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Young Skilled Deaf Readers Have an Enhanced Perceptual Span in Reading

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Abstract

Recently, Bélanger, Slattery, Mayberry and Rayner (2012) showed, using the moving window paradigm, that profoundly deaf adults have a wider perceptual span during reading relative to hearing adults matched on reading level. This difference might be related to the fact that deaf adults allocate more visual attention to simple stimuli in the parafovea (Bavelier, Dye & Hauser, 2006). Importantly, this reorganization of visual attention in deaf individuals is already manifesting in deaf children (Dye, Hauser & Bavelier, 2009). This leads to questions about the time course of the emergence of an enhanced perceptual span (which is under attentional control; Rayner, 2014; Miellet, O'Donnell, & Sereno, 2009) in young deaf readers. The present research addressed this question by comparing the perceptual spans of young deaf readers (age 7-15) and young hearing children (age 7-15). Young deaf readers, like deaf adults, were found to have a wider perceptual span relative to their hearing peers matched on reading level, suggesting that strong and early reorganization of visual attention in deaf individuals goes beyond the processing of simple visual stimuli and emerges into more cognitively complex tasks, such as reading.

Keywords: Beginning Readers, Deaf Readers, Perceptual Span, Word Processing Efficiency

Word count: **5008**

Illiteracy rates in the deaf population have been extremely high for decades (Kelly & Barac-Cikoja, 2007). The main explanation for their low reading levels is that auditory deprivation prohibits young deaf children from accessing spoken language forms. Deaf children are at a disadvantage when learning to read a language they cannot hear and often have not fully mastered, as opposed to hearing children who constantly hear and produce such linguistic input. Deaf children in the U.S. have a smaller English vocabulary and more difficulty comprehending complex syntactic structures relative to their hearing peers (Kelly & Barac-Cikoja, 2007, for a review; Quigley, Wilbur, Power, Montanelli & Steinkamp, 1976). When learning to read alphabetical languages, deaf children have no way to fully grasp the specific associations of sounds (that they have partial or no access to) to letters. Because phonological processing plays a central role in read acquisition for hearing readers, much research on deaf readers has focused on whether or not they activate phonological representations when reading, and whether such abilities determine reading skill (Daigle & Armand, 2008; Hanson & Fowler, 1987; Perfetti & Sandak, 2000). While these questions still dominate the field (Emmorey, McCullough & Weisberg, 2016; Hirshorn, Dye, Hauser, Supalla, & Bavelier, 2015), no consensus exists about the role of phonology for deaf readers, likely due to the heterogeneity of the population and to methodological differences across studies: some find phonological activation in deaf readers (Daigle & Armand, 2008; Transler, Gombert, & Leybaert, 2001) while others do not (Bélanger, Baum & Mayberry, 2012; Bélanger, Mayberry & Rayner, 2013; Cripps, McBride, & Forster, 2005; Waters & Doehring, 1990).

However, deaf individuals are a unique population in that they process the world and language through the visual channel (sign and spoken languages are perceived visually; see Kuntze, Golos & Enns, 2014). They may use different reading strategies than hearing readers in order to take advantage of the selective enhancements in visual cognition following auditory deprivation (Bavelier, Dye, Hauser, 2006 for a review). Specifically, research with attention-demanding tasks involving low-level visual discrimination of shapes presented centrally or peripherally demonstrate this enhanced perceptual/attentional span (Bavelier, et al., 2006). Such results raise a critical question: Does enhanced attention into the periphery also influence how deaf individuals read?

In hearing individuals, the study of eye movements during reading has yielded crucial information about visual, attentional, word-level, and sentence-level processing, and about the interplay between cognitive and oculomotor control during written-language processing (Rayner, 1998, review). Processing efficiency is indexed by *fixation durations* (how long the eyes linger before moving; 250 ms on average), *saccade lengths* (how far the eyes travel between fixations; 7-9 English characters on average), skipping rates (how often words are *not* fixated; about 30% of the time), *regression probability* (how often the eyes go back into the text; about 10-15% of the time (Rayner, 1998 for a review). Moreover, such research has established the size of the perceptual span (the region in which readers use and process visual information in order to guide their eye movements; McConkie & Rayner, 1975, see Rayner, 2014). Importantly, these measures are sensitive to several properties of language processing (e.g., frequency, predictability, word length), and to readers' individual differences, particularly reading speed and reading-level.

Recent research on deaf readers' eye movements has found two important distinctive characteristics of deaf readers, which open new questions about reading processes in this population (Bélanger & Rayner, 2015, review). First, using the moving window paradigm (McConkie & Rayner, 1975), a paradigm where some information in parafoveal vision is blocked (with a series of Xs or jumbled letters) preventing the access of information from the parafovea (see Rayner, 2014), Bélanger, Slattery, Mayberry and Rayner (2012) found that relative to skilled hearing readers, skilled deaf readers have a wider perceptual span. In skilled deaf readers, the perceptual span is equivalent to 18 characters to the right of fixation, wider than the average span of 14 characters for skilled hearing readers (Bélanger et al., 2012). In other words, skilled deaf readers grasped more low-level visual information during a single fixation and this affected their eye movement behavior during reading—they made longer forward saccades on average.

A second, related, set of findings shows that skilled deaf readers regress back in the text (i.e., reread) less often, skip words more often, and refixate words less often compared to reading-matched hearing participants (Bélanger & Rayner, 2015). Although we have observed this unique pattern of eye movement in deaf readers (Bélanger & Rayner, 2013; Bélanger, Mayberry & Rayner, 2013), it is not yet clear exactly which processes underlie the effects we find. Bélanger and Rayner (2015) proposed the *Word Processing Efficiency* (WPE) hypothesis, which suggests that deaf readers are "more efficient" than hearing readers at processing words (fixated and upcoming) within a single fixation (because they grasp more information extrafoveally), cancelling the need for a direct fixation or a refixation. They termed this behavior "efficient" because deaf readers did not have to reread the text as often as hearing readers to support equivalent comprehension (accuracy to comprehension questions in the tasks equaled 90%+ for skilled hearing and skilled deaf readers). Surprisingly, less-skilled adult deaf readers (grade 5 reading level) read slower than skilled hearing and skilled deaf adult readers (11-12th grade reading level), but crucially they showed skipping, refixations, and rereading patterns that were similar to skilled hearing readers, suggesting present but weaker patterns of WPE (Bélanger

& Rayner, 2105). The WPE for deaf readers could be explained by (1) *visual processing enhancements* (faster or earlier processing of visual information), (2) *linguistic processing adaptations* (more direct links between orthography and semantics), or 3) a mix of these factors. A visual account of WPE derives from selective enhancements in visual processing or visual attention found in deaf individuals (Bavelier et al., 2006; Bottari et al., 2010; 2012; Emmorey, 2002). Within the linguistic domain, WPE could mark an alternative division of labor during word processing, where phonology is bypassed (or less critical; see Bélanger, et al., 2012; Bélanger et al., 2013), and where skilled deaf readers show greater orthographic sensitivity and/or faster connections between orthographic and semantic representations compared to hearing readers (Hirshorn et al, 2015). More research is needed to confirm whether WPE is indeed explained by one of these points.

Research on beginning hearing readers suggests that their eye movement behavior changes as they become more proficient readers; they make fewer fixations and regressions within a sentence along with shorter fixations (Blythe, 2014, review; Rayner, 1986). Certain oculomotor control processes are already well-developed by the time children finish the first grade, such as rapid visual information encoding during a fixation (Blythe, Liversedge, Joseph, White & Rayner, 2009), saccade targeting towards the middle of words (Joseph, Liversedge, Blythe, White, Gathercole & Rayner, 2009), and the asymmetrical properties of the perceptual span (Rayner, 1986). Recent research shows that beginning readers' perceptual span expands around grade 2 and 3 (Häikiö, Bertram, Hyönä & Niemi, 2009; Sperlich, Meixner & Laubroch, 2016), and reaches adult-size around around grade 6 (Rayner, 1986).

Finally, in addition to the factors noted above, the results of Bélanger et al. (2012) showing an enhanced perceptual span in adult deaf readers suggests that auditory deprivation and its related selective enhancements in the visual-attentional domain also exert an influence on the size of the perceptual span. This may be related to the finding in the non-reading literature showing that individuals who are born profoundly deaf allocate greater attentional resources towards the parafovea relative to hearing participants (Bosworth & Dobkins, 2002; Proksch & Bavelier, 2002). This is due to auditory deprivation rather than to exposure to sign language because greater attentional resources into the visual periphery was only found for deaf signers, but not for hearing individuals who were native signers (Bavelier, Brozinsky, Tomann, Mitchell, Neville, & Liu, 2001). Crucially, Dye, Hauser and Bavelier (2009) also found increased levels of attentional allocation in the periphery in deaf children (11-17 year olds) relative to hearing children. Therefore, an open question is whether enhanced allocation of attention to the periphery leads to an enhanced perceptual span and more efficient reading patterns in young deaf readers.

To investigate this, we used the moving-window paradigm and varied window sizes to the right of fixation to determine how far out to the right young deaf readers can project their attentional resources during reading. In line with the findings of a wider span for the deaf adults, and with Dye et al.'s (2009) findings of early adaptation of visual attention in the periphery by deaf children, we expected to find larger perceptual spans for young deaf readers relative to their hearing counterparts of similar ages or reading levels. A secondary goal of the paper was to explore whether evidence of WPE can also be found in young deaf readers' eye movement patterns. In order to fill this important gap in the literature, we compared young hearing and young severely to profoundly deaf readers' perceptual span and general eye movement behavior during reading.

Methods

Participants

Twenty-seven deaf participants were recruited from the California Schools for the Deaf in Riverside and in Fremont, along with 33 hearing participants, recruited via Craigslist. One deaf participant was removed from the analyses because her reading speed was remarkably fast compared to her peers (495 words per minute; 1.5 standard deviations above the mean); two other participants were removed because of low accuracy (< 70% accuracy) in the comprehension questions included in the experimental reading task, resulting in a final sample of 24 young deaf readers. The deaf participants were educated in a school where American Sign Language (ASL) is the language of instruction, and were all learning to read in English, thus they are all bilingual. All children were born deaf, the majority (19/26) were severely to profoundly deaf (hearing loss > 71dB in the better ear), three children had a loss of 70 dB in one ear, one child had a moderate loss in the better ear (65 dB), one child had a moderate to severe hearing loss in both ears (57-65 dB), and degree of hearing loss is missing for two siblings (their parent confirmed that hearing loss was severe to profound for both children). In large part, the children were born to deaf parents (22/26) and were exposed to ASL from birth or within their first year of life, and most had some exposure to English before entering school. However, all children had ASL as the dominant language in their daily life (as established via parental report). Only two deaf children were exposed to ASL after their first birthday (2 y.o. and 10 y.o.).

All hearing readers (n = 33) were also learning to read in English, and all had English as a first language. All participants had normal or corrected-to-normal vision and received financial compensation for their participation. These randomly sampled groups, though matched on age and on non-verbal IQ, were not matched on reading level (Table 1). The deaf readers read two grade levels below their age-matched peers, a historically persistent delay for this population

(Allen, 1986; Qi & Mitchel, 2012).

The main goal of this paper, however, was to investigate eye movement patterns of hearing and deaf readers matched on reading level (following Bélanger et al., 2012). Thus, we present analyses for a subset of participants matched on reading-level to establish a baseline of eye movement characteristics for young readers who are equally skilled. We matched 13 hearing (labelled "Hmatch") and 13 deaf readers (Dmatch) on their reading comprehension score on a standardized reading test (see below). The groups did not significantly differ on age, though the deaf readers were 10 months older than the hearing readers (Table 1). Because of the large discrepancy in reading levels between the two full groups of participants, we matched on reading level (4th grade-level) rather than by age. We could not match these two subsets on non-verbal IQ, but we used the remaining hearing and deaf participants who were not matched as comparison groups to form two more groups to investigate the contribution of these factors. Four older (14-15 y.o.) hearing participants were removed from the analyses for group-matching purposes. A group of skilled hearing readers (labelled "SKH") who read at a higher level (n=16), was matched on NVIQ to the Dmatch group, and a group of less-skilled deaf readers (n = 11; "LSKD") who had lower reading skills was matched on NVIQ to the Hmatch group (see Table 1).

[Insert Table 1 here]

Background Assessments

Reading level was assessed with the *Peabody Individual Achievement Test-Revised* (PIAT-R; Markwardt, 1989), a normed reading comprehension test where participants match sentences to pictures. The graded difficulty in vocabulary items and syntactic structures provide a comprehensive measure of lexical-semantics and syntax during reading. The testing was stopped when children made five errors within seven consecutive trials.

We assessed the children's non-verbal IQ with the Block Design subtest from the Wechsler Abbreviated Scale of Intelligence – 2nd Edition (WASI-II; Wechsler, 2011). Children saw increasingly complex shapes in a booklet and were required to recreate the shapes with red and white blocks. The test was terminated after two consecutive errors. The maximum score for children 7-8 years old is 57, whereas it is 71 for the older children.

Stimuli

Children read 60 single-line sentences containing between 9 and 16 words that are familiar to children. Eighty-five percent of the words were from the thousand most-frequent words produced by children between 5 and 7 years old (*VocabProfile-kids*; Cobb & Roessingh, 2008), suggesting that the vocabulary used should be accessible to our youngest readers. An additional 7% of the words were proper names used in the sentences, for a total of 92% of very easily accessible words to the youngest readers in our sample. We avoided complex syntactic structures to ensure maximum reading comprehension across all children (e.g.: one independent clause, or two independent clauses joined by a conjunction).

Apparatus

An Eyelink 1000 Plus eyetracker (sampling rate of 1000Hz; SR Research, Kanata, Canada) was used in desktop mode to record children's eye movements while they read on a computer screen. Participants sat 60 cm from a 20" HP p1230 CRT monitor (refresh rate of 150Hz, screen resolution of 1024 x 768) on which they read sentences. They were presented with the UMass *Eye Track 0.7.10h* software (Stracuzzi & Kinsey, 2006), in black, 15pt, fixed-width

Consolas font, on a light gray background to attenuate glare. One degree of visual angle comprised 3.8 characters.

Viewing was binocular, but only the right eye was recorded. Head movements were minimized with a chinrest and a headrest for greater tracking accuracy. Display changes for the moving window were completed quickly, on average within 4 ms (range = 0-7 ms) after the camera detected the eye crossing an invisible boundary (placed after each letter, because of our letter-based manipulation of window sizes).

Design and Procedure

Participants read unmasked sentences (control condition labelled "no window") or masked sentences where the number of visible characters to the right of fixation was manipulated, showing either 2, 6, 10, 14 or 18 characters (labelled W2, W6, W10, W14, and W18). Only the rightward window sizes were manipulated and four letters to the left of fixation were visible in all masked conditions. The words beyond the window of visible text were replaced with lowercase *x*'s (also replacing the spaces between words; see Fig.1). As the eyes moved along the sentence, the window of visible text followed the gaze and upcoming characters were revealed and previous characters were replaced with *x*'s. The baseline condition served to determine regular eye movement behavior in our participants. The different window size conditions were presented in random order to the participants (i.e. not blocked). We used the most limiting version of the moving-window paradigm where the spaces between words, an important clue used to help correctly target saccades, are blocked, in order to replicate the methods from our research with adults (Bélanger et al., 2012). This paradigm also allows us to determine the fullest expansion of extrafoveal attentional resources during reading.

[Insert Figure 1 here]

Upon arrival, participants completed the reading test, followed by the Block Design test. For the experimental task, participants were instructed, verbally (hearing) or in ASL (deaf), to read silently for comprehension, and to respond to yes/no comprehension questions by pressing one of two buttons on a gamepad. Following a 3-point calibration procedure (ensuring eye position errors were less than 0.3^{O}), the participants read eight practice sentences (with four comprehension questions), and then read the 60 experimental sentences, which were counterbalanced across participants and conditions. To ensure high tracking accuracy, the eyetracker was recalibrated whenever the experimenter noticed drifting of the gaze relative to the prior calibration values (error above 0.3^{o} of visual angle). To verify comprehension during the reading task, questions were presented after 38% of the experimental sentences. Both groups had high levels of comprehension on these questions (Table 1).

Analysis

We analyzed reading rate (calculated in words per minute – wpm) as a function of group and window size. Reading rate is a composite measure that has been traditionally used in moving-window experiments to determine the size of the perceptual span. It includes the number and duration of fixations across the sentence. In order to determine whether young deaf readers also show patterns of word processing efficiency, we also analyzed group differences for forward saccade length as a function of group and window size, and number of regressive fixations per group. The forward saccade length measure also serves as an indicator of how much information is grasped within one fixation as it is linked to the extrafoveal distribution of visual attention (Rayner, 1998).

Fixations shorter than 80 msec that were within one-character space of another fixation were combined with that fixation (< 2% of the fixations). Trials (complete sentences) in which there were 3 or more blinks were removed from the analyses (< 3% of the data). Additionally, outliers two standard deviations above the mean per participant and per condition were removed (< 3% of data for the WPM measure, ~4% for the forward saccade length measure, and, 5% for the number of regressive fixations).

We used the lme4 package to analyze the data (Bates, et al., 2015, which is available in the R environment (R Development Core Team, 2016). Because distributions of eye movement data are positively skewed, we analyzed the raw reading speed (wpm) and forward saccade length data using a Gamma distribution, and the raw number of regressive fixations using a Poisson distribution, with the *glmer* function in lme4 (see Lo & Andrews, 2015). The reported (absolute) *t*-values equal or greater than 1.96 indicate effects that are significant at the .05 alpha level.

A model was specified for each dependent variable where participants and items were specified as crossed random effects (Baayen, Davidson & Bates, 2008). For the reading rate and mean forward saccade length measures, fixed effects were set up with three successive difference contrasts (Venables & Ripley, 2002) to assess differences between pairs of groups, comparing LSKD to Hmatch, Hmatch to Dmatch, and Dmatch to SKH. Five successive difference contrasts were also setup to assess the effect of increasing window size (W2 vs. W6, W6 vs. W10, W10 vs. W14, W14 vs. W18, and W18 vs Baseline/No window). In this model, the interactions represent the increase between two given window sizes for a given pair of groups. Models with the maximal random structure did not converge due to overparameterization; therefore, we reduced the number of random effects using gradual model reductions followed by a likelihood ratio test to verify the best fit of the models to the data. All models presented were reduced to random intercepts for subject and for item. For the number of regressive fixations, we only present analyses by group, for brevity, but present the means as a function of group and window size in Table 4.

Results

On average, deaf children in the Dmatch group read much faster (248 wpm; *SD* = 124) than hearing children in the Hmatch group (178 wpm; *SD* = 72; *b* = 74.33, *t* = 8.33; Figure 2 and Table 2). The LSKH readers were much slower (129 wpm; *SD* = 58) than the Hmatch readers, (*b* = 51.68, *t* = 4.91), and the difference in reading speed between the Dmatch and SKH groups was non-significant (245 wpm; *SD* = 121; *b* = -18.01, *t* = -1.76) despite a difference of two grade levels in reading ability.

The increase in reading rate from W2 to W6 was significantly greater for the Hmatch group relative to the LSKD group (*b* = 18.81, *t* = 3.32). Crucially, the increase in reading speed was greater for the Dmatch group relative to the Hmatch group (*b* = 18.05, *t* = 3.15), but also for the Dmatch group relative to the SKH group (*b* = -24.81, *t* = -4.67). The increase from W6 to W10 was significantly greater for the LSKD relative to the Hmatch group (*b* = -21.07, *t* = -3.42), and also for the Dmatch relative to the Hmatch group (*b* = 21.03, *t* = 3.05). Three other interactions were significant, but are artifacts of a reading speed decrease in the W18 condition for the SKH and LSKD groups (see Table 2 for details). All other interactions were not significant (all |*t*s | < 1.60). The interactions between W2 and W6, and W6 and W10 suggest that, while they read faster overall, deaf readers in the Dmatch group were also more negatively affected by the smaller windows than hearing readers in the Hmatch and SKH groups were (Figure 2) and benefited more from increasing window sizes than other groups did.

Models of reading rate as a function of window size were run separately for each group of readers to unpack the interactions above and better estimate the size of the perceptual span for each group (in other words, to determine at which window size does reading speed reach asymptote). For deaf readers in the Dmatch group, reading rate significantly increased between W2 and W6 (*b* = 63.01, *t* = 8.89), and between W6 and W10 (*b* = 20.43, *t* = 2.36). The increases in reading rate were not significant between W10 and W14, W14 and W18, or between W18 and the baseline (no window) conditions (all *t*s < 1.77), suggesting that for these deaf readers reading speed reached asymptote with a window size of 10 characters to the right of fixations. For hearing readers in the Hmatch group, the only significant increase in reading rate was found between W2 and W6 (*b* = 52.67, *t* = 11.21), and reading rate plateaued for the remaining conditions (all *t*s < 1.37), suggesting that young hearing readers' spans extended only six characters to the right of fixation. Interestingly, the LSKD readers, reading two grade level below the hearing readers in the Hmatch group (and matched on NVIQ) showed a similar pattern of results to the Dmatch group (i.e. asymptote was reached with 10 characters to the right of fixation): reading rate significantly increased between W2 and W6 (*b* = 31.23, *t* = 6.63), and between W6 and W10 (*b* = 25.29, *t* = 4.24). The interactions between W14 and W18, and between W18 and the No Window condition were also significant for this group (*b* = -12.14, *t* = -2.06, and *b* = 20.40, *t* = 3.38, respectively); however, this is due to an unexplained increase in regressive fixations in the W18 condition, which slowed down reading speed relative to the W14 and the No Window conditions (see Table 4) for this group. We conducted a separate analysis to compare the reading speed for the LSKD group in the No Window condition relative to the W10 and W14 conditions separately and both comparisons were not significant (*b* = -3.28, *t* = -0.51, and *b* = -8.26, *t* = -1.30, respectively). Thus, the results for the LSKD group show that, just like the Dmatch group, they reach asymptote with a window size of 10 characters to the right of fixation. Note (Figure 2) that this reading speed decrease in the W18 condition is also visible (though not statistically significant) in the Hmatch group, and is also related to an increase in regressions in this condition (see Table 4). Finally, the better readers, the SKH group, performed just like the Dmatch and LSKD groups (the deaf participants): reading rate significantly increased between W2 and W6 ($b = 49.38$, $t = 10.45$), and between W6 and W10 ($b = 14.96$, $t = 2.64$). Reading rate plateaued for the remaining conditions (all *t*s < 1.37), suggesting that the SKH group has a perceptual span extending to 10 characters to the right of fixation.

[Insert Table 2 here]

There were no significant differences in mean forward saccade length between groups (see Tables 3 and 4); however several interactions were found between group and window size. A significant increase in saccade length was found from W6 to W10 between the Dmatch and Hmatch groups ($b = 0.68$, $t = 3.10$), and between the SKH and Dmatch groups ($b = -0.76$, $t = -3.57$). There were also interactions between W10 and W14 for the Dmatch and Hmatch groups ($b = 0.84$, $t = 3.36$), and for the SKH and Dmatch groups ($b = -0.52$, $t = -2.14$), again reflecting a greater increase in saccade lengths for the Dmatch group relative to the Hmatch and SKH groups. Finally, we also found a significant interaction between the LSKD and Hmatch group for the W14-W18 contrast ($b = 0.53$, $t = 2.06$) reflecting the greater increase in saccade lengths for the Hmatch group relative to the LSKD readers. Overall, these results suggest that the Dmatch group benefited more from increasing window sizes than the Hmatch and SKH groups. In other words, for the Dmatch readers, saccade targeting was more impeded with smaller windows than for the two groups of hearing readers.

[Insert Table 3 here]

Crucially, even if some deaf readers (Dmatch) grasped more information within one fixation relative to other groups, as shown in the forward saccade length analyses, this information was precise enough that it did not induce a significantly greater number of regressions back into the text for this group (Dmatch, $M = 2.3$; $SD = 2.9$). In fact, they regressed back in the text (i.e. reread) significantly less often relative to the Hmatch group ($M = 3.1$; $SD = 2.6$). The difference between the LSKD ($M = 4.2$; $SD = 3.1$) and Hmatch groups, and between the Dmatch and SKH ($M = 2.1$; $SD = 2.3$) groups were not significant (all $|t\text{s}| < 1.37$).

[Insert Table 4 here]

Discussion

The present experiment investigated whether young beginner deaf readers, like deaf adults, exhibit a wider perceptual span relative to hearing readers matched on reading level. Analyses between the four subgroups created from our sample reveal a wider perceptual span for a group of young deaf readers (Dmatch) when compared to young hearing readers matched on reading level (Hmatch; 10 characters vs. six characters to the right of fixation, respectively[1]). This increased perceptual span is related in part to the deaf readers making significantly longer forward saccades relative to reading-matched hearing children. Since attention shifts to the parafovea prior to a saccade being targeted to a specific location (Rayner, 1998; Miellet, O'Donnell & Sereno, 2009), our results can be attributed to greater attentional resources towards the periphery in young deaf children (Dye et al., 2009).

Young deaf readers (Dmatch) also read significantly faster and made longer forward saccades than hearing readers in the reading-level matched sample (Hmatch). This cannot be

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[1] Surprisingly, the size of the span for our hearing readers is smaller than what has originally been reported by Rayner (1986) for 4th grade children (whose span extended 11 character beyond fixation). This may be due to the fact that the window size variable was not blocked (cf. Rayner, 1986 in which blocking may lead to the adoption of reading strategies to deal with the experimental manipulation).

interpreted as evidence that young deaf readers adopt a “riskier” or more careless reading strategy because they did not make more regressions back into the text and still showed an equivalent level of comprehension in the experimental task. That is, young deaf readers read faster and made longer forward saccades, yet they did not need to go back more often in the text for adequate comprehension. This pattern of efficiency we find in young deaf readers parallels similar findings in adult deaf readers (which Bélanger & Rayner, 2015 termed “word processing efficiency”). Our deaf readers were 10 years old on average, suggesting that even when their reading system is evolving and has not yet completely stabilized, marked enhancements can be found relative to hearing readers matched on reading level

Reading speed has been shown to influence the size of the perceptual span (Rayner, Slattery & Bélanger, 2010), thus it could be surmised that the enhanced perceptual span we find here in the Dmatch group of participants is only an artifact of the deaf readers’ greater speed relative to the hearing readers or their markedly higher scores on the Block design task. However, these are unlikely considering that the LSKD’s perceptual span is similar to that of the SKH group and greater than that of the Hmatch group despite being much slower, reading at a lower grade level, and having a lower NVIQ score than both hearing groups. Thus, we suggest that it is the enhanced visual attention allocated to the periphery caused by auditory deprivation that drives the enhanced perceptual span, rather than merely reading speed or nonverbal IQ level.

In summary, deaf individuals experience selective visual enhancements as a result of early-onset deafness (Bavelier et al., 2006, review). They show enhanced extrafoveal attentional during discrimination of simple stimuli in the presence of foveally and parafoveally presented distractors as young as 11 years old (Dye et al., 2009). Among deaf adults this enhanced attentional allocation into the parafovea also translates to a wider perceptual span in reading compared to reading-level matched hearing adults (Bélanger et al., 2012). Our results show that enhanced extrafoveal attention recruited in complex cognitive processes, such as reading, also begins early in development and affects how deaf children develop reading skill before it is completely mastered. Finally, parallel to our findings with adult deaf readers, we find evidence of word processing efficiency (longer saccades leading to more skipped words and fewer refixations, as we find for adults), which may be due to faster processing of visual information, and/or to tighter orthography-to-meaning connections, in absence of phonological processing (Bélanger & Rayner, 2015).

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Figure Captions

Figure 1. Example of a moving window on three consecutive fixations. The asterisks represent 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 young hearing and young deaf readers. LSKD = less-skilled deaf readers, H-matched = hearing readers, D-matched = deaf readers, SKH = skilled hearing readers

Table 1. Participant characteristics.

Full sample (n = 57)	**Age (Range)**	**PIAT – Raw Score (Range)**	**Reading - Grade level equiv.**	**Block Design - Raw Score (Range)**	**Comprehe Question (Rang**
Deaf readers (n = 24)	10y 9 m (7-15 years)	54 (23-80)	Grade 3	22 (4-41)	92% (73-10
Hearing readers (n = 33)	10y 9m (7-15 years)	71 (34-95)	Grade 5	22 (2-47)	95% (75-10
	p = 0.74	p < 0.001		p = 0.69	p = 0.0
Four group sample (n = 53)					
Skilled Hearing Readers (n = 16)	11y.o. (7-15)	74 (34-95)	Grade 6	25 (2-47)	96% (83-10
Deaf RL-matched (n = 13)	10y 10m (8-13)	63 (50-80)	Grade 4	25 (9-41)	94% (73-10
Hearing RL-matched (n = 13)	9y 8m (8-12)	65 (53-84)	Grade 4	16 (4-31)	95% (75-10
Less-skilled deaf readers (n = 11)	10y 7m (7-15)	42 (23-57)	Grade 2	17 (4-30)	90% (73-9

Table 2. Group x Window Size results for Reading Rate (wpm; significant results are shown in bold).

	b	SE	*t-value*
(Intercept)	203.12	7.82	25.97
Hmatch-LSKD	**51.68**	**10.53**	**4.91**
Dmatch-Hmatch	**74.33**	**8.85**	**8.40**
SKH-Dmatch	-18.01	10.25	-1.76
Window6-Window2	**47.58**	**2.57**	**18.48**
Window10-Window6	**15.26**	**3.20**	**4.77**
Window14-Window10	-1.68	3.44	-0.49
Window18-Window14	-0.82	3.26	-0.25
NoWindow-Window18	**6.68**	**3.40**	**1.97**
Hmatch-LSKD X Window6-Window2	**18.81**	**5.66**	**3.32**
Dmatch-Hmatch X Window6-Window2	18.05	5.73	3.15
SKH-Dmatch X Window6-Window2	**-24.81**	**5.31**	**-4.67**
Hmatch-LSKD X Window10-Window6	**-21.07**	**6.15**	**-3.42**
Dmatch-Hmatch X Window10-Window6	**21.03**	**6.90**	**3.05**
SKH-Dmatch X Window10-Window6	-4.70	6.09	-0.77
Hmatch-LSKD X Window14-Window10	7.73	6.33	1.22
Dmatch-Hmatch X Window14-Window10	1.64	7.24	0.23
SKH-Dmatch X Window14-Window10	-2.38	7.38	-0.32
Hmatch-LSKD X Window18-Window14	11.27	7.06	1.60
Dmatch-Hmatch X Window18-Window14	**14.69**	**6.59**	**2.23**
SKH-Dmatch X Window18-Window14	**-14.95**	**7.21**	**-2.07**
Hmatch-LSKD X NoWindow-Window18	**-28.61**	**8.22**	**-3.48**
Dmatch-HmatchX NoWindow-Window18	10.32	9.71	1.06
SKH-Dmatch X NoWindow-Window18	7.21	9.74	0.74

LSKD = Less-skilled deaf readers, Hmatch = group of hearing readers matched to deaf readers on reading level, Dmatch = group of deaf readers matched to hearing readers on reading level, SKH = group of hearing readers with higher reading skills, but matched on matched on NVIQ and age to the Dmatch group. Significant t-values are bolded.

Table 3. Group x Window Size results for forward saccade length (significant results are in bold).

	b	SE	*t-value*
(Intercept)	6.60	0.23	28.63
Hmatch-LSKD	0.76	0.66	1.16
Dmatch-Hmatch	0.99	0.61	1.63
SKH-Dmatch	-0.34	0.56	-0.60
Window6-Window2	**1.50**	**0.06**	**24.22**
Window10-Window6	**0.81**	**0.08**	**10.55**
Window14-Window10	**0.47**	**0.09**	**5.49**
Window18-Window14	**0.27**	**0.09**	**2.92**
NoWindow-Window18	0.16	0.09	1.68
Hmatch-LSKD X Window6-Window2	0.05	0.18	0.30
Dmatch-Hmatch X Window6-Window2	0.11	0.18	0.65
SKH-Dmatch X Window6-Window2	-0.19	0.17	-1.11
Hmatch-LSKD X Window10-Window6	-0.07	0.22	-0.33
Dmatch-Hmatch X Window10-Window6	**0.68**	**0.22**	**3.10**
SKH-Dmatch X Window10-Window6	**-0.77**	**0.21**	**-3.57**
Hmatch-LSKD X Window14-Window10	-0.21	0.24	-0.88
Dmatch-Hmatch X Window14-Window10	**0.84**	**0.25**	**3.36**
SKH-Dmatch X Window14-Window10	**-0.53**	**0.25**	**-2.14**
Hmatch-LSKD X Window18-Window14	**0.53**	**0.26**	**2.06**
Dmatch-Hmatch X Window18-Window14	-0.19	0.27	-0.72
SKH-Dmatch X Window18-Window14	-0.36	0.26	-1.37
Hmatch-LSKD X NoWindow-Window18	-0.08	0.26	-0.31
Dmatch-HmatchX NoWindow-Window18	-0.10	0.28	-0.37
SKH-Dmatch X NoWindow-Window18	0.38	0.27	1.41

LSKD = Less-skilled deaf readers, Hmatch = group of hearing readers matched to deaf readers on reading level, Dmatch = group of deaf readers matched to hearing readers on reading level, SKH = group of hearing readers with higher reading skills, but matched on matched on NVIQ and age to the Dmatch group. Significant t-values are bolded.

Table 4. Means and standard deviations (in parenthesis) for number of regressive fixations and forward saccade length as a function of group and window size.

Number of regressive fixations

	W2	W6	W10	W14	W18	No Window
LSKD	4.0	4.4	3.6	4.1	5.0	4.4
	(2.9)	(3.1)	(2.8)	(2.9)	(3.7)	2.8)
Dmatch	2.1	2.1	2.2	2.7	2.2	2.5
	(3.0)	(3.2)	(2.6)	(3.8)	(2.4)	(2.3)
Hmatch	2.5	2.4	2.7	3.2	3.6	4.3
	(2.3)	(1.9)	(1.9)	(2.5)	(2.7)	(3.3)
SKH	2.1	1.8	2.1	2.2	2.4	2.3
	(2.4)	(2.3)	(2.4)	(2.4)	(2.5)	(1.9)

Forward saccade length

	W2	W6	W10	W14	W18	No Window
LSKD	3.5	5.2	5.9	6.3	6.4	6.5
	(1.0)	(1.2)	(1.4)	(1.5)	(1.9)	(1.9)
Dmatch	4.1	5.5	6.4	6.6	7.3	7.3
	(1.0)	(1.1)	(1.6)	(2.0)	(2.4)	(2.3)
Hmatch	4.2	5.9	7.3	8.4	8.8	8.8
	(1.1)	(1.3)	(1.9)	(1.8)	(2.3)	(2.2)
SKH	4.4	6.0	6.8	7.2	7.5	7.8
	(1.4)	(1.8)	(2.2)	(3.0)	(3.0)	(3.0)

LSKD = Less-skilled deaf readers, Hmatch = group of hearing readers matched to deaf readers on reading level, Dmatch = group of deaf readers matched to hearing readers on reading level, SKH = group of hearing readers with higher reading skills, but matched on matched on NVIQ and age to the Dmatch group.


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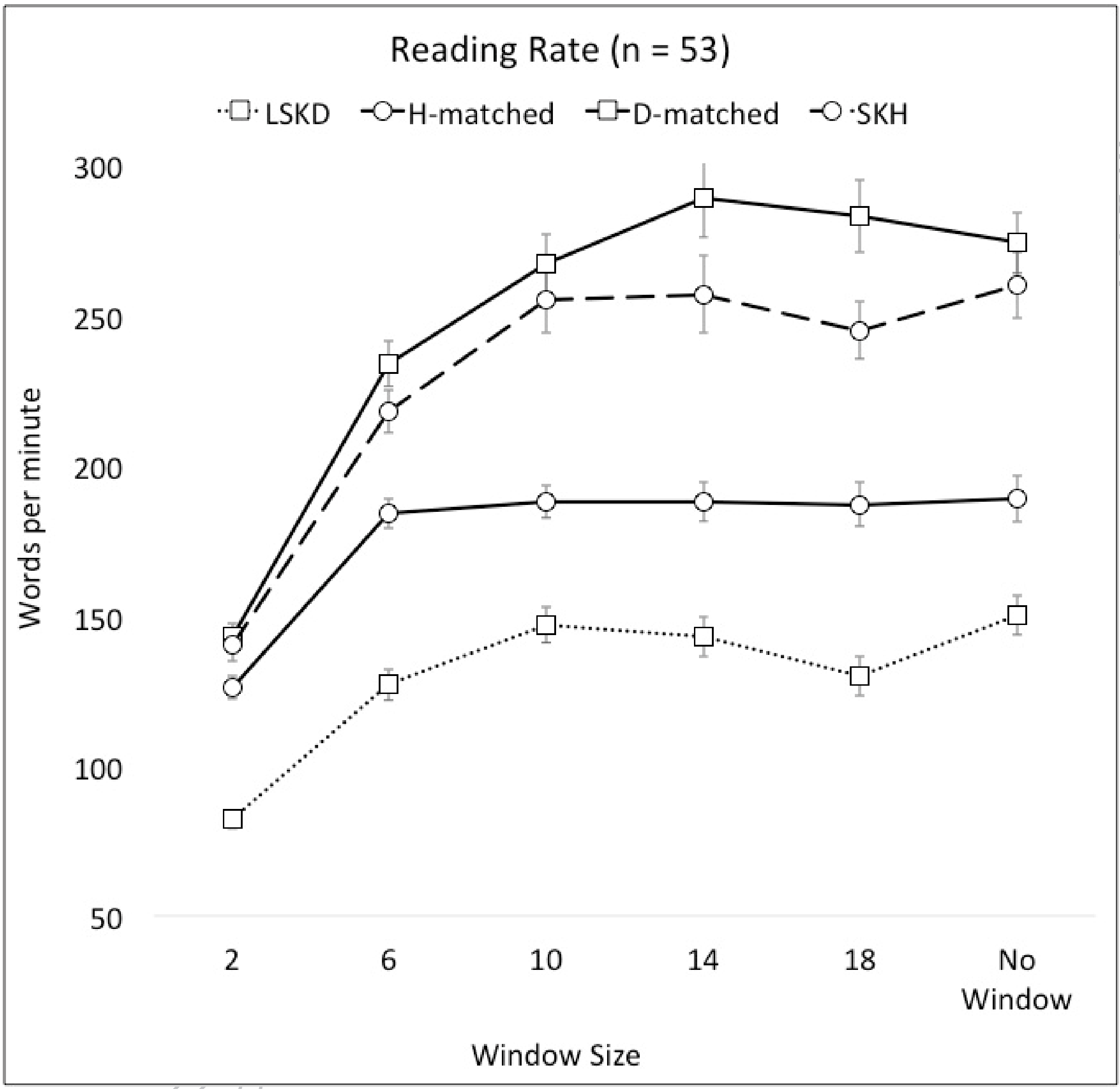
xxxxxxxxxle girl was hapxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx.
*
xxxxxxxxxxxxxxxxxwas happy to wixxxxxxxxxxxxxxxxxxxxxxxx.
*
xxxxxxxxxxxxxxxxxxxxxxxxxxxxto win the racexxxxxxxxxxxxxx.
Moving window
on three
consecutive
fixations
The little girl was happy to win the race last weekend.
Normal text


Reading Rate (n = 53)
LSKD
H-matched
D-matched
SKH
Words per minute
300
250
200
150
100
50
2
6
10
14
18
No Window
Window Size