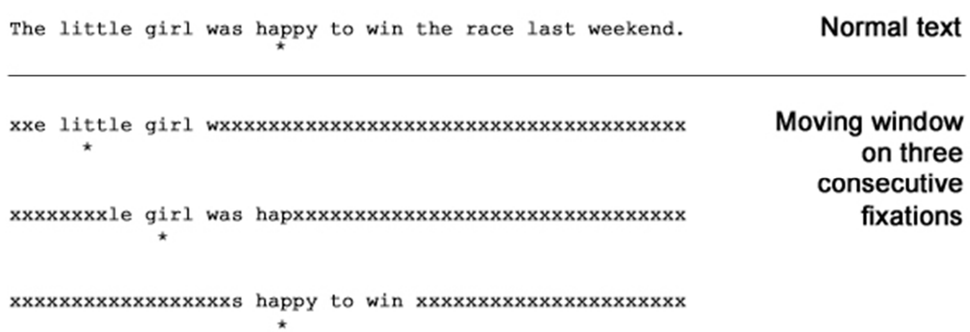
[4] Reading rate decreased from WS18 to NW for the SKH readers - this was due to an increase in regressions in the NW condition (see Figure 2). This could be due to these readers being more willing to reread under the less demanding NW condition.

Figure Captions

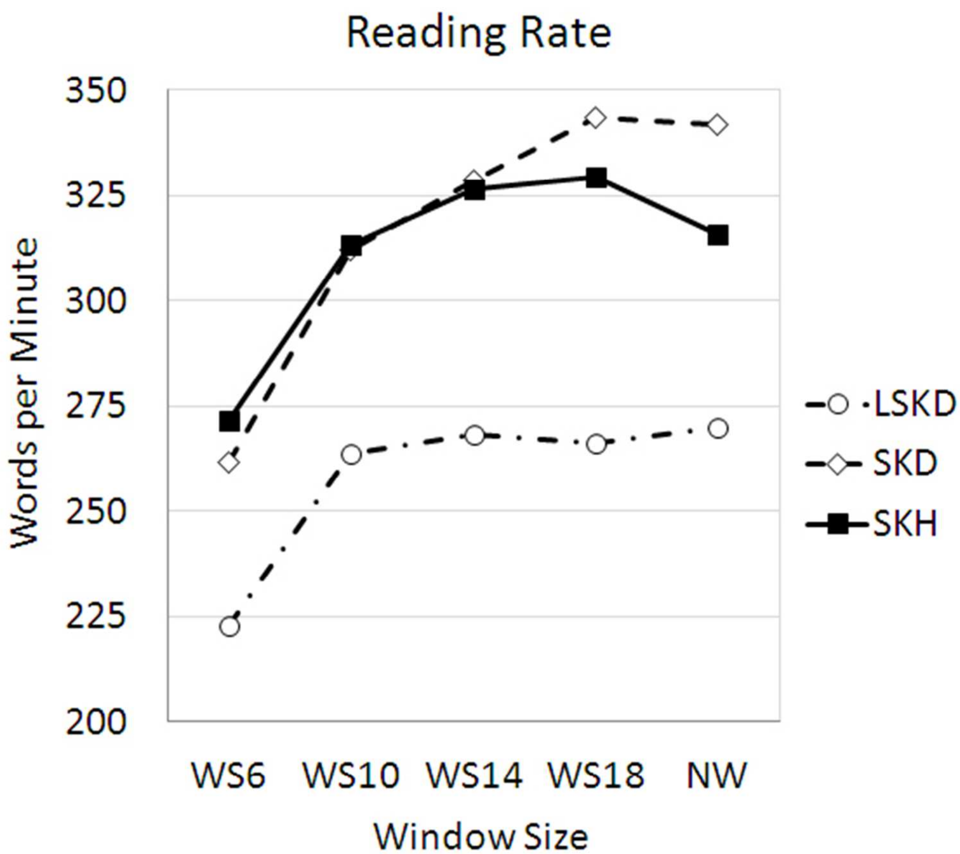
Figure 1. Example of a moving window on three consecutive fixations. The asterisk represents the position of the eye. In this example, the window is asymmetrical and shows 4 character positions to the left and 10 character positions to the right of fixation.

Figure 2. Reading rate (words per minute) as a function of window size for the skilled hearing readers (SKH), skilled deaf readers (SKD) and less skilled deaf readers (LSKD).

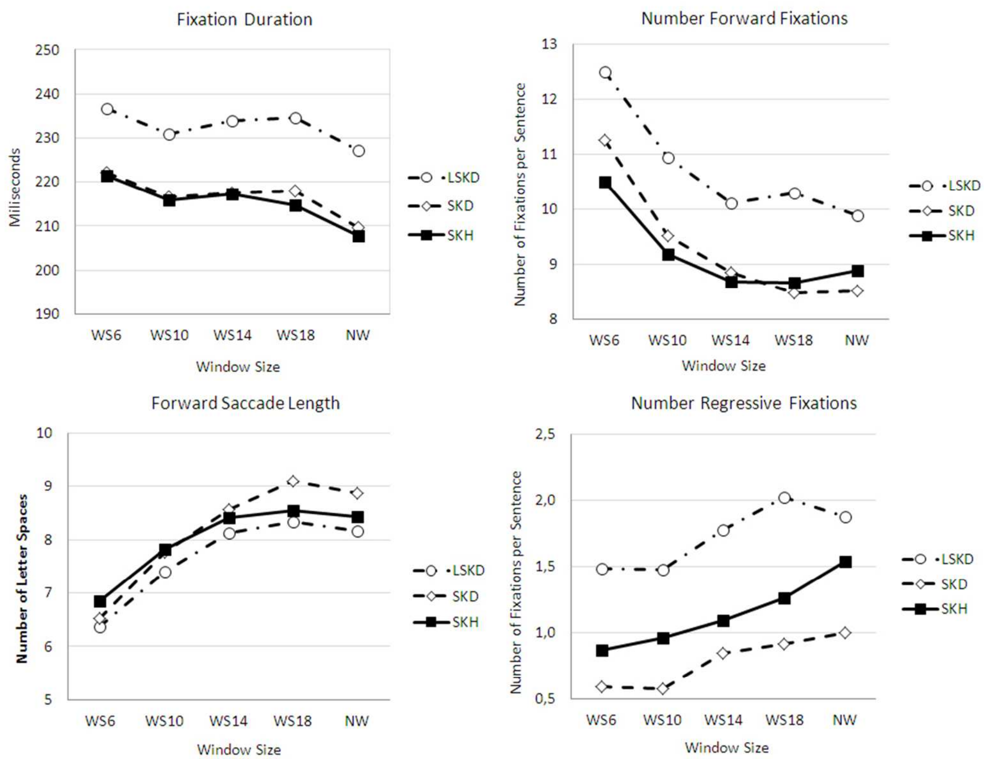
Figure 3. Results for four eye movement measures for each group of participants as a function of window size.



Example of a moving window on three consecutive fixations. The asterisk represents the position of the eye. In this example, the window is asymmetrical and shows 4 character positions to the left and 10 character positions to the right of fixation.



Reading rate (words per minute) as a function of window size for skilled hearing readers (SKH) and skilled deaf readers (SKD) and less skilled deaf readers (LSKD).
202x180mm (72 x 72 DPI)



Results for four eye movement measures for each group of participants as a function of window size.
346x268mm (72 x 72 DPI)