Original Article

QJEP

Quarterly Journal of Experimental Psychology
1–13

DOI: 10.1177/17470218241232407
qjep.sagepub.com
Sage

Deaf readers use leftward information to read more efficiently: Evidence from eye tracking

Casey Stringer[1], Frances Cooley[1], Emily Saunders[2], Karen Emmorey[2] and Elizabeth R Schotter[1]

Abstract

Little is known about how information to the left of fixation impacts reading and how it may help to integrate what has been read into the context of the sentence. To better understand the role of this leftward information and how it may be beneficial during reading, we compared the sizes of the leftward span for reading-matched deaf signers ($n = 32$) and hearing adults ($n = 40$) using a gaze-contingent moving window paradigm with windows of 1, 4, 7, 10, and 13 characters to the left, as well as a no-window condition. All deaf participants were prelingually and profoundly deaf, used American Sign Language (ASL) as a primary means of communication, and were exposed to ASL before age eight. Analysis of reading rates indicated that deaf readers had a leftward span of 10 characters, compared to four characters for hearing readers, and the size of the span was positively related to reading comprehension ability for deaf but not hearing readers. These findings suggest that deaf readers may engage in continued word processing of information obtained to the left of fixation, making reading more efficient, and showing a qualitatively different reading process than hearing readers.

Keywords

Perceptual span; word identification span; deaf readers; eye movements; reading

Received: 25 April 2023; revised: 31 October 2023; accepted: 4 November 2023

It has been assumed that readers largely ignore information to the left of fixation and focus instead on text that has yet to be read.[1] Therefore, the vast amount of past research has investigated the spatial extent of readers' attention to rightward information (i.e., the size of the *rightward reading span*[2]) and concludes that a larger rightward span is associated with efficient reading. Little is known about whether attending to already read information (i.e., within the *leftward span*) might also allow for more-efficient reading. Information to the left of fixation could be useful for incorporating what has been read into the reader's understanding of the text and allow readers to move efficiently through the text by not needing to make backward eye movements (i.e., *regressions*) to re-process or continue to process previously seen text.

The extent of reading spans is studied with the gaze-contingent moving window paradigm, in which letters outside of a "window" are masked (McConkie & Rayner, 1975; See Figure 1a). Reading rates in each condition are compared to determine the span size—the smallest window in which reading does not significantly differ from normal reading (or the largest window with a significant improvement from the next smallest window; see Figure 1b). Because reading is not disrupted by the remaining information outside the window being masked, it is assumed that that information would not have been used by the reader anyway.

Although it is taken as a fact that rightward span extends 14 characters to the right and 4 characters to the left when reading English (McConkie & Rayner, 1975; McConkie & Rayner, 1976; Underwood & McConkie, 1985 see Rayner, 2014), the sizes of these spans are not uniform across individuals. For example, the rightward span is related to reading ability; its extent increases with reading speed (Rayner et al., 2010), increasing age or year in school (Meixner

[1]Department of Psychology, University of South Florida, Tampa, FL, USA
[2]Department of Psychology, San Diego State University, San Diego, CA, USA

Frances Cooley is also affiliated to Department of Liberal Studies, National Technical Institute for the Deaf, Rochester Institute of Technology, Rochester, NY

Corresponding author:
Casey Stringer, Department of Psychology, University of South Florida, 4202 E. Fowler Ave. PCD 4118G, Tampa, FL 33620, USA.
Email: cstringer@usf.edu

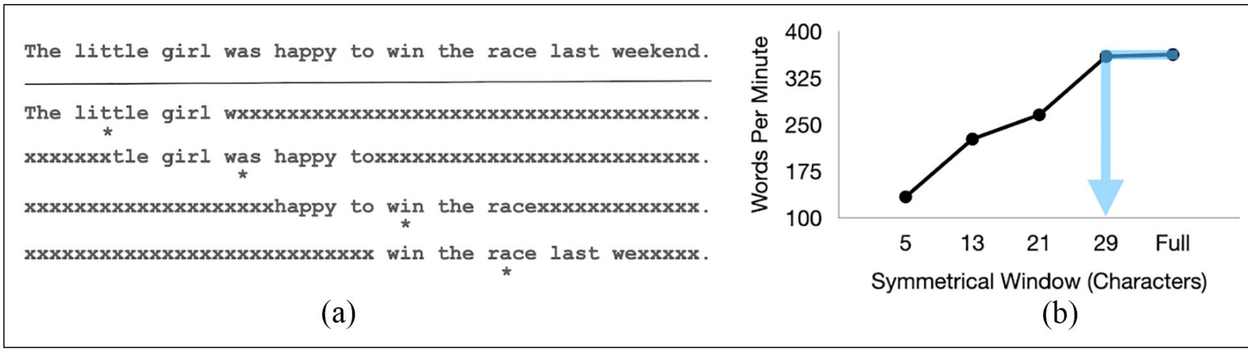

Figure 1. Example of the moving window paradigm (a) and relationship between the window size and reading rate (b). *Source.* Adapted from McConkie and Rayner (1975).

et al., 2022; Rayner, 1986; Sperlich et al., 2016; Sperlich et al., 2015), and even with increasing reading skill among college-aged readers (Choi et al., 2015; Veldre & Andrews, 2014). Again, less is known about how the extent of the leftward span is related to reading skill. However, a study by Veldre et al. (2021) examined the leftward span of older readers (M_{age} = 70.6 years) and compared that to the pattern they had observed in younger college-aged adults (M_{age} = 19.8 years) in a prior study (Veldre & Andrews, 2014). The older adults showed reading rate benefits when the visible window extended up to nine characters to the left, whereas the leftward span for the younger adults tested by Veldre and Andrews (2014) was only six characters. They also found a reduced extent of the rightward span for older compared to younger readers, suggesting that the difference in the leftward span was a shift in the symmetry of the distribution of the span, rather than a bilateral enhancement in the spans.

Veldre et al. (2021) suggested that the older readers' larger span was due to their use of *late confirmatory processes*—verifying their comprehension of what they had already read by attending to text to the left of their fixation, rather than making regressions. In fact, they found that as the leftward window size increased, both older and younger readers made fewer regressions, suggesting that this increased attention to leftward information may allow for processes that reduce the need for regressions. However, although the older adults had a larger leftward span, they also read more slowly and made more regressions overall, contradicting the claim that the leftward span may be related to reading efficiency. Furthermore, there was no relationship between reading proficiency and leftward span size for either the younger or older readers, even though reading proficiency was positively associated with rightward span size for both groups (Veldre & Andrews, 2014; Veldre et al., 2021). Thus, although leftward information is used to make reading more efficient by reducing the need for regressions, this characteristic may not necessarily be a hallmark of skilled reading for hearing people. Rather, it may be a strategic adaptation to cognitive demands on the reading system associated with aging (Rayner et al., 2006). Clearly, more investigation into the extent of the leftward span is needed, and comparisons between groups who are known to differ in the rightward reading span may be particularly revealing. One such group is deaf readers, who have been found to have a larger rightward span than their hearing counterparts who are matched on reading ability (Bélanger et al., 2012, 2018)

Deaf people navigate the world by using visual information (Kuntze et al., 2014), and deaf individuals are better at perceiving visual information in both directions in the periphery (Bavelier et al., 2001; Chen et al., 2006, 2010; Dye, 2016; Dye et al., 2007, 2009; Lore & Song, 1991; Neville & Lawson, 1987; Parasnis & Samar, 1985; Proksch & Bavelier, 2002; Seymour et al., 2017; Sladen et al., 2005; Stevens & Neville, 2006). Deaf signers also have a different linguistic experience because of their use of sign language; when viewing and comprehending signs, the face of the signer is mostly kept in central vision, while the signs may occur anywhere within the signing space, including above the head or down in front of the chest (Bosworth et al., 2019; Emmorey et al., 2009; Stoll & Dye, 2019). Fluent signers are therefore practised at extracting lexical information from outside of central fixation. Either or both these factors may influence their span size and lead them to utilise information differently in their reading process. Research with deaf readers may be particularly insightful for investigating the leftward span, as most signs in American Sign Language (ASL) are performed with the dominant hand, which for the majority of people is the right hand. Thus, when an ASL comprehender is watching a right-handed signer, the signs will often fall towards the left visual field because signers fixate on the face. This pattern suggests that signers are experienced in extracting lexical information to the left of fixation. It is possible that, in addition to extracting more information to the right of fixation than hearing readers, deaf signers may be more adept than hearing readers at extracting lexical information to the left of fixation during reading, which may make their reading process more efficient.

Previous research has reported larger rightward spans for deaf signers who are skilled readers, both children (Bélanger et al., 2018) and adults (Bélanger et al., 2012), than for their reading-level-matched hearing counterparts. The rightward spans extend up to 18 characters for skilled deaf adult readers and up to 10 characters to the right for skilled deaf child readers, an additional four characters relative to each groups' reading-level-matched hearing peers. The rightward spans of less-skilled deaf readers in both age groups were smaller than those of the skilled deaf readers and equivalent to those of the skilled hearing readers (Bélanger et al., 2018, 2012). To explain the enhanced spans of the skilled-reader deaf signers, Bélanger and Rayner (2015) proposed the *word processing efficiency hypothesis*, which states that deaf readers are more efficient at extracting linguistic information from visual input within one fixational pause. They argued that this increased efficiency not only explains their increased span sizes but also leads skilled deaf readers to read faster by skipping words more often and making shorter fixations, fewer regressions, and longer forward saccades (Bélanger et al., 2018, 2012; Traxler et al., 2021), which are characteristics of skilled readers (Rayner, 1998). Because deaf readers tend to make fewer regressions overall (Bélanger et al., 2018, 2012; Bélanger and Rayner, 2015), they may also engage in the late confirmatory processes described by Veldre et al. (2021) by attending to information to the left of fixation instead of making regressions. If deaf readers show an enhanced visual field on both sides during reading, as has been found in nonlinguistic tasks, this would suggest that they have a qualitatively different reading process compared to hearing readers, as their span size would be greater in both directions and perhaps nearly symmetrical, rather than the highly asymmetric span observed in hearing readers.

To date, only one study has examined the leftward span of deaf readers. Liu et al. (2021) studied deaf signers reading Chinese who were matched on age or reading ability with their hearing peers. Using the gaze-contingent moving window paradigm, in which both the left and right windows were manipulated, they found that the spans of deaf readers extended farther to both the right and the left. However, they did not separately analyse the leftward and rightward spans, making it difficult to make inferences about the leftward span on its own. While this study suggests that the leftward span of deaf readers is larger than that of hearing readers, the findings need to be replicated and investigated directly as these results may not generalise to reading alphabetic scripts.

Current study

Here, we investigate the size of the leftward span to determine how linguistic information from already read parts of the text is used, and we compare the size of the span between deaf signers and hearing nonsigners to determine whether the leftward span is adaptable to unique visual and linguistic experiences. We manipulated the size of the leftward span by masking the letters outside of a visible window, and we measured reading rate, saccade length, regression rate, and fixation duration. We compared these measures across window sizes and estimated the size of the leftward span as the window size at which participants did not improve in reading rate if a larger window was provided. As in the study by Veldre et al. (2021), we test the leftward word identification span (i.e., mask only the letters and not the spaces) to determine whether readers continue to attend to past text to perform linguistic processing, rather than to facilitate the targeting of regressions in the case that re-reading is necessary.[3]

We hypothesised that deaf readers would show a larger leftward span than hearing readers. Such a finding would support the premise that deaf readers engage in late confirmatory processes to make the reading process more efficient. If so, then we predict that they would also make fewer regressions than hearing readers, particularly in conditions with a larger leftward window size. If, however, no difference is found between the leftward span size of deaf and hearing readers, this would suggest that (a) deaf readers, similarly to hearing readers, have an asymmetrical span and rely mostly on rightward information to inform their reading process and (b) changes in visual attention experienced by deaf signers only impact the rightward reading span.

Method

Participants

We collected data from 108 participants, but because we were concerned with matching the two groups on reading ability, we excluded hearing participants in such a way that ensured the two groups did not significantly differ on this, as measured by the PIAT-R score (Table 1). We also collected data about their age, years of education, and accuracy answering comprehension questions in our experiment, which did not significantly differ between the groups (although deaf signers were slightly older, had slightly more years of education, and had slightly lower accuracy in our experiment). The final dataset used in the analysis reported below contained 72 participants, consisting of 40 hearing nonsigners recruited from the Tampa, FL, area and 32 deaf signers recruited from the San Diego, CA, and Austin, TX, deaf communities. The deaf participants were prelingually and profoundly deaf (dB loss of 70 dB or greater), used ASL as a primary means of communication, and were exposed to ASL before age eight. The hearing participants were native English speakers, had normal hearing, and had little to no knowledge of ASL. All participants were between the ages of 18 and 55, had normal or corrected-to-normal eyesight, were proficient

Table 1. Participant demographic information.

	Hearing	Deaf	*p* Value
PIAT-R score	85.15 (10.30)	85.09 (10.45)	0.98
Years in college	5.21 (2.93)	6.62 (3.21)	0.06
Age	30.55 (9.50)	34.09 (8.41)	0.10
Accuracy (percent)	91.97 (5.92)	88.59 (8.20)	0.06

This table shows the mean (with standard deviation in parenthesis) for demographic information, PIAT-R scores, and accuracy on comprehension questions of each group as well as the *p* value of the independent two-sample *t*-test comparing the two groups.

English readers, and had no history of reading or cognitive impairments. Participants were assessed on their reading comprehension ability via the Peabody Individual Achievement Test-Revised (PIAT-R; Dunn & Markwardt, 1989), in which they read single sentences and matched its meaning to one of four pictures.[4] The scores on this assessment were used to match hearing and deaf participants on reading comprehension and in the analysis of the relationship between span size and reading ability. Participants were compensated either with $10 per half hour of participation or course credit.

Power analysis

Previous studies with similar manipulations have found significant effects with 18 skilled deaf and 20 hearing participants with 33 items per window condition (Bélanger et al., 2012) and 24 hearing and 36 deaf participants with 20 items per window condition (Liu et al., 2021), so we aimed to test at least 24 participants in each group with 20 items per window condition. An a priori sensitivity analysis was conducted using the PANGEA analysis tool (Westfall, 2016) with a design that included two random factors (participants and sentences) and two fixed factors (participant group and window size), with the participant factor nested in the participant group factor and the sentence factor nested in the window size factor. Based on a sample size of 48 participants (i.e., an equal groups design with 24 hearing and 24 deaf participants) and 20 sentences per condition, we estimated that the minimum effect size (Cohen's d) that we could observe for the interaction between participant group and window size is 0.39 with power equal to 0.80. At the request of a reviewer, to increase power, we included more participants in the hearing group resulting in unequal sample sizes, and we included a greater number of deaf participants than we had determined in our a priori power analysis because we had continued collecting data as part of a larger project.

Materials and design

This experiment used a 2 (participant group) × 6 (window size) mixed factorial design. Windows were either presented normally (i.e., the full, no mask condition) or with a moving window, in which 1, 4, 7, 10, or 13 characters to the left were visible; outside of this window, letters were masked with "x"s, but spaces remained intact. For the moving window conditions, the rightward window extended out eight characters, as this represents the average span from which readers take in lexical information (Rayner, 1998; Rayner et al., 1982) to encourage readers to use information as they naturally would, rather than adapting their reading strategy to use more lexical information to the right in conditions where it was less available to the left. A total of 120 sentences were read as a part of this study, with 20 sentences in each of the six conditions, as well as a practice sentence at the beginning of the experiment.[5] Sentences were obtained and adapted from two studies—Schotter et al. (2015; $n=25$) and Plummer et al. (2015; $n=3$)—or otherwise written by members of the lab conducting the study to be natural, with low constraint (i.e., low cloze probability) and syntax that was not complicated ($n=92$). Sentences in all conditions were matched on average word frequency, average word length, reading level, sentence length, and complexity (see Table 2 for more details).

Equipment

Eye movements were tracked using either an SR Research Eyelink 1000plus eye tracker in desktop setup (1000 Hz; in Tampa and San Diego) or an SR Research Eyelink Duo eye tracker (in Austin), and stimuli were presented on an LCD monitor at a viewing distance of 65 cm, 85 cm, or 55 cm for participants in Tampa, San Diego, and Austin, respectively. A chin and headrest were used to minimise head movements. Viewing was binocular, but eye movements from only the right eye were recorded. Participants used a response pad to indicate when they finished reading the sentence and to respond to comprehension questions.

Procedure

Prior to the experimental session, participants gave their consent to participate in the study. They also completed the PIAT-R reading assessment and a demographics questionnaire containing information about age, gender, race, ethnicity, education, occupation, and knowledge of languages other than English. Deaf participants answered additional questions about their hearing level, age of ASL exposure, and ASL usage. Communication with the deaf participants was in ASL. Once participants arrived, they watched an instruction video (in either ASL or spoken English) describing the task. Eye tracker calibration was then performed with a three-point model until calibration error at each point was under 0.3 degrees of the visual angle. During the experiment, the sentences were presented on the screen in Courier New 14 pt. font in black, presented

Table 2. Descriptive statistics (mean with standard deviation in parenthesis) for the lexical characteristics of sentences in each condition.

Measure	Full	L1	L4	L7	L10	L13
Average word frequency (HAL: occurrences/4 Mil)	3,495,905 (782,836)	3,294,725 (1,124,575)	3,260,946 (950,631)	3,266,381 (844,598)	3,084,526 (821,468)	3,298,025 (831481)
Average word frequency (Log(HAL))	12.47 (0.49)	12.01 (0.61)	12.23 (0.72)	12.10 (0.63)	12.29 (0.66)	12.31 (0.60)
Average word frequency (subtitle: occurrences/Mil)	5,724 (1253)	5,115 (1340)	5,148 (1343)	5,193 (1176)	5,110 (1444)	5,254 (1278)
Average word frequency (Log [Subtitle])	4.36 (0.22)	4.17 (0.28)	4.38 (0.31)	4.29 (0.31)	4.40 (0.30)	4.32 (0.30)
Total number of characters	79.7 (4.24)	78 (3.84)	77.95 (2.93)	79.45 (4.20)	79.55 (3.28)	78.50 (3.53)
Total number of words	14.4 (1.54)	13.8 (1.51)	14.80 (1.54)	14.45 (1.43)	14.50 (1.64)	14.05 (1.57)
Average word length	4.70 (0.77)	4.84 (0.58)	4.44 (0.64)	4.66 (0.60)	4.41 (1.06)	4.75 (0.54)
Estimated reading level	8.4 (1.93)	8.88 (1.96)	7.40 (1.85)	8.45 (1.61)	8.20 (2.09)	8.85 (1.76)
Total number of clauses	1.8 (0.83)	1.50 (0.61)	1.55 (0.60)	1.7 (0.66)	1.80 (0.70)	1.40 (0.60)
Complex T-unit ratio	0.55 (0.51)	0.45 (0.51)	0.45 (0.51)	0.60 (0.50)	0.70 (0.47)	0.35 (0.49)

Measures of frequency and word length were determined using the English Lexicon Project (Balota et al., 2007), reading level was determined using the INK Reading Level Checker (INK Co., n.d.), and measures related to syntactic complexity were determined using the Haiyang Ai Web-based L2 Syntactic Complexity Analyzer (Lu & Ai, 2015).

on a grey background so that each character subtended 0.27 (in Tampa), 0.22 (in San Diego), or 0.32 (in Austin) degrees of visual angle. Participants first read sentences related to a larger study that were not analysed for this project,[6] then a block of sentences with no mask, followed by a practice sentence for this study, and then the experimental sentences. Each sentence was shown only once, and conditions were blocked such that window size increased with each block.[7] Within these blocks, the order of presentation of the sentences was randomised for each participant to prevent order effects. Yes/no comprehension questions were presented after 25% of trials to ensure participants were paying attention and reading for comprehension.

Results

First, all practice trials were removed. Fixations that were interrupted by the participant pressing the button to end the trial were excluded. Fixations greater than 80 ms were combined with the adjacent fixation (within one character space), and if not within one character space, they were excluded. Fixations greater than 800 ms were also excluded as is standard practice because they are determined not to reflect cognitive processing, similar to the fixations excluded for being too short. Trials with fewer than five fixations or more than 30 fixations were excluded from the analysis as this was interpreted as reflecting participants either skimming or continuing to look at the sentence after they had finished reading, respectively. Participants with fewer than 15 usable trials per condition (hearing $n=3$; deaf $n=2$) or those who had an accuracy of less than 70% on the comprehension questions (deaf $n=4$) were also excluded to ensure participants included were reading for comprehension and understood what they read. After exclusions, a total of 32 deaf and 40 hearing participants were included, with a total of 3,763 trials for deaf participants (97.99% of total) and 4,734 trials for hearing participants (98.63% of total).

We calculated four dependent variables on each trial. *Reading rate* (i.e., words per minute [wpm]) was measured as the number of words in the sentence divided by the sentence reading time (i.e., the number of milliseconds between when the sentence was first presented until the participant pressed the button indicating they had finished reading), which was divided by 60,000 (i.e., the number of milliseconds in a minute). *Percent regressions* were measured as the percentage of fixations on a given trial that were located on a word further to the left than the fixation immediately preceding it. For the calculation of this variable, fixations preceding a blink that began a saccade were excluded, as were fixations after a blink that ended a saccade. *Forward saccade length* was measured as the average across a trial of the number of characters between one fixation and the immediately preceding fixation, so long as the preceding fixation was further to the left than the current one. Fixations with blinks were excluded for this variable in the same manner as when calculating percent regressions. *Average fixation duration* was measured as the average duration (in ms) of all the fixations included on a trial, excluding fixations immediately before and immediately after a blink.

To analyse the data, we used (generalised) linear mixed-effects regression models using the lmer() function for linear models of reading rate and fixation durations and the glmer() function with the family set to Poisson for percent regressions and saccade length[8] from the lme4 package (Bates et al., 2015) within the R Environment for Statistical Computing (R Core Team, 2016). To investigate the effects of the window manipulation (see Table 3 for results), the fixed effects included participant group, four contrasts for the differences between window sizes, and the interactions between these comparisons and the participant group. The participant group was entered with a treatment contrast so that the baseline was the hearing group (coded as 0), and the deaf group (coded as 1) was compared to it. The window size factor was entered with successive difference contrasts so that the baseline was the average across all conditions and each contrast tested the difference between each consecutive window size (i.e., 4 vs. 1, 7 vs. 4, 10 vs. 7, 13 vs. 10). Thus, the tests for the main effects of window size are for the hearing group only, and the interaction tests whether the effects for a given contrast are larger for the deaf group than for the hearing group. The random effects included an intercept and slope of window size for participant (for all dependent variables) and an intercept for sentence for all dependent variables (and slope of participant group for reading rate and percent regressions).[9]

To test for the main effects of window size contrasts in the deaf group, another set of analyses were performed for just the deaf participants (see Table 4 for results), with four successive differences contrasts for window size as the fixed effects, and random effects for participant (intercept and slope for window size) and sentence (intercept only). The group differences in the full condition were analysed separately (see section "Full condition (normal reading)" below).

Reading rate

In the full model, the mean reading rate of the hearing group significantly increased from one character to the left to four characters to the left, but there were no significant differences for any of the larger window size comparisons, indicating that the leftward span for hearing readers extends up to four characters. There was no significant main effect of group, suggesting that the average reading rate across conditions did not differ between groups. None of the interactions were statistically significant, although the interaction between group and the difference between the 7- and 10-character conditions was marginally significant. In addition, the difference between the 7-character and 10-character conditions was significant for the deaf group (as was the difference between the one and four

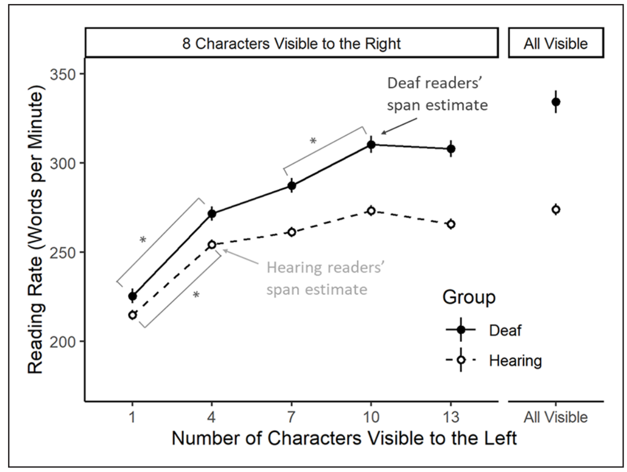

Figure 2. Reading rates (words per minute) of deaf and hearing groups at each window size.

condition) in the subset analysis that only included these participants (Table 4), indicating deaf readers have a word identification span extending up to 10 characters to the left (Figure 2).

Percent regressions

None of the comparisons between window sizes were significant for percent regressions for the hearing group, although there was a downwards trend in the number of regressions as the window size increased. There was also no significant main effect of group. Although the interactions between group and each window size comparison were not significant, there was a significant decrease in percent regressions from the four-character to the seven-character condition in the analysis for the deaf readers alone. No other changes in percent regressions between window sizes were significant (see Figure 3A).

Saccade length

The hearing readers showed no significant differences in saccade length across any windows. There was no significant main effect of group. No interactions between group and window size were significant. However, the deaf group showed small, incremental increases in saccade length at each successive window size. In the analysis for the deaf readers alone, there was a significant increase in saccade length when the window size increased from seven characters to 10 characters, as well as a marginally significant increase from one character to four characters (see Figure 3B).

Fixation duration

For the analysis of fixation duration, both hearing and deaf participants showed a significant decrease in fixation

Table 3. Results of linear mixed-effects models for the hearing group and the interaction between the two groups.

	Reading rate (wpm)				Percent Regressions				Mean saccade Length (characters)				Mean fixation Duration (ms)			
Predictors	*Est.*	*SE*	*t*	*p*	*Est.*	*SE*	*t*	*p*	*Est.*	*SE*	*t*	*p*	*Est.*	*SE*	*t*	*p*
(Intercept)	253.23	12.27	20.64	< **0.001**	6.99	1.21	11.25	< **0.001**	9.88	0.32	70.27	< **0.001**	229.71	4.89	47.00	< **0.001**
Group (deaf vs hearing)	26.69	17.99	1.48	0.138	0.72	0.18	-1.29	0.196	0.99	0.05	-0.27	0.784	2.07	7.30	0.28	0.777
Window: 4 vs. 1	40.41	10.29	3.93	< **0.001**	0.96	0.11	-0.36	0.715	1.02	0.02	0.93	0.350	-20.60	2.72	-7.56	< **0.001**
Window: 7 vs. 4	6.79	9.89	0.69	0.492	0.82	0.10	-1.68	0.092	1.00	0.02	-0.01	0.992	-4.10	2.41	-1.70	0.089
Window: 10 vs 7	12.18	9.03	1.35	0.177	0.96	0.09	-0.47	0.636	1.02	0.02	1.39	00.164	-2.73	2.08	-1.31	0.189
Window: 13 vs. 10	-7.74	8.70	-0.89	0.374	1.02	0.09	0.19	0.849	1.00	0.02	-0.10	0.920	2.44	2.04	1.20	0.232
Group × Window: 4 vs. 1	6.07	9.36	0.65	0.517	0.96	0.15	-0.25	0.804	1.02	0.03	0.68	0.499	-5.90	3.42	-1.72	0.085
Group × Window: 7 vs. 4	8.51	8.31	1.02	0.306	0.84	0.14	-1.00	0.319	1.01	0.03	0.33	0.741	3.43	2.84	1.21	0.228
Group × Window: 10 vs. 7	10.86	5.70	1.90	0.057	0.90	0.11	-0.87	0.386	1.02	0.03	0.68	0.495	-3.98	2.18	-1.83	0.068
Group × Window: 13 vs. 10	5.66	4.43	1.28	0.201	0.97	0.11	-0.28	0.782	1.02	0.02	0.91	0.363	-3.72	2.08	-1.79	0.074

Significant effects are shown in boldface.

Table 4. Results of linear mixed-effects models for the deaf group.

	Reading rate (wpm)				Percent Regressions				Mean saccade Length (characters)				Mean fixation Duration (ms)			
Predictors	*Est.*	*SE*	*t*	*p*	*Est.*	*SE*	*t*	*p*	*Est.*	*SE*	*t*	*p*	*Est.*	*SE*	*T*	*p*
(Intercept)	279.88	16.19	17.28	< **0.001**	4.92	1.09	7.17	< **0.001**	9.74	0.38	58.58	< **0.001**	231.78	7.14	32.47	< **0.001**
Window: 4 vs. 1	46.50	12.42	3.74	< **0.001**	0.90	0.11	-0.86	0.388	1.04	0.02	1.89	0.059	-26.51	2.97	-8.94	< **0.001**
Window: 7 vs. 4	15.27	11.21	1.36	0.173	0.70	0.09	-2.72	**0.007**	1.01	0.02	0.32	0.749	-0.67	2.47	-0.27	0.785
Window: 10 vs 7	23.03	10.22	2.25	**0.024**	0.83	0.12	-1.32	0.186	1.04	0.02	2.02	**0.043**	-6.69	2.44	-2.74	**0.006**
Window: 13 vs. 10	-2.07	9.64	-0.21	0.830	0.99	0.12	-0.08	0.940	1.02	0.02	0.93	0.352	-1.28	-2.01	-0.64	0.523

Significant effects are shown in boldface.

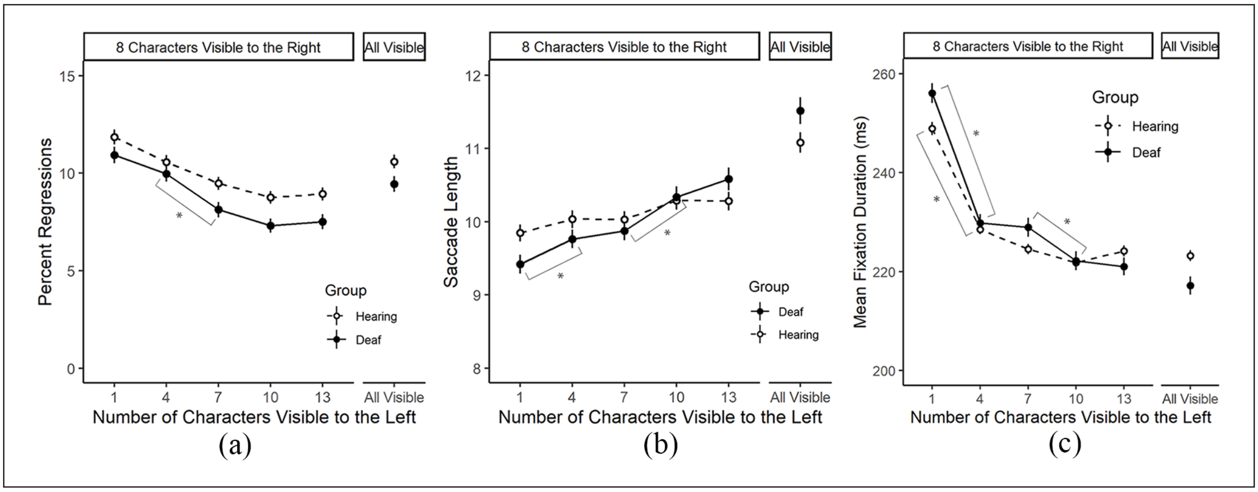

Figure 3. Results of the percent regressions (a), saccade length (b), and mean fixation duration (c) of deaf and hearing groups at each window size.

duration when the window size was increased from one character to four characters. The deaf readers additionally showed a significant decrease from 7 to 10 characters, mirroring the results of reading rate and saccade length such that information up to 10 characters allowed for more efficient reading (see Figure 3C).

Full condition (normal reading)

The full window condition was not included in the analyses described earlier because the rightward extent of the visible text also differed from the other conditions. To analyse the group differences for the full (normal reading) condition, we used (generalised) linear mixed-effects regression models as defined earlier, but using only the full window size condition and with group as the only fixed effect, and random effects for the intercept for participant (for all dependent variables) and the intercept and slope of group for sentence (for percent regressions).

Deaf readers read significantly faster than hearing readers ($M_{deaf}=336$, $SD_{deaf}=150$, $M_{hearing}=273$, $SD_{hearing}=72$; $b=63.15$, $SE=26.88$, $t=2.35$, $p=.02$), supporting the idea that deaf signers read more efficiently than their hearing counterparts (Bélanger et al., 2018, 2012; Bélanger & Rayner, 2015) The analysis of the fine-grained reading measures suggests that this may be related to a marginally reduced rate of regressions ($M_{deaf}=9.39$, $SD_{deaf}=7.58$, $M_{hearing}=10.70$, $SD_{hearing}=6.28$; $b=0.62$, $SE=0.15$, $z=-1.93$, $p=.05$), numerically longer but not statistically different forward saccades ($M_{deaf}=11.52$, $SD_{deaf}=3.51$, $M_{hearing}=11.04$, $SD_{hearing}=2.69$; $b=1.03$, $SE=0.06$, $z=0.53$, $p=.59$), and numerically shorter fixation durations ($M_{deaf}=217$, $SD_{deaf}=42$, $M_{hearing}=223$, $SD_{hearing}=21$; $b=-6.20$, $SE=7.52$, $t=-0.82$, $p=.41$).

The relationship between span size and reading comprehension

To examine the relationship between leftward span size and reading ability, we performed a linear regression to predict leftward span size based on group, PIAT score, and their interaction. Group was entered as a treatment contrast with the hearing group as the baseline, and PIAT score was entered as the z-score value for the participant's respective group. With this model structure, the intercept represents the span size estimate for a hearing reader with an average PIAT score, and the effect of group represents the difference in span size between average readers in each group. The effect of PIAT score represents the increase in span size for every increase in one PIAT z-score for the hearing group, and the interaction represents the difference in the slope of the relationship between PIAT and span size for the deaf group compared to the hearing group.

To estimate the leftward span size for each participant, we first performed a nonlinear mixed-effects regression analysis using the nlme() function from the nlme package (Lindstrom & Bates, 1990) with window size as the predictor variable and reading rate as the outcome variable. This analysis was used to fit an asymptotic curve to each participant's data and to derive asymptote and linear rate of change (lrc) values (Sperlich et al., 2016). From these values, we estimated the window size at which the participant's reading rate would reach 95% of their asymptote, which does not necessarily map on to a tested window size. Three participants (deaf $n=2$, hearing $n=3$) had to be excluded from this analysis as their reading rates in the largest window condition were lower than their reading rates in the smallest window condition, which prohibited the model from creating an estimate of their span size, which is derived from an asymptotic curve.

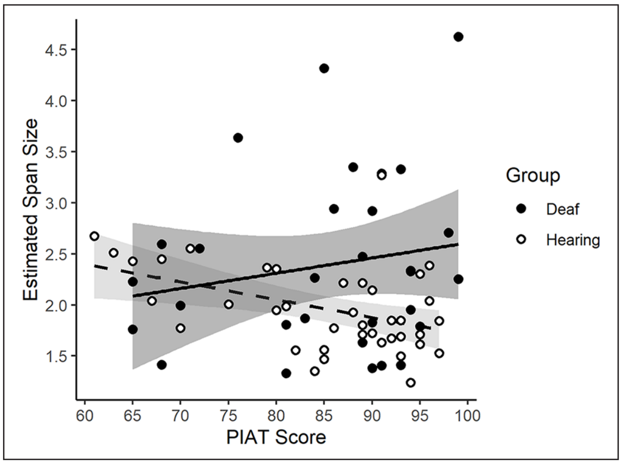

Figure 4. The relationship between participants' PIAT score and estimated span size.

For the linear regression predicting span size based on PIAT score and group, the effect of group was significant, showing that, on average, the deaf group had a larger span size. For the hearing readers, there was a marginally significant negative relationship between PIAT score and span size, suggesting that hearing readers with better comprehension had smaller spans. There was also a significant interaction between group and the effect of PIAT score on span size such that deaf readers showed the opposite pattern whereby deaf readers with better comprehension had larger leftward spans (see Figure 4, Table 5).[10]

Table 5. Results of the linear regression predicting span size as a function of group, reading comprehension score, and their interaction.

	Est.	*SE*	*t*	*p*
(Intercept)	**1.96**	**0.10**	**19.33**	**< 0.001**
Group (Deaf vs. Hearing)	**0.42**	**0.15**	**2.76**	**0.008**
PIAT Z-Score	-0.18	0.10	-1.76	0.084
Group × PIAT	**0.34**	**0.16**	**2.14**	**0.036**

Significant effects are shown in boldface.

Discussion

The purpose of this study was to investigate how information to the left of fixation may be used in reading by comparing the size of the leftward spans of deaf and hearing readers and exploring the relationship between reading ability and leftward span size. We found that deaf readers had a larger leftward span than hearing readers who were matched on reading ability. Specifically, deaf readers had an estimated span size of up to 10 characters to the left, whereas for hearing readers, the span extended only up to four characters. This result replicates and extends the increased leftward span found for deaf readers of Chinese (Liu et al., 2021) to an alphabetic script. Because the average word length in English is about eight characters (Balota et al., 2007), this result suggests that deaf readers actively process nearly an additional full word to the left as compared to hearing readers. The finding that deaf readers had a larger leftward span than hearing readers suggests that they read in a fundamentally different way, making use of information that hearing readers tend to largely ignore.

We also found an interesting difference in the relationship between reading comprehension ability and span size for the two groups. There was a significant interaction between PIAT score and group in the analysis predicting span size (see also supplementary linear mixed model analysis in the online Supplementary Material) whereby reading ability was negatively (but marginally) related to leftward span size for hearing readers, but the opposite trend was observed for the deaf signers. This interaction suggests that leftward information represents different things for deaf and hearing readers, with more skilled hearing readers tending to use less leftward information (see also Veldre & Andrews, 2014; Veldre et al., 2021), and more skilled deaf readers tending to use more leftward information. This result may indicate that, for hearing readers, reading skill is associated with a more asymmetrical, larger rightward span (Choi et al., 2015; Meixner et al., 2022; Rayner, 1986; Sperlich et al., 2015, 2016; Veldre & Andrews, 2014) and that attention to the leftward span is associated with an inefficient reading process. However, the findings for deaf readers suggest that more skilled readers use both rightward (Bélanger et al., 2012, 2018) and leftward information to read more efficiently. These different patterns strengthen the hypothesis that skilled deaf readers use a qualitatively different reading process compared to hearing readers.

It should be noted that the span estimates calculated for individual participants are smaller than the group estimates determined from the main analysis. Although we followed a procedure using nonlinear mixed-effects regressions via the nlme package reported elsewhere (Meixner et al., 2022; Sperlich et al., 2015, 2016), these methods are relatively new with respect to reading span research and have never been applied to study the leftward span. An advantage of the nlme approach is that it allows for an estimate of a span size that need not coincide with a tested window size condition, allowing for a more fine-grained estimate that may allow for more precision in an individual differences analysis. However, the way the nlme approach works is to fit an asymptotic curve to the condition mean data for each participant, and with only five conditions to use for this estimate, the curve fitting algorithm may be susceptible to an outlier for any of these individual means. Therefore, although the data from the participant-level analysis are broadly consistent with our group-level analysis (i.e., that deaf readers have a significantly larger leftward span than hearing readers), more work is needed to determine the most appropriate way to calculate the leftward span size for individual participants.

As discussed in the introduction, increased efficiency of deaf readers has been theorised to arise from deaf readers' efficiency at extracting linguistic information from visual input within one fixational pause (i.e., the word processing efficiency hypothesis; Bélanger & Rayner, 2015). This hypothesis has been used to explain deaf reader's faster overall reading rates, shorter fixation durations, higher skipping rates, lower regression rates, and larger rightward span. Our data extend this hypothesis and suggest that it may also explain their larger leftward span, if deaf readers not only extract information more efficiently from central vision and to the right of fixation but also use leftward information to continue processing and integrating word-level information into their understanding of the text.

Deaf readers read significantly faster and made numerically fewer regressions than hearing readers in the full condition, patterns that are similar to what was found in previous studies on English reading (Bélanger et al.,2018, 2012; Bélanger & Rayner, 2015) but not previous studies of the leftward span in deaf signers reading Chinese (see Liu et al., 2021). Because the reading characteristics of deaf signers are understudied, more work is needed to determine exactly which aspects of their reading process differs from that of hearing readers and the conditions that are necessary to demonstrate those differences.

With respect to the influence of window size on the fine-grained reading measures, the largest effect we observed for both groups was a severe impairment to reading when only one character was available to the left of fixation, which resulted in much slower reading rates and longer fixation durations (Figures 2 and 3c). A window size of one character would often include the currently fixated word, and this likely impacted the speed of recognising the fixated word. Interestingly, deaf readers exhibited a significant increase in forward saccade length when the window size was increased up to 10 leftward characters (similar to the pattern in reading rate), whereas the saccade length of hearing readers was unaffected (Figure 3b). Because the lexical information to the left of fixation appears to have no bearing on the saccade length of hearing readers, we infer that they do not use this information in saccade planning. Instead, they may exclusively use rightward information (which was not manipulated in this paradigm), as increases in rightward span size are associated with increased saccade length (Bélanger et al., 2012; Choi et al., 2015; Veldre & Andrews, 2014). In contrast, deaf readers appear to use lexical information to the left of fixation, such that when more information is available, they plan a saccade farther into the text. Deaf readers also decreased their regression rate when the leftward window size increased from four to seven characters, in contrast to hearing readers. This pattern suggests that when more information becomes available to the left of fixation, deaf readers are more likely to engage in late confirmatory processes (Veldre et al., 2021) or continued word identification, allowing for a reduction in regressions.

It is not clear whether deaf readers' larger leftward span is due to deafness, ASL use, or both. To tease these apart, future studies should compare deaf signers, deaf non-signers, hearing signers, and hearing non-signers. If the effects reported here are a consequence of deafness, we would see a larger leftward span for deaf readers (signers and non-signers) but not hearing readers (signers or nonsigners). In contrast, if these effects are due to ASL experience, we would see larger leftward spans for deaf and hearing signers, but not for deaf and hearing nonsigners. If the increased leftward span results from a combination of deafness and ASL experience, then we would see a graded pattern whereby deaf signers have the largest leftward span, hearing nonsigners have the smallest leftward span, and hearing signers and deaf nonsigners are in between those groups. It is possible that effects might be more likely to be due to ASL experience because of the inherent use of the leftward visual field in sign language comprehension and the need to extract lexical information from this area, but empirical data are necessary to determine this.

Overall our results suggest that, while reading, deaf adults attend to a greater amount of information that has already been processed (i.e., to the left of fixation), which we theorise helps them to read faster, plan longer forward saccades, and integrate words into the sentence without needing to make regressions. In contrast, hearing readers do not take advantage of leftward lexical information when reading; instead they must clear up ambiguities by breaking up the flow of their reading to regress back into the text. Together with the finding that deaf readers have larger rightward spans (Bélanger et al., 2012, 2018), our results suggest that deaf readers take in information farther from fixation than hearing readers in both directions. Therefore, information that has already been read, which was previously assumed to be unimportant for hearing readers, may be an important facet of reading for deaf signing individuals. Consequently, deaf signers' experiences outside of text reading, either communicating through sign or navigating the world visually, can impact how written language is processed. We conclude that deaf readers exhibit a qualitatively different and more efficient reading process than skill-matched hearing readers.

Acknowledgements

The authors thank Grace Sinclair for assistance with data collection.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: Our work was funded by the National Science Foundation (grants BCS-2120546 and BCS-2120507) and The Psi Chi International Honours Society (the 2021-22 Mamie Phipps Clark Diversity Research Grant).

ORCID iD

Casey Stringer https://orcid.org/0000-0003-3566-968X

Data availability

This study was registered with OSF (https://doi.org/10.17605/OSF.IO/VBECX). Trial-level data, stimuli, and the code used for analyses can be found here: https://doi.org/10.17605/OSF.IO/RN3G5

Supplementary material

The supplementary material is available at qjep.sagepub.com.

Notes

1. The current study investigates English, which is read from left to right. Therefore, we use the concept of "left of fixation" to refer to text that has already been read or skipped and "right of fixation" to refer to incoming text.
2. There are many terms to refer to the spans (e.g., perceptual span, attentional span, word identification span, span of effective vision, etc.). Here, we use general terms (e.g., reading span or span) to refer to the general concept and touch on the distinction between these spans and the specific one tested here in the current study section.
3. Past studies on deaf readers (Bélanger et al.,2018, 2012) used a manipulation in which both the letters in words and the spaces between words were masked outside of the visible window, conflating effects related to readers perceiving the visuo-spatial layout of the text (i.e., the *perceptual span*) and the orthographic information used to activate word meanings (i.e., the *word identification span*; Rayner, 1998).
4. The PIAT-R is a 100-item test of increasing difficulty, and we started at item 60 because we were testing adults. Items were scored up until the participant made five errors across seven items, at which point the last incorrect item was counted as the ceiling item, and the number of correct answers prior to this item were counted as the final score.
5. This study was run as a part of a larger study, and the full task included a total of 308 sentences.
6. The larger project investigates the rightward perceptual and word identification spans. Participants read sentences that had a perceptual span manipulation (i.e., spaces but not letters were masked), sentences that had a word identification span manipulation (i.e., letters but not spaces were masked), as well as sentences without a window manipulation.
7. This allowed for a more direct investigation of the impact of reading comprehension ability on individual differences between participants without the differences of presentation order.
8. The variable of saccade length, in characters, was rounded to the nearest integer for this analysis.
9. The slope for participant group was removed from the random-effects structure for fixation duration and saccade length because it was perfectly correlated with the random intercept for items.
10. In addition, we performed a supplementary analysis like the linear mixed model for reading rate reported earlier in which we included in the fixed effects the participant's PIAT score and interactions with window size and group. This analysis supports the conclusions reported here (see the online Supplementary Material).

References

Balota, D. A., Yap, M. J., Cortese, M. J., Hutchison, K. A., Kessler, B., Loftis, B., Neely, J. H., Nelson, D. L., Simpson, G. B., & Treiman, R. (2007). The English Lexicon Project. *Behavior Research Methods*, *39*, 445–459.

Bates, D., Maechler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, *67*, 1–48.

Bavelier, D., Brozinsky, C., Tomann, A., Mitchell, T., Neville, H., & Liu, G. (2001). Impact of early deafness and early exposure to sign language on the cerebral organization for motion processing. *Journal of Neuroscience*, *21*(22), 8931–8942. https://doi.org/10.1523/JNEUROSCI.21-22-08931.2001

Bélanger, N. N., Lee, M., & Schotter, E. R. (2018). Young skilled deaf readers have an enhanced perceptual span in reading. *Quarterly Journal of Experimental Psychology*, *71*(1), 291–301. https://doi.org/10.1080%2F17470218.2017.1324498

Bélanger, N. N., & Rayner, K. (2015). What eye movements reveal about deaf readers. *Current Directions in Psychological Science*, *24*(3), 220–226. https://doi.org/10.1177%2F0963721414567527

Bélanger, N. N., Slattery, T. J., Mayberry, R. I., & Rayner, K. (2012). Skilled deaf readers have an enhanced perceptual span in reading. *Psychological Science*, *23*(7), 816–823. https://doi.org/10.1177%2F0956797611435130

Bosworth, R. G., Wright, C. E., & Dobkins, K. R. (2019). Analysis of the visual spatiotemporal properties of American Sign Language. *Vision Research*, 164, 34–43. https://doi.org/10.1016/j.visres.2019.08.008

Chen, Q., He, G., Chen, K., Jin, Z., & Mo, L. (2010). Altered spatial distribution of visual attention in near and far space after early deafness. *Neuropsychologia*, *48*(9), 2693–2698. https://doi.org/10.1016/j.neuropsychologia.2010.05.016

Chen, Q., Zhang, M., & Zhou, X. (2006). Effects of spatial distribution of attention during inhibition of return (IOR) on flanker interference in hearing and congenitally deaf people. *Brain Research*, *1109*(1), 117–127. https://doi.org/10.1016/j.brainres.2006.06.043

Choi, W., Lowder, M. W., Ferreira, F., & Henderson, J. M. (2015). Individual differences in the perceptual span during reading: Evidence from the moving window technique. *Attention, Perception, & Psychophysics*, *77*(7), 2463–2475. https://doi.org/10.3758/s13414-015-0942-1

Dunn, L. M., & Markwardt, F. C. (1989). *Peabody individual achievement test-revised*. American Guidance Service.

Dye, M. W. (2016). Foveal processing under concurrent peripheral load in profoundly deaf adults. *Journal of Deaf Studies and Deaf Education*, *21*(2), 122–128. https://doi.org/10.1093/deafed/env054

Dye, M. W., Baril, D. E., & Bavelier, D. (2007). Which aspects of visual attention are changed by deafness? The case of the Attentional Network Test. *Neuropsychologia*, *45*(8), 1801–1811. https://doi.org/10.1016/j.neuropsychologia.2006.12.019

Dye, M. W., Hauser, P. C., & Bavelier, D. (2009). Is visual selective attention in deaf individuals enhanced or deficient? The case of the useful field of view. *PLOS ONE*, *4*(5), e5640. https://doi.org/10.1371/journal.pone.0005640

Emmorey, K., Thompson, R., & Colvin, R. (2009). Eye gaze during comprehension of American Sign Language by native and beginning signers. *Journal of Deaf Studies and Deaf Education*, *14*(2), 237–243. https://doi.org/10.1093/deafed/enn037

INK Co. (n.d.). *Reading grade level Checker Tool*. https://app.inkforall.com/reading-level-checker

Kuntze, M., Golos, D., & Enns, C. (2014). Rethinking literacy: Broadening opportunities for visual learners. *Sign Language Studies*, *14*, 203–224. http://doi.org/10.1353/sls.2014.0002

Lindstrom, M. J., & Bates, D. M. (1990). Nonlinear mixed effects models for repeated measures data. *Biometrics*, *46*, 673–687. https://doi.org/10.2307/2532087

Liu, Z. F., Chen, C. Y., Tong, W., & Su, Y. Q. (2021). Deafness enhances perceptual span size in Chinese reading: Evidence from a gaze-contingent moving-window paradigm. *Psych Journal*, *10*(4), 508–520. https://doi.org/10.1002/pchj.442

Lore, W., & Song, S. (1991). Central and peripheral visual processing in hearing and nonhearing individuals. *Bulletin of the Psychonomic Society*, *29*(5), 437–440. https://doi.org/10.3758/BF03333964

Lu, X., & Ai, H. (2015). Syntactic complexity in college-level English writing: Differences among writers with diverse L1 backgrounds. *Journal of Second Language Writing*, *29*, 16–27.

McConkie, G. W., & Rayner, K. (1975). The span of the effective stimulus during a fixation in reading. *Perception & Psychophysics*, *17*, 578–586. https://doi.org/10.3758/BF03203972

McConkie, G. W., & Rayner, K. (1976). Asymmetry of the perceptual span in reading. *Bulletin of the Psychonomic Society*, *8*(5), 365–368. https://doi.org/10.3758/BF03335168

Meixner, J. M., Nixon, J. S., & Laubrock, J. (2022). The perceptual span is dynamically adjusted in response to foveal load by beginning readers. *Journal of Experimental Psychology: General*, *151*(6), 1219–1232. https://doi.org/10.1037/xge0001140

Neville, H. J., & Lawson, D. (1987). Attention to central and peripheral visual space in a movement detection task. III. Separate effects of auditory deprivation and acquisition of a visual language. *Brain Research*, *405*(2), 284–294. https://doi.org/10.1016/0006-8993(87)90297-6

Parasnis, I., & Samar, V. J. (1985). Parafoveal attention in congenitally deaf and hearing young adults. *Brain and Cognition*, *4*(3), 313–327. https://doi.org/10.1016/0278-2626(85)90024-7

Plummer, P., Perea, M., & Rayner, K. (2015). *The influence of contextual diversity on eye movements in reading* [Data Set]. Keith Rayner Eye Movements in Reading Data Collection. UC San Diego Library Digital Collections. http://doi.org/10.6075/J0RF5RZ9

Proksch, J., & Bavelier, D. (2002). Changes in the spatial distribution of visual attention after early deafness. *Journal of Cognitive Neuroscience*, *14*(5), 687–701. https://doi.org/10.1162/08989290260138591

R Core Team. (2016). R: A language and environment for statistical computing. *R Foundation for Statistical Computing*. https://www.R-project.org/

Rayner, K. (1986). Eye movements and the perceptual span in beginning and skilled readers. *Journal of Experimental Child Psychology*, *41*(2), 211–236. https://doi.org/10.1016/0022-0965(86)90037-8

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, *124*(3), 372–422. https://doi.org/10.1037/0033-2909.124.3.372

Rayner, K. (2014). The gaze-contingent moving window in reading: Development and review. *Visual Cognition*, *22*(3–4), 242–258. https://doi.org/10.1080/13506285.2013.879084

Rayner, K., Reichle, E. D., Stroud, M. J., Williams, C. C., & Pollatsek, A. (2006). The effect of word frequency, word predictability, and font difficulty on the eye movements of young and older readers. *Psychology and Aging*, *21*(3), 448. https://doi.org/10.1037/0882-7974.21.3.448

Rayner, K., Slattery, T. J., & Bélanger, N. N. (2010). Eye movements, the perceptual span, and reading speed. *Psychonomic Bulletin & Review*, *17*(6), 834–839. https://doi.org/10.3758/PBR.17.6.834

Rayner, K., Well, A. D., Pollatsek, A., & Bertera, J. H. (1982). The availability of useful information to the right of fixation in reading. *Perception & Psychophysics*, 31, 537–550. https://doi.org/10.3758/BF03204186

Schotter, E. R., Bicknell, K., Howard, I., Levy, R., & Rayner, K. (2015). *Task effects reveal cognitive flexibility responding to frequency and predictability: Evidence from eye movements in reading and proofreading* [Data Set]. Keith Rayner Eye Movements in Reading Data Collection. UC San Diego Library Digital Collections. http://doi.org/10.6075/J0X63JTD

Seymour, J. L., Low, K. A., Maclin, E. L., Chiarelli, A. M., Mathewson, K. E., Fabiani, M., & Dye, M. W. (2017). Reorganization of neural systems mediating peripheral visual selective attention in the deaf: An optical imaging study. *Hearing Research*, *343*, 162–175. https://doi.org/10.1016/j.heares.2016.09.007

Sladen, D. P., Tharpe, A. M., Ashmead, D. H., Grantham, D. W., & Chun, M. M. (2005). Visual attention in deaf and normal hearing adults. *Journal of Speech, Language, and Hearing Research*, *48*(6), 1529–1537. https://doi.org/10.1044/1092-4388(2005/106)

Sperlich, A., Meixner, J., & Laubrock, J. (2016). Development of the perceptual span in reading: A longitudinal study. *Journal of Experimental Child Psychology*, *146*, 181–201. https://doi.org/10.1016/j.jecp.2016.02.007

Sperlich, A., Schad, D. J., & Laubrock, J. (2015). When preview information starts to matter: Development of the perceptual span in German beginning readers. *Journal of Cognitive Psychology*, *27*(5), 511–530. https://doi.org/10.1080/20445911.2014.993990

Stevens, C., & Neville, H. (2006). Neuroplasticity as a double-edged sword: Deaf enhancements and dyslexic deficits in motion processing. *Journal of Cognitive Neuroscience*, *18*(5), 701–714. https://doi.org/10.1162/jocn.2006.18.5.701

Stoll, C., & Dye, M. W. G. (2019). Sign language experience redistributes attentional resources to the inferior visual field. *Cognition*, *191*, 103957. https://doi.org/10.1016/j.cognition.2019.04.026

Traxler, M., Banh, T., Craft, M., Winsler, K., Brothers, T., Hoversten, L., Piñar, P., & Corina, D. (2021). Word skipping in deaf and hearing bilinguals: Cognitive control over eye movements remains with increased perceptual span. *Applied Psycholinguistics*, *42*(3), 601–630. https://doi.org/10.1017/S0142716420000740

Underwood, N. R., & McConkie, G. W. (1985). Perceptual span for letter distinctions during reading. *Reading Research Quarterly*, *20*, 153–162. https://doi.org/10.2307/747752

Veldre, A., & Andrews, S. (2014). Lexical quality and eye movements: Individual differences in the perceptual span of skilled adult readers. *Quarterly Journal of Experimental Psychology*, *67*, 703–727. http://doi.org/10.1080/17470218.2013.826258

Veldre, A., Wong, R., & Andrews, S. (2021). Reading proficiency predicts the extent of the right, but not left, perceptual span in older readers. *Attention, Perception, & Psychophysics*, *83*, 18–26. https://doi.org/10.3758/s13414-020-02185-x

Westfall, J. (2016). *PANGEA: Power analysis for general ANOVA designs* (working paper).