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The Role of Perceptual and Word Identification Spans in Reading Efficiency: Evidence From Hearing and Deaf Readers

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Theories of reading posit that decisions about "where" and "when" to move the eyes are driven by visual and linguistic factors, extracted from the *perceptual span* and *word identification span*, respectively. We tested this hypothesized dissociation by masking, outside of a visible window, either the spaces between the words (to assess the perceptual span, Experiment 1) or the letters within the words (to assess the word identification span, Experiment 2). We also investigated whether deaf readers' previously reported larger reading span was specifically linked to one of these spans. We analyzed *reading rate* to test overall reading efficiency, as well as *average saccade length* to test "where" decisions and *average fixation duration* to test "when" decisions. Both hearing and deaf readers' perceptual spans extended between 10 and 14 characters, and their word identification spans extended to eight characters to the right of fixation. Despite similar sized rightward spans, deaf readers read more efficiently overall and showed a larger increase in reading rate when leftward text was available, suggesting they attend more to leftward information. Neither rightward span was specifically related to where or when decisions for either group. Our results challenge the assumed dissociation between type of reading span and type of saccade decision and indicate that reading efficiency requires access to both perceptual and linguistic information in the parafovea.

Public Significance Statement
Our work shows that reading efficiency requires access to both perceptual and linguistic information in the upcoming text. In addition, skilled deaf readers have a unique reading profile hallmarked by faster reading rates, fewer skipped words, and less rereading of text without loss of comprehension. Deaf readers also attend more to information to the left of fixation, perhaps due to changes in visual attention that occur with early deafness and/or sign language experience.

Keywords: reading, eye movements, perceptual span, word identification span, deaf readers

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The process of skilled reading is so efficient that a typically hearing reader takes in information about twice as fast as they can comfortably take in spoken information (Rayner et al., 2016). This contrast is quite striking when considering that typically hearing children begin to make sense of spoken language at or before birth (Saffran et al., 1996), whereas formal reading instruction in the United States usually starts around 5 years of age. This developmental time course, along with findings suggesting that typically skilled hearing readers recode written text into a speech-based representation in order to access meaning (Castles et al., 2018; Leinenger, 2014), raises the question of how reading can be more efficient than another cognitive process upon which it depends. In addition, it raises questions about how readers who do not recode text into speech (i.e., congenitally deaf individuals who use sign language as a primary means of communication) are able to become skilled readers, and why those who are skilled readers end up reading more efficiently than their reading-level matched hearing counterparts (Bélanger et al., 2012, 2018; Bélanger & Rayner, 2015; Traxler et al., 2021).

One critical difference between reading and speech recognition is the opportunity to access multiple visual and linguistic elements simultaneously in central and parafoveal vision, which contributes to the efficiency of the reading process (Schotter et al., 2012; Vasilev & Angele, 2017). Access to parafoveal text may facilitate reading efficiency in at least two ways (Morris et al., 1990): (a) perception of the text's visuospatial layout can allow readers to effectively *plan saccades* (eye movements), leading to faster word recognition once they land on a word, and (b) perception of the orthographic form of parafoveal words can allow readers to *initiate word identification* prior to fixation. We investigated how these processes may contribute to reading efficiency in general, as well as the enhanced reading efficiency observed for skilled deaf readers, and thus how perceptual and linguistic experiences may shape the reading system.

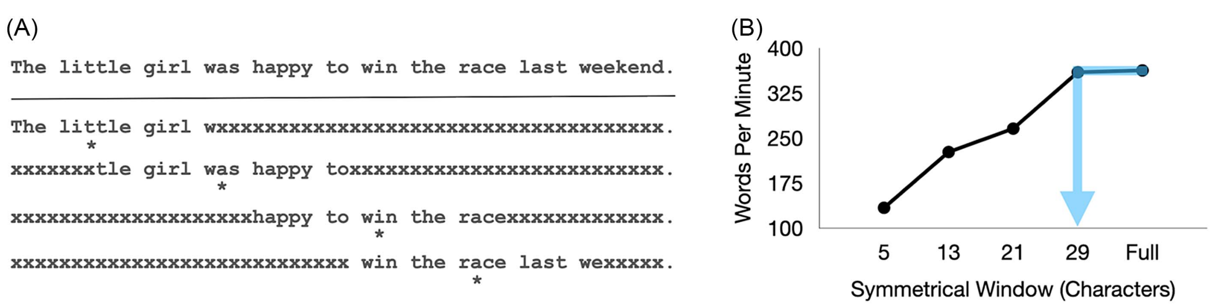
Dissociations Between the Perceptual Span and Word Identification Spans

Reading involves allocating attention across the text, and the size of this span is measured via the *moving window paradigm* (McConkie & Rayner, 1975), an eye-tracking paradigm in which only the text immediately around the reader's fixation location is available (Rayner, 1998, 2014). Outside of the visible window, the text is replaced by a mask, and the window moves instantaneously with the reader's fixation location, allowing them to control what they see at each moment within the window (Figure 1a). The reader's eye movement behavior is a direct indication of the ease of processing the text: When reading is easier, they read faster (i.e., more *words per minute—wpm*) because they make fewer and shorter eye fixations, longer saccades, skip over words more, and reread words less (Rayner, 1998). On different trials, the size of the window is varied so that these measures of reading efficiency can be evaluated for different amounts of visible text; the span size is indicated by the smallest window in which reading does not significantly differ from normal reading, or the largest window that shows a significant improvement from the next smallest window (Figure 1b).

It has long been claimed that readers have a wider *perceptual span* (the area from which they perceive the visuospatial features of the text, 14–15 characters to the right of fixation) than *word identification span* (the area from which they identify word meanings, seven characters to the right of fixation; Rayner, 1975, 1998, 2014; Rayner et al., 1982; Underwood & McConkie, 1985). The potential distinction between the perceptual span and word identification span may be related to a theoretical distinction between two different types of saccade decisions that are hypothesized to jointly contribute to reading: "when decisions" (i.e., timing decisions about how long the eyes should remain in place before an eye movement is executed) and "where decisions" (i.e., location decisions about which word or character within a word in the text to move the eye; Meixner et al., 2022; Rayner, 1998, 2009; Schotter & Rayner, 2015). This theoretical distinction is motivated by the fact that these aspects of the oculomotor system are governed by relatively autonomous systems (Findlay & Walker, 1999) and in the context of the reading process are impacted by different properties of the text (Morris et al., 1990).

The duration-based "when" decisions are mostly determined by linguistic information extracted from the text (e.g., lexical properties of words and contextual properties of the sentences in which those words are encountered; Heilbron et al., 2023). For example, readers fixate longer on low-frequency than high-frequency words (Chaffin et al., 2001; Inhoff & Rayner, 1986; Kliegl et al., 2004; Rayner & Duffy, 1986; Schilling et al., 1998; see Rayner, 2009) and longer on

Figure 1
The Moving Window Paradigm



Note. Panel a: Example of a symmetrical (i.e., bilateral) 21-character window that manipulates both the perceptual and word identification spans because both the spaces and letters are replaced with a mask outside of the visible window. Note the asterisk represents the location of the reader's fixation location. Panel b: The size of the span in skilled readers. See the online article for the color version of this figure.

Figure 2
Manipulations in the Moving Window Paradigm

The little girl was happy to win the race last weekend.	Original Text (indicates normal reading efficiency)
Thexlittlexgirlxwasxhappyxto win the racexlastxweekend. *	Filled Spaces Outside Window (assesses perceptual span)
xxx xxxxxx xxxx xxx xxxxx to win the race xxxx xxxxxxx. *	Replaced Letters Outside Window (assesses word identification span)

Note. (1) The original text; (2) the spaces are replaced with a mask (i.e., assesses the perceptual span; Experiment 1); and (3) the letters are replaced with a mask (i.e., assesses the word identification span; Experiment 2). The asterisk represents the location of the reader's fixation location.

unpredictable than predictable words (Balota et al., 1985; Carroll & Slowiaczek, 1986; Ehrlich & Rayner, 1981; Morris, 1994; Rayner & Well, 1996; Zola, 1984; see Staub, 2015). In contrast, the location-based "where" decisions are mostly determined by visuospatial aspects of the text (e.g., word length and spacing information; Heilbron et al., 2023). For example, readers make longer saccades approaching longer words than they do approaching shorter words, showing an effect of word length on saccade amplitude (O'Regan, 1979, 1980). This suggests that information perceived within the word identification span allows readers to determine how long they will remain on the currently fixated word, while information perceived within the perceptual span allows readers to determine where to move their eyes next.

However, these "when" and "where" decisions are not always cleanly dissociable in their sensitivity to different properties of the text. For example, although "when" decisions tend to be determined by lexical processing, some studies have found increases in first fixation duration, gaze durations, and total reading time when perceptual information was manipulated (i.e., the spaces between words were removed or replaced; McGowan et al., 2014; Paterson & Jordan, 2010; Rayner et al., 1998). Studies have suggested that the effect of perceptual manipulations on "when" decisions may be due to the adoption of a strategy governing the timing and location of eye movements to identify words within unspaced text (Mirault et al., 2019), or a disruption of lexical representations (thus reflecting interference with linguistic processes; Veldre et al., 2017). This latter claim is strengthened by Veldre et al.'s (2017) finding that readers with higher vocabulary and spelling ability (i.e., stronger lexical representations) were more resistant to detrimental effects of spacing manipulations.

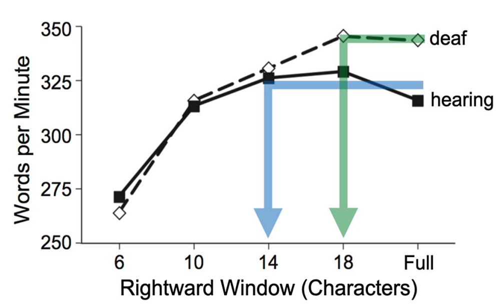
In order to determine whether the perceptual and word identification spans are unique, we propose that they must be assessed independently using different variations of the moving window paradigm (see Figure 2). To manipulate the perceptual span, the paradigm must *only mask the spaces between the words* outside of the visible window and therefore primarily disrupt the ability to accurately perceive the spatial layout of the text in a normally spaced language (i.e., English). Because the information about the letters is still available outside of the window, lexical information should still mostly be available to the reader in this version of the paradigm. To manipulate the word identification span, the paradigm must *only mask the letters within the words* outside of the visible window and therefore only disrupt the ability to accurately perceive the orthographic–linguistic information about a word from parafoveal vision. Because the information about the spaces between the words is still available outside of the window, perceptual information should still be available to the reader in this version of the paradigm. Because few studies have assessed the spans independently, it may be that the "perceptual span" that extends out to 14–15 characters to the right of fixation is actually not specifically the area from which readers extract information about the perceptual properties of the text, but rather the area from which they extract and integrate both visual and linguistic information.

Unique Spans in Deaf Readers

Although reading in a second language is associated with a reduced reading span (Whitford & Titone, 2015, 2016), deaf native/early signers of American Sign Language (ASL) who are skilled readers of English (i.e., a second language) have a span of 18 characters (Bélanger et al., 2012; Figure 3). This span size is four more characters than that of hearing readers with equal reading skill (Bélanger et al., 2012) and two more than the size reported for adults with higher than average reading skill (Choi et al., 2015; Veldre & Andrews, 2014).

Based on deaf readers' enhanced span, Bélanger and Rayner (2015) proposed the *word processing efficiency hypothesis*, which stated that deaf readers access word meanings directly from orthography (Mayberry et al., 2011; Sehyr & Emmorey, 2022) and bypass the phonological decoding process hearing readers use (Castles et al., 2018). Therefore, skilled deaf readers

Figure 3
The Size of the Perceptual Span in Skilled Deaf and Hearing Adult Readers



Note. Data are from readers matched on comprehension ability. "Skilled deaf readers have an enhanced perceptual span in reading" by N. N. Bélanger, T. J. Slattery, R. I. Mayberry, and K. Rayner, 2012, *Psychological Science*, *23*(7), 816–823 (https://doi.org/10.1177%2F0956797611435130). See the online article for the color version of this figure.

> Are extremely attuned to the visual-orthographic makeup of words and quickly detect precise word form, within a single fixation … even while words are still in the parafovea (as shown by the larger proportion of skipped words). (Bélanger & Rayner, 2015; p. 224)

This hypothesis has been used to explain deaf readers' increased span (Bélanger et al., 2012, 2018) and the fact that they *skip* words more often (i.e., move their eyes past them without stopping to fixate them; Bélanger et al., 2013; Bélanger & Rayner, 2013; Traxler et al., 2021). However, it is unclear whether this increased efficiency is the consequence of more efficient foveal processing during each fixation, or whether it implies that deaf readers begin preprocessing information in the parafovea before a word is fixated. Word skipping may reflect both parafoveal lexical processing (related to "when" decisions like fixation duration) and parafoveal perceptual processing (related to "where" decisions like saccade length). For example, visuospatial properties of the text, as well as lexical and contextual properties of words, can be obtained and processed in parafoveal vision, leading to those properties affecting word skipping decisions (Brysbaert et al., 2005; Brysbaert & Vitu, 1998; Kliegl et al., 2004; Rayner, 1998, 2009)—a decision that the word both requires no processing time during direct fixation and that the eyes should move past it in space (i.e., both "when" and "where" decisions). Therefore, word skipping may reflect the integration of perceptual and linguistic information, and it may be that deaf readers have a unique ability to perform this integration, which leads to their increased efficiency, particularly via increased skipping.

Although one of the most consistent findings in the literature on the eye movements of deaf readers is higher skipping rates compared to their hearing peers (Bélanger et al., 2013; Bélanger & Rayner, 2013; Traxler et al., 2021), the data on other fine-grained eye-tracking measures, which may be more cleanly dissociable between the two spans and saccade decisions, is mixed. Some studies find that deaf readers make significantly shorter fixations than their hearing counterparts (Traxler et al., 2021), whereas others find numerically shorter fixation durations that are not statistically significant (Bélanger et al., 2012, 2013; Bélanger & Rayner, 2013; Stringer et al., 2024; Yan et al., 2015). Likewise, some studies find that deaf readers make longer saccades, but these differences are not statistically significant (Bélanger et al., 2012, 2018; Stringer et al., 2024). Because Bélanger et al. (2012, 2018) manipulated the combined reading span (i.e., replaced both the letters and spaces outside the window with the mask), it is unclear whether deaf readers' enhanced spans are larger perceptual spans (i.e., they are better able to process visual information to plan saccades), larger word identification spans (i.e., they are better able to initiate word identification in parafoveal vision, prior to fixating on the word), or are the consequence of an ability to integrate perceptual and linguistic information obtained in the parafovea.

In addition, there is emerging evidence that deaf readers also have larger leftward spans than their hearing counterparts (Liu et al., 2021; Stringer et al., 2024). Using a manipulation of the leftward word identification span (i.e., masking the letters but preserving the spaces), Stringer et al. (2024) found that the leftward spans of deaf readers extended out to 10 characters. This contrasts with the size of the leftward span for their reading-level matched hearing peers, whose spans extended only to four characters to the left, replicating findings from prior studies that find minimal effects of masking leftward lexical information for hearing readers (Veldre & Andrews, 2014) and smaller effects compared to rightward masking (Rayner et al., 2014). Therefore, deaf readers may make use of leftward lexical information in a way that hearing readers do not; in particular, they may engage in continued lexical processing, leading to their faster reading rates despite their increased skipping. Deaf individuals have generally superior parafoveal/peripheral visual processing abilities (see Pavani & Bottari, 2012, for review); they demonstrate enhanced peripheral processing for simple stimuli like the location, orientation, and motion of dots and lines (Bavelier et al., 2001; Dye et al., 2009; Neville & Lawson, 1987), suggesting a general perceptual enhancement due to deafness may underlie an enhanced perceptual span in reading. However, the deaf participants in all past span studies were native or early signers who communicate primarily with a sign language (Bélanger et al., 2012, 2018; Liu et al., 2021; Stringer et al., 2024), leaving open the possibility of additional benefits to the word identification span attributed to experience with the visual processing demands of comprehending sign language. Therefore, it is reasonable to think that deaf signers' enhanced spans, faster reading rates, and higher skipping rates could be due to either enhanced parafoveal perceptual processing, enhanced linguistic processing in the parafovea, or potentially a combination of these two influences.

Like text, sign language allows for and requires the simultaneous perception of several *meaningful* linguistic features across the visual field (Dye, 2016; Stoll & Dye, 2019); central vision is used to perceive grammatical facial expressions while parafoveal/peripheral vision is used to perceive manual signs (e.g., Emmorey, Bosworth, et al., 2009; Siple, 1978). Sign comprehenders tend to fixate the signer's face to recognize linguistically meaningful facial expressions (Agrafiotis et al., 2003; Emmorey, Thompson, et al., 2009; Mastrantuono et al., 2017; Muir & Richardson, 2005) so that the majority of manual signs are perceived far away from fixation (e.g., ∼6.5° away from the eyes in ASL narratives; Bosworth et al., 2019). Despite this, signers are able to accurately perceive the visual components of signs (e.g., handshape) even when they are presented as far as 12° in the periphery, and their ability to do so is enhanced when the handshape is part of a meaningful sign compared to a pseudosign (i.e., there is a peripheral sign superiority effect; Schotter et al., 2020). Thus, while a reader fixates on one word, the words before and after it are available to them in a way that does not happen during speech, but does have parallels with sign recognition. The opportunity to perceive parafoveal linguistic elements is one proposed source of reading efficiency (Schotter, 2018), and experience distributing attention to meaningful elements in the parafovea/periphery during sign perception may prepare deaf readers to take advantage of this opportunity.

The Present Study

We conducted two experiments that systematically disentangled the perceptual and the word identification spans and compared the sizes of the spans between deaf and hearing readers. In Experiment 1, we investigated the perceptual span by masking the spaces between the words outside of a visible window, whereas in Experiment 2, we investigated the word identification span by masking the letters within the words outside of the visible window (see Figure 2). Based on prior research (see Rayner, 1998, 2009, 2014), we measured *reading rate* as an index of reading efficiency that incorporates all components of reading, and we hypothesized that the perceptual span of hearing readers would be 14 characters (i.e., they would show reading rate increases up to our 14-character window size, but not beyond; Experiment 1), and the word identification span would be eight characters (i.e., they would show reading rate increases up to our eight-character window size, but not beyond; Experiment 2).

If the perceptual and word identification spans are indeed unique and dissociable, we expected the manipulations in the two experiments to differentially affect different dependent variables, the "when" and "where" saccade decisions (see more details in the introduction to each experiment below). Therefore, we also measured *average saccade length* (an index of "where" decisions), which should be more affected than other eye-tracking variables by the perceptual span manipulation in Experiment 1, and *average fixation duration* (an index of "when" decisions), which should be more affected than other variables by the word identification span manipulation in Experiment 2.

With respect to deaf readers, we hypothesized that they would have wider spans than their reading-level matched hearing counterparts. Our two experimental manipulations will enable us to determine whether this enhancement is more related to the perceptual span and "where" decisions, the word identification span, and "when" decisions, or whether it is the consequence of an enhanced ability to integrate visual and linguistic information from outside of central fixation (see further discussion below).

Experiment 1: The Perceptual Span

The aim of Experiment 1 was to use a variation of the moving window paradigm that primarily disrupted the perceptual span by filling in the spaces between the words outside the visible window while mostly preserving the word identification span by leaving the identities of the letters visible outside of the window. We hypothesized that the perceptual span of hearing readers would be approximately 14 characters (McConkie & Rayner, 1975; see Rayner, 1998, 2014), based on the window size at which their reading rate significantly increased from the smaller window sizes but did not significantly increase beyond this window. Furthermore, because the window manipulations in this experiment should disrupt the ability to segment the text into word locations, and therefore the ability to appropriately plan saccades, we hypothesized that these manipulations would have a greater influence on the dependent variable of saccade length than fixation duration, because the former is hypothesized to be more related to "where" saccade decisions than "when" saccade decisions. If deaf readers' documented larger reading span is due to an enhanced perceptual span, their reading rate should increase for comparisons between window sizes that are larger than 14 characters. Further, this increase should be apparent not only in the analysis of reading rate but also saccade length. Because past research has suggested that the perceptual span only extends out to three to four characters to the left of fixation (McConkie & Rayner, 1976; see Rayner, 1998, 2014), we did not expect the reading rate of hearing readers to differ between the largest rightward window size and the full condition. If deaf readers obtain more perceptual information from the left of fixation (possibly due to heightened visual attention in the parafovea), they should show a decrease in reading rate for the largest window size condition compared to the full condition.

Method

Transparency and Openness

This study is part of a larger project and was preregistered in the Open Science Framework prior to data collection (https://doi.org/10.17605/OSF.IO/A8SYJ). The raw data and the scripts used to analyze the data have been made publicly available in the Open Science Framework, as well (https://doi.org/10.17605/OSF.IO/54ACX).

Participants

We collected data from 103 hearing participants from the Tampa, Florida, area and 44 deaf signers from deaf communities in Austin, Texas; San Diego, California; and Washington, DC. The hearing participants were native English speakers, had normal hearing, and had no knowledge of ASL. The deaf participants were prelingually and profoundly deaf (loss of 70 dB or greater),[1] used ASL as a primary means of communication, and were exposed to ASL before age 8. All participants were between the ages of 18 and 55, had normal or corrected to normal vision, were proficient English readers, and had no history of speech/language or cognitive impairments. Participants were compensated with either $10 per half hour of participation or course credit.

To be included in the final data set, all participants had to have at least 10 usable trials per condition, which led to the exclusion of two deaf participants. For the analyses reported below, we selected a subset of eligible hearing participants such that the two groups were matched (i.e., there was no statistically significant difference in an independent two-sample t test) on a number of assessments of cognitive and linguistic skills, including reading ability (PIAT-R score), nonverbal intelligence (Kaufman Brief Intelligence Test score), and spelling ability (Spelling Recognition score).[2] The deaf participants were, on average, about three and a half years older with two more years of education, but this is unlikely to account for any group differences (see General Discussion). These matching criteria led to a final data set that contained 42 deaf signers and 60 matched hearing readers[3] (see Table 1). We also measured accuracy in response to the comprehension questions in the experiment, which was similar between the groups and was overall quite high, suggesting that the participants were paying attention when reading the text.

Reading comprehension ability was measured via the Peabody Individual Achievement Test–Revised (PIAT-R; Dunn & Markwardt, 1989; test–retest reliability $r = .88$), which involves reading sentences and matching their meaning to pictures. Items were scored until the participant made five errors within seven consecutive items, at which point the last incorrect item was counted as the ceiling item and the

[1] Nine deaf participants had cochlear implants.

[2] For the deaf signers, we also measured their ASL comprehension ability (ASL-CT score) in order to ensure that they were proficient signers.

[3] Participants provided demographic information in a multiple choice questionnaire that included a question about gender with options for male (11 hearing; 24 deaf), female (49 hearing; 17 deaf), or prefer not to say (0 hearing; 1 deaf); a question about race with options for Black (7 hearing; 1 deaf), American Indian/Alaskan Native (1 hearing; 0 deaf), Asian (5 hearing; 0 deaf), Hawaiian/Pacific Islander (1 hearing; 0 deaf), White (37 hearing; 33 deaf), more than one race (7 hearing; 8 deaf), or unknown/decline to answer (2 hearing; 0 deaf); and a question about ethnicity with options for Hispanic or Latino (13 hearing; 6 deaf), not Hispanic or Latino (46 hearing; 36 deaf), or unknown/decline to answer (1 hearing; 0 deaf).

Table 1
Participant Information

Variable	Hearing (N = 60)	Deaf (N = 42)	p
English reading comprehension ability (PIAT-R score)	85.2 (9.90)	83.9 (10.59)	.53
Nonverbal intelligence (KBIT score)	38.7 (3.62)	37.5 (5.50)	.27
English spelling ability (spelling recognition score)	73.5 (7.3)	73.2 (9.93)	.84
Comprehension accuracy (from the experiments)	92.78 (5.40)	90.33 (6.83)	.06
Age (years)	29.7 (10.02)	33.3 (8.03)	.05
Education (years in college)	4.3 (2.96)	6.3 (3.21)	<.01
Sign language comprehension ability (ASL-CT score)		25.12 (2.89)	

Note. The values in parentheses are standard deviations. PIAT-R = Peabody Individual Achievement Test–Revised; KBIT = Kaufman Brief Intelligence Test; ASL-CT = American Sign Language Comprehension Test.

number of correct answers prior to this were counted as the final score[4] and the possible range was 60–100. These scores were the primary variable used to match hearing and deaf participants in order to determine the final samples for the analysis.

Nonverbal reasoning ability was measured via the Kaufman Brief Intelligence Test (Kaufman & Kaufman, 2004; test–retest reliability $r = .85$), in which participants select a completion for a sequence of visual objects. The final score was the total number of correct answers, and the possible range was 15–46. This test has been used in past studies to assess nonverbal intelligence in deaf and hearing readers (see Morere & Allen, 2012).

Spelling ability was measured via the Spelling Recognition Test (Andrews & Hersch, 2010; test–retest reliability, $r = .93$), in which participants identified misspelled words from a visually presented list that contained half correctly spelled and half incorrectly spelled words.[5] The final score was the total number of correct answers and the possible range was 0–87. This test is an established predictor of reading ability, which is distinct from reading comprehension and correlates highly with other spelling tests (e.g., spelling dictation; $r = .78$; Andrews et al., 2020). Importantly, it can be performed by deaf individuals because it does not involve auditorily presented words.

Sign language comprehension (deaf participants only) was measured via the American Sign Language Comprehension Test (ASL-CT; Hauser et al., 2016; internal reliability $\alpha = .83$), in which participants matched pictures or videos to the meanings of signed ASL sentences, analogous to the PIAT-R test for English comprehension. The final score was the total number of correct answers, and the possible range was 0–30.

Statistical Power

A previous study comparing deaf and hearing span sizes (Bélanger et al., 2012) found significant effects with 18 skilled deaf participants and 20 hearing participants with 33 sentences per window condition. Because we had fewer items per condition (due to time constraints based on our larger study), we performed a sensitivity analysis to estimate the minimum effect size we would be able to detect given our planned number of participants and items using the PANGEA analysis tool (Westfall, 2016). The design included two fixed factors (group and window size) and two random factors (participants and sentences) where the participant factor was nested in the group factor and the sentence factor was nested in the window size factor. It was based on a design with 20 sentences per condition, and a sample size of 84 participants (42 hearing and 42 deaf).[6] This analysis revealed that we would be able to detect a small-to-moderate effect size (Cohen's $d = 0.3435$) for the interaction between group and window condition with power equal to 0.79.

Materials and Design

This experiment used a 2 (group) × 6 (window size) mixed factorial design. The text was either presented normally (i.e., full, no mask condition) or with a moving window in which four characters were visible to the left of the reader's fixation, and either 6, 10, 14, 18, or 22 characters were visible to the right. Outside of this window, the spaces were masked with "x"s, but the letters remained intact (see Figure 2). Stimuli consisted of 11–19 word sentences (max 86 characters). 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).

A total of 120 experimental sentences were read by the participants, with 20 items in each condition, as well as six practice sentences at the beginning of the experiment. Window conditions were blocked such that window size increased with each block, each sentence was shown only once in the same condition for each participant, and the order of the sentences was randomized within a block.

Equipment

Eye movements were tracked using an SR Research EyeLink 1000 Plus eye tracker in desktop setup (1,000 Hz; in Tampa and San Diego), or an SR Research EyeLink Duo eye tracker (1,000 Hz; in Austin and Washington, DC). Stimuli were presented on an LCD monitor at a viewing distance of 65 cm (in Tampa), 85 cm (in San Diego), or 55 cm (in Austin and Washington, DC).[7] To minimize movements, participants used a chin and headrest. While the

[4] Since the PIAT-R is designed to assess reading skills even for young children, it has 100 items that increase in difficulty; we started at item 60 to shorten the testing session and counted all untested items as correct.

[5] We excluded one correctly spelled item that used the British spelling because the test was developed in Australia.

[6] This tool assumes an equal number of participants per group, but note that we have a larger sample of hearing participants than deaf participants so this analysis may in fact overestimate the minimum effect size.

[7] The differences in viewing distance across sites were an oversight. However, these differences yielded only small differences in the perceived stimulus size (with a character subtending between 0.22° and 0.32° of visual angle; see below), and the hearing group was run on the intermediate viewing distance so these differences are unlikely to have systematically skewed our results.

Table 2

Descriptive Statistics (Mean With Standard Deviation in Parenthesis) for the Lexical Characteristics of Sentences in Each Condition in Experiment 1

Measure	Full	6	10	14	18	22
Average word frequency (HAL: occurences/131 mil)	3,380,511 (887,251)	3,149,774 (1,044,378)	3,435,711 (905,404)	3,299,737 (849,620)	3,069,134 (898,323)	3,185,997 (1,107,655)
Average word frequency (log (HAL))	12.25 (0.66)	12.51 (0.44)	12.39 (0.60)	12.53 (0.56)	12.22 (0.68)	12.30 (0.62)
Average word frequency (subtitle: occurences/mil)	5,601 (1,347)	5,340 (1819)	5,636 (1,428)	5,477 (1,186)	4,994 (1,397)	5,074 (1,437)
Average word frequency (log (subtitle))	4.33 (0.36)	4.45 (0.22)	4.40 (0.35)	4.53 (0.26)	4.37 (0.28)	4.31 (0.28)
Total number of characters	78.45 (3.71)	78.25 (3.55)	78.95 (4.38)	78.55 (3.44)	79.35 (3.17)	78.00 (3.61)
Total number of words	14.15 (1.27)	14.85 (1.23)	14.70 (1.63)	14.65 (1.60)	14.30 (1.22)	13.90 (1.29)
Average word length	4.75 (0.56)	4.36 (0.49)	4.54 (0.57)	4.49 (0.56)	4.68 (0.57)	4.74 (0.49)
Estimated reading level	8.55 (2.24)	7.8 (1.82)	7.95 (1.79)	8.05 (1.93)	1.94 (1.55)	8.45 (1.54)
Total number of clauses	1.8 (0.70)	1.75 (0.72)	1.5 (0.61)	1.75 (0.64)	1.55 (0.69)	1.2 (0.62)
Complex *T*-unit ratio	0.55 (0.51)	0.525 (0.50)	0.4 (0.60)	0.6 (0.50)	0.25 (0.44)	0.15 (0.37)

Note. 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). HAL = Hyperspace Analogue to Language.

viewing was binocular, only eye movements from the right eye were recorded. Saccades and fixations were parsed from the sample data using the algorithm from the EyeLink recording software; the saccade detection was set to normal and the sample filter was set to high, and the link filter was turned off (to reduce sampling delay for the moving window manipulation). Participants made manual responses on a response pad to indicate when they had finished reading and to respond to comprehension questions.

Procedure

Participants gave their consent to participate in the study in accordance with the Institutional Review Boards at the University of South Florida, San Diego State University, University of Texas at Austin, and Gallaudet University, which approved the study. Participants first completed a demographics questionnaire containing information about age, gender, race, ethnicity, education, occupation, and knowledge of languages other than English. The deaf participants were also asked questions about their signing exposure and usage. When the participants arrived for their in-person session, they watched instruction videos (in English or ASL, as appropriate) informing them about the calibration procedure and the task. A fluent ASL signer was available to answer any questions from the deaf participants. The participants were then seated and had the eye tracker adjusted to where it was comfortable and able to accurately track their eye movements. A 3-point calibration procedure was used until the calibration error at each point was under 0.3° of visual angle. All participants performed Experiment 1, followed by Experiment 2 in the same experimental session but in separate blocks.[8]

At the start of each trial, a fixation point was presented in the center of the screen, which the participant had to fixate before the experimenter started the trial. Next, a gaze box appeared on the left side of the screen, at the location of the start of the sentence. Once the participant fixated inside of the box, the sentence appeared, presented in black Courier New 14 pt. font on a gray background with each character subtending either 0.27° (in Tampa), 0.22° (in San Diego), or 0.32° (in Austin and Washington, DC) of visual angle. The participants read the sentence silently to themselves until they were satisfied with their understanding, at which point they fixated a target sticker on the right-hand side of the screen and indicated they were done reading by pressing a button on a response pad. Yes/no comprehension questions were presented after 25% of trials to ensure participants were paying attention and reading for comprehension.

Results

Fixations that were interrupted by the participant pressing the button to end the trial and those greater than 800 ms were excluded. Fixations shorter than 80 ms were combined with the adjacent fixation if they were within the spatial extent of one character space, and otherwise were excluded. Trials with fewer than five or more than 30 fixations were excluded from the analysis, leaving a total of 4,893 trials for deaf participants (98.37% of total) with an average of

[8] For two deaf participants, the experiment crashed (one during Experiment 1 and one during Experiment 2), and they completed the experiment at a second experimental session. Only trials from the second session that they had not already seen in the first session were retained in the analysis.

Table 3

Results of Linear Mixed Effects Models Testing the Effect of Group, the Effects of the Rightward Perceptual Span for the Hearing Group, the Interaction Between Group and the Rightward Perceptual Span, and the Rightward Perceptual Span for Deaf Readers in Experiment 1

	Reading rate (wpm)				Mean saccade length (character)				Mean fixation duration (ms)			
Predictor	Est.	*SE*	*t*	*p*	Est.	*SE*	*t*	*p*	Est.	*SE*	*t*	*p*
Full model (hearing reader as baseline)												
(Intercept)	227.25	10.39	21.87	<.001*	10.51	0.33	74.86	<.001*	228.02	3.37	67.71	<.001*
Group: deaf versus hearing (averaged across windows)	47.95	15.67	3.06	.002*	0.99	0.05	−0.22	.829	−1.07	5.21	−0.21	.837
Window: 10 versus 6 (hearing only)	21.57	9.26	2.33	.020*	1.10	0.02	5.20	<.001*	−8.28	1.90	−4.35	<.001*
Window: 14 versus 10 (hearing only)	14.85	8.95	1.66	.097	1.01	0.02	0.62	.536	−3.24	1.81	−1.79	.073
Window: 18 versus 14 (hearing only)	3.07	8.95	0.34	.732	0.99	0.02	−0.34	.733	1.56	1.74	0.90	.370
Window: 22 versus 18 (hearing only)	1.95	8.95	0.22	.828	0.99	0.02	−0.55	.583	0.18	1.75	0.10	.917
Group × Window: 10 versus 6	13.65	6.45	2.12	.034*	0.99	0.02	−0.30	.761	1.20	2.11	0.57	.570
Group × Window: 14 versus 10	3.51	5.31	0.66	.509	1.07	0.02	2.98	.003*	−0.63	1.90	−0.33	.739
Group × Window: 18 versus 14	−3.89	5.31	−0.73	.464	1.01	0.02	0.31	.756	−0.78	1.74	−0.45	.653
Group × Window: 22 versus 18	0.74	5.32	0.14	.889	1.02	0.02	0.81	.421	0.64	1.76	0.37	.714
Deaf readers only												
(Intercept)	275.23	16.27	16.92	<.001*	10.40	0.40	61.11	<.001*	226.94	5.14	44.13	<.001*
Window: 10 versus 6	35.08	11.45	3.06	.002*	1.09	0.02	4.40	<.001*	−7.08	2.16	−3.27	.001*
Window: 14 versus 10	18.40	10.80	1.70	.088	1.08	0.02	3.91	<.001*	−3.87	2.18	−1.78	.076
Window: 18 versus 14	−0.81	10.72	−0.08	.940	1.00	0.02	0.26	.794	0.76	2.01	0.38	.706
Window: 22 versus 18	2.64	10.73	0.25	.805	1.01	0.02	0.30	.763	0.85	2.00	0.42	.672

Note. Est. = estimated; *SE* = standard error.
$^{*}p < .05$.

116 (*SD* = 5.57, range = 91–120) trials per participant and 7,020 trials for hearing participants (97.70% of total) with an average of 117 (*SD* = 5.12, range = 95–120) trials per participant.

After removing all practice trials, we calculated three dependent variables on each trial. *Reading rate* (words per minute; wpm) was measured as the number of words in the sentence divided by the sentence reading time (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 (the number of milliseconds in a minute). *Forward saccade length* was measured as the number of characters[9] between one fixation and the immediately preceding fixation, so long as the preceding fixation was further to the left than the current one. 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. *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 analyze the data, we used (generalized) 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 saccade length from the lme4 package (Bates et al., 2015) within the *R* environment for statistical computing (R Core Team, 2016). We ran four separate sets of models for each dependent variable. One model assessed the rightward span (i.e., compared the different rightward window size conditions) while holding the leftward window size constant and compared these estimates between the deaf and hearing group. Because this model only estimated the interaction between group and window comparisons, we used a second model to derive estimates for the same window size effects for the deaf group only. A third model allowed us to estimate reading behavior in the full condition and compare it between the groups, as well as assess the impact of the leftward span by comparing the full condition to the largest window size condition.[10] A fourth model tested the leftward span for the deaf group only.

The first model included fixed effects for group (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), five contrasts for the differences between window sizes (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: 10 vs. 6, 14 vs. 10, 18 vs. 14, 22 vs. 18), and the interactions between these comparisons and group (see Table 3 for results). 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 different for the deaf group compared to the hearing group. The second model included only deaf participants; the fixed effects included only the window size factor, entered with the same contrasts as described above (see Table 3 for results). In both models, 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 fixation duration in the case of the first model).

The third model included fixed effects for group (entered with a treatment contrast, as above), the difference between the 22-character condition and the full condition (entered with a treatment contrast so that the baseline was the full condition [coded as 0], and the largest window size [coded as 1] was compared to it), and the interactions between this comparison and group (see Table 4 for results). Thus, the main effect of group represents the difference in the dependent variable in the full condition, the main effect of the

[9] The variable of saccade length was calculated by the eye tracker in terms of number of pixels, which we then converted to number of characters, based on the fixed-width font, and rounded to the nearest integer.

[10] This analysis was not preregistered but was added after the discovery of a larger leftward span by Stringer et al. (2024).

Table 4
Results of Linear Mixed Effects Models Testing the Effects of Group in the Full Condition, the Leftward Span (Difference Between the Largest Window Size and the Full Condition) for the Hearing Group, the Interaction Between Group and the Leftward Span, and the Leftward Span for the Deaf Group in Experiment 1

	Reading rate (wpm)				Mean saccade length (character)				Mean fixation duration (ms)			
Predictor	Est.	*SE*	*t*	*p*	Est.	*SE*	*t*	*p*	Est.	*SE*	*t*	*p*
Full model (hearing reader as baseline)												
(Intercept)	253.71	14.52	17.47	<.001*	10.67	0.37	69.19	<.001*	221.22	3.92	56.45	<.001*
Group: deaf versus hearing (full condition only)	66.82	20.04	3.33	.001*	1.05	0.05	0.97	.334	−2.04	5.92	−0.34	.730
Window: 22 versus full (hearing only)	−12.75	10.72	−1.19	.234	1.00	0.02	−0.07	.940	4.92	2.06	2.39	.017*
Group × Window: 22 versus full	−16.50	7.61	−2.17	.030*	0.98	0.02	−1.05	.296	1.05	2.42	0.43	.664
Deaf readers only												
(Intercept)	320.54	22.67	14.14	<.001*	11.22	0.49	55.73	<.001*	219.17	6.13	35.73	<.001*
Window: 22 versus full	−29.26	12.99	−2.25	.024*	0.98	0.02	−1.33	.183	5.97	2.65	2.26	.024*

Note. Est. = estimated; *SE* = standard error.
* $p < .05$.

window manipulation represents the effect for the hearing group only, and the interaction represents the degree to which the effect of window is different for the deaf group compared to the hearing group. The fourth model included only deaf participants (see Table 4 for results). The random effects included the intercept and slope of window size for participant and the intercept for sentence for all dependent variables.

Reading Rate

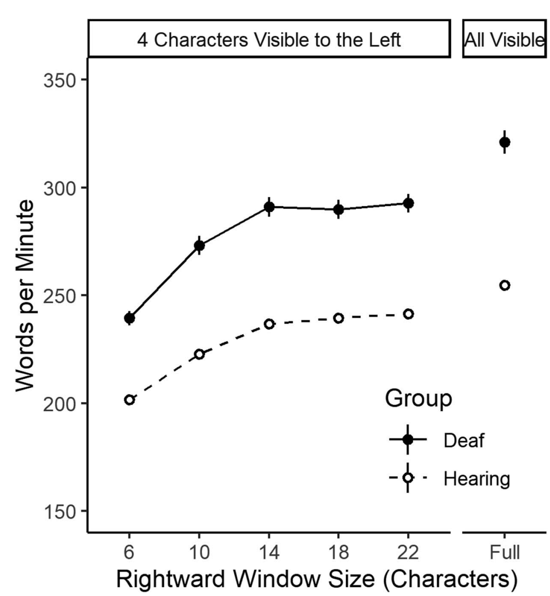
Effects of Rightward Window Size Manipulation. There was a significant effect of group, indicating that, even when perceptual information was restricted, deaf readers read faster than their hearing counterparts. Hearing readers' reading rate increased significantly from six to 10 characters to the right, marginally from 10 to 14 characters, and did not increase for any of the larger window size comparisons, indicating that their rightward perceptual span extends up to 10 characters and possibly a bit further. The interaction between group and the comparison between the six and 10 character conditions was statistically significant, with deaf readers showing a larger increase. None of the other interactions were statistically significant, suggesting that deaf readers do not have a wider perceptual span than their hearing counterparts. The model of just the deaf readers showed a similar pattern to the hearing readers in that their reading rate increased significantly from six to 10 characters to the right, marginally from 10 to 14 characters, and did not increase for any of the larger window size comparisons.

Effect of the Full Versus Largest Window Manipulation (Effects of Leftward Span). In the full condition, there was a significant effect of group such that deaf readers read faster than hearing readers when perceptual information was not restricted. Although hearing readers showed no difference between the largest window size condition and the full condition, there was a significant interaction, and the model of the deaf readers indicated that their reading rate significantly decreased from the full condition to the largest window size condition (see Figure 4). Thus, having access to the entire spatial layout of the text, including leftward perceptual information, allows deaf readers to read more efficiently, but this information is not used by hearing readers.

Saccade Length

Effects of Rightward Window Size Manipulation. There was no significant overall effect of group. Hearing readers made significantly longer saccades in the 10-character condition than in the six-character condition, but no other window size comparisons were significant, suggesting that restricting nearby spacing information inhibits the targeting of the upcoming saccade. There was no significant interaction between the 6- and 10-character comparison, suggesting that deaf readers were similarly impacted by the disruption of nearby perceptual information, but there was a significant interaction between group and the comparison between the 10- and 14-character window condition whereby deaf readers showed a larger increase to the 14-character condition. In the model

Figure 4
Reading Rates (Words per Minute) of Deaf and Hearing Groups at Each Window Size in Experiment 1



Note. Error bars represent ±1 SEM. SEM = standard error of the mean.

of the deaf readers alone, they showed a significant increase in saccade length from 10 to 14 characters, suggesting that they may take advantage of perceptual information from a larger area of the text than hearing readers, at least in terms of saccade targeting (see Figure 5A). None of the other interactions between group and window size, nor the window size comparisons for the deaf group, were statistically significant.

Effect of the Full Versus Largest Window Manipulation (i.e., Effects of Leftward Span). There was no significant effect of group in the full condition, suggesting that when perceptual information is not restricted, deaf and hearing readers make similar length saccades. Neither group showed any significant differences between the largest window size and the full condition, suggesting that access to perceptual information from the far right and left parafovea does not have a significant influence on forward saccade length.

Fixation Duration

Effects of Rightward Window Size Manipulation. There was no significant overall effect of group, suggesting that deaf and hearing readers make fixations of similar durations when perceptual information is disrupted. Hearing readers made significantly shorter fixations in the 10-character than the six-character condition, but no other window size comparisons were significant. This minimal influence may be related to the fact that fixation duration is a measure mostly affected by "when" decisions, which is more closely related to linguistic than perceptual information. There were no significant interactions between group and any of the window size comparisons, and like hearing readers, deaf readers only showed a significant difference between the 10-character and six-character condition, suggesting that rightward perceptual information impacts deaf and hearing readers similarly with respect to deciding when to end a fixation.

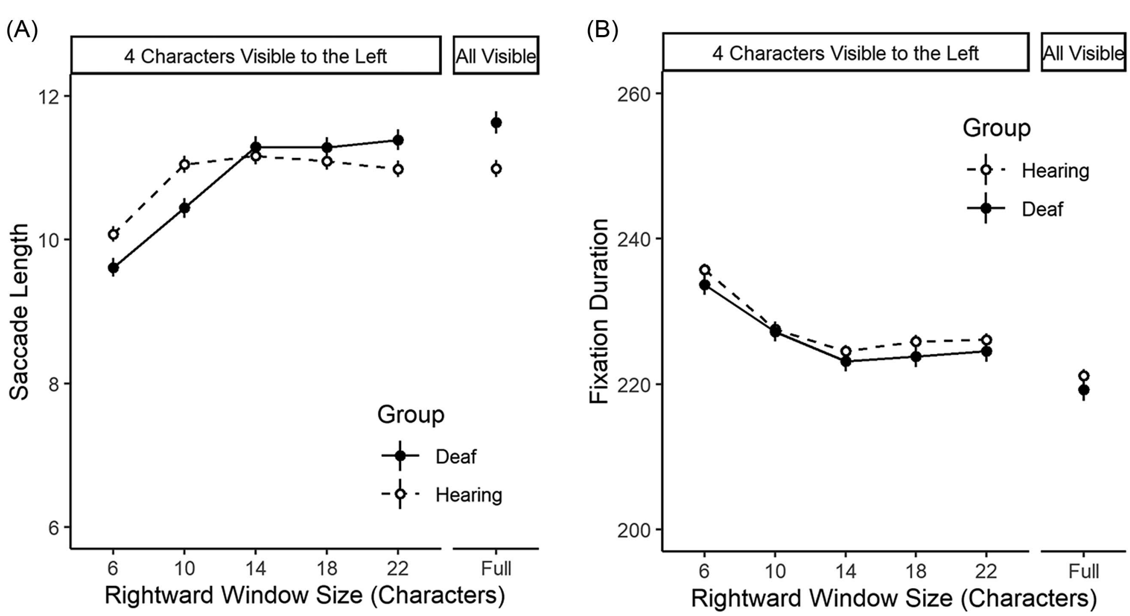
Effect of the Full Versus Largest Window Manipulation (Effects of Leftward Span). There was no effect of group in the full condition. Hearing readers showed a significant increase in fixation duration for the largest window size condition compared to the full condition, suggesting that leftward perceptual information affects the fixation durations of hearing readers (see Figure 5B). There was no significant interaction between groups and this comparison, but the difference for deaf readers was only marginally significant, suggesting that the impact of leftward perceptual information on "when" decisions may be weaker for deaf readers.

Summary of Experiment 1

The size of the perceptual span for hearing readers was slightly smaller than we expected based on prior literature; although we expected it to extend to 14 characters to the right of fixation, the comparison between that condition and the 10-character window size condition was only marginally significant. The increase from the six- to 10-character condition was statistically significant, so we can estimate that hearing readers' perceptual span is somewhere between 10 and 14 characters. These increases in reading rate are not specifically more related to changes in fixation duration or saccade length, as both dependent variables showed similar patterns of effects of the window manipulation for hearing readers (i.e., only significant differences between the two smallest window sizes). Furthermore, for the comparison between the largest window size and the full condition, hearing readers showed no changes in reading rate or saccade length but a numerically small (i.e., 4.92 ms) although statistically significant ($p < .05$) decrease in fixation duration when the full text was available. Overall, these data suggest that hearing readers'

Figure 5

Forward Saccade Length (Panel A) and Average Fixation Duration (Panel B) of Deaf and Hearing Groups at Each Window Size in Experiment 1



Note. Error bars represent ±1 SEM. SEM = standard error of the mean.

perceptual span does not extend past four characters to the left (i.e., the leftward extent of all of our window conditions).

The size of the perceptual span of deaf readers was also somewhere between 10 and 14 characters to the right of fixation, suggesting that deaf readers' larger reading spans are not specifically tied to an enhanced perceptual span but rather may be due to an enhanced word identification span, which we test in Experiment 2. However, the deaf readers did differ from the hearing readers in terms of the impact of perceptual information on "where" saccade decisions. The saccade lengths for deaf readers changed more in response to the availability of perceptual information further from fixation, significantly increasing up to 14 characters (see Figure 5A). Additionally, deaf readers differed from hearing readers with respect to their use of leftward perceptual information: their reading rates increased when provided with the full sentence compared to the largest window size condition.

These findings suggest that both hearing and deaf readers use rightward perceptual information out to between 10 and 14 characters to read more efficiently. While there do not seem to be drastic differences between the aspects of reading (i.e., "when" vs. "where" saccade decisions) that are impacted by the availability of this information in the periphery, deaf readers show a tighter connection between the availability of rightward perceptual information and "where" saccade decisions (i.e., saccade length as opposed to fixation duration). Furthermore, while deaf readers do not seem to use perceptual information further out to the right than hearing readers, they do take advantage of this information from further to the left of fixation.

Experiment 2: Word Identification Span

The aim of Experiment 2 was to test the word identification span by masking the letters within the words outside the visible window, while preserving the perceptual span by maintaining the spaces between the words outside of the window (see Figure 2). As noted above, we hypothesized that the word identification span of hearing readers would be approximately eight characters (Underwood & McConkie, 1985), based on the window size at which their reading rate significantly increased from the smaller window sizes, but did not significantly increase beyond this window. Furthermore, because the window manipulations in this experiment should disrupt the ability to initiate orthographic processing, we hypothesized that manipulations in this experiment would have a greater influence on the dependent variable of fixation duration than saccade length, because the former is more related to "when" saccade decisions than "where" saccade decisions. Because past research has suggested that the word identification span only extends out to three to four characters to the left of fixation, we did not expect the reading rate of hearing readers to differ between the largest rightward window size and the full condition.

If deaf readers' larger reading span is tied to an enhanced word identification span, their reading rate should increase beyond eight characters, and this increase should be apparent not only in the analysis of reading rate, but also average fixation duration. We expected that deaf readers would obtain lexical information further to the left of fixation than hearing readers (Liu et al., 2021; Stringer et al., 2024), and therefore they should show a larger decrease in reading rate than hearing readers for the largest window size condition compared to the full condition.

Method

Participants, Equipment, and Procedure

The participants, equipment, and procedure were the same as in Experiment 1. The blocks of trials from Experiment 2 immediately followed the blocks from Experiment 1, with a practice trial preceding the experimental blocks. The blocking and randomization scheme was similar to Experiment 1.

Materials and Design

This experiment used a 2 (group) × 5 (window size) mixed factorial design. Windows were presented normally or in moving window conditions in which "x"s replaced the letters within the words while the spaces were preserved; four characters were visible to the left of the reader's fixation, and either 4, 6, 8, or 10 were visible to the right of the reader's fixation. As in Experiment 1, sentences were 11–18 words long and were matched across conditions on average word frequency, average word length, reading level, sentence length, and complexity (see Table 5 for more details). One hundred sentences

Table 5
Descriptive Statistics (Mean With Standard Deviation in Parenthesis) for the Lexical Characteristics of Sentences in Each Condition in Experiment 2

Measure	Full	4	6	8	10
Average word frequency (HAL: occurrences/131 Mil)	3,495,905 (782,836)	3,079,552 (1,029,912)	3,111,935 (956,325)	3,260,946 (950,631)	3,074,902 (895,273)
Average word frequency (log (HAL))	12.47 (0.49)	12.39 (0.63)	12.32 (0.53)	12.23 (0.72)	12.22 (0.63)
Average word frequency (subtitle: occurrences/mil)	5,724 (1,253)	5,261 (1,753)	5,034 (1,326)	5,148 (1,343)	4,903 (1,011)
Average word frequency (log (subtitle))	4.36 (0.22)	4.45 (0.29)	4.41 (0.23)	4.38 (0.31)	4.36 (0.31)
Total number of characters	79.7 (4.24)	79.50 (3.43)	78.20 (2.71)	77.95 (2.93)	78.55 (3.35)
Total number of words	14.4 (1.54)	14.30 (1.53)	14.25 (1.65)	14.80 (1.54)	14.50 (1.36)
Average word length	4.70 (0.77)	4.69 (0.57)	4.62 (0.59)	4.44 (0.64)	4.49 (0.42)
Estimated reading level	8.4 (1.93)	8.15 (1.84)	8.2 (1.67)	7.40 (1.85)	8 (1.49)
Total number of clauses	1.8 (0.83)	1.65 (0.88)	1.7 (0.73)	1.55 (0.60)	1.65 (0.59)
Complex *T*-unit ratio	0.55 (0.51)	0.525 (0.50)	0.55 (0.51)	0.45 (0.51)	0.5 (0.51)

Note. 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). HAL = Hyperspace Analogue to Language.

Table 6

Results of Linear Mixed Effects Models Testing the Effect of Group, the Rightward Word Identification Span for the Hearing Group, the Interaction Between Group and the Rightward Word Identification Span, and the Rightward Word Identification Span for the Deaf Group in Experiment 2

	Reading rate (wpm)				Mean saccade length (character)				Mean fixation duration (ms)			
Predictor	Est.	*SE*	*t*	*p*	Est.	*SE*	*t*	*p*	Est.	*SE*	*t*	*p*
Full model (hearing reader as baseline)												
(Intercept)	228.36	7.74	29.50	<.001*	9.33	0.26	81.52	<.001*	233.76	3.46	67.60	<.001*
Group: deaf versus hearing (averaged across windows)	23.30	11.36	2.05	.040*	0.99	0.04	−0.32	.748	3.84	5.34	0.72	.472
Window: 6 versus 4 (hearing only)	28.94	8.21	3.52	<.001*	1.12	0.02	6.41	<.001*	−14.59	2.20	−6.62	<.001*
Window: 8 versus 6 (hearing only)	24.24	7.88	3.07	.002*	1.08	0.02	5.23	<.001*	−6.04	1.78	−3.39	.001*
Window: 10 versus 8 (hearing only)	−2.44	7.90	−0.31	.758	1.05	0.01	3.45	.001*	−1.14	1.76	−0.65	.517
Group × Window: 6 versus 4	3.15	5.67	0.56	.578	0.98	0.03	−0.79	.427	1.58	2.76	0.57	.566
Group × Window: 8 versus 6	1.86	4.39	0.42	.673	0.99	0.02	−0.57	.569	1.02	1.88	0.55	.586
Group × Window: 10 versus 8	8.42	4.48	1.88	.060	1.00	0.02	0.17	.866	−0.47	1.84	−0.26	.798
Deaf readers only												
(Intercept)	251.66	11.41	22.05	<.001*	9.20	0.31	66.06	<.001*	237.60	5.38	44.18	<.001*
Window: 6 versus 4	31.98	9.59	3.33	.001*	1.10	0.02	4.30	<.001*	−13.01	2.85	−4.57	<.001*
Window: 8 versus 6	26.20	9.13	2.87	.004*	1.07	0.02	3.72	<.001*	−5.04	1.89	−2.67	.008*
Window: 10 versus 8	5.90	8.88	0.67	.506	1.05	0.02	3.18	.001*	−1.59	2.10	−0.76	.450

Note. Est. = estimated; *SE* = standard error.
* $p < .05$.

were read by the participants, 20 in each condition, in addition to one practice sentence at the beginning of the experiment.

Results

We applied the same data processing procedures and calculated the same dependent variables as in Experiment 1, including a total of 4,104 trials for deaf participants (99.06% of total) with an average of 97 ($SD = 3.39$, range = 85–100) trials per participant and 5,904 trials for hearing participants (98.63% of total) with an average of 98 ($SD = 2.87$, range = 85–100) trials per participant. We analyzed the data with the same statistical approach as in Experiment 1, except the contrasts for the window size comparisons in the models comparing window conditions contained four contrasts (i.e., 6 vs. 4, 8 vs. 6, 10 vs. 8; see Table 6 for results for both groups and the deaf group only, respectively), the random effects only included a slope of participant group for reading rate but not fixation duration in the case of the first model, and the largest window size condition in the model comparing the effect of the leftward span was the 10-character condition (see Table 7 for results for both groups and the deaf group only, respectively).

Reading Rate

Effects of Rightward Window Size Manipulation. There was a significant effect of group, suggesting that when nearby rightward lexical information was restricted, deaf readers read more efficiently than hearing readers. The hearing group showed significant increases in reading rate from the four-character to six-character condition and from the six-character to eight-character condition but not from the eight-character to the 10-character condition, suggesting that they have a word identification span extending up to eight characters to the right of fixation. The interactions with group were not significant for the two smallest window size comparisons but were marginally significant for the comparison between the 8 and 10 window size condition, suggesting that deaf readers may have a slightly larger rightward word identification span. However, the model for deaf readers showed a similar pattern of only increasing reading rate up to eight characters as did hearing readers in the first model (see Figure 6). Therefore, both deaf and hearing readers take advantage of lexical information up to eight characters to the right of fixation.

Effect of the Full Versus Largest Window Manipulation (Effects of Leftward Span). There was a significant effect of group in the full condition (as in Experiment 1), indicating that deaf readers read significantly faster than hearing readers when lexical information is not restricted. Although hearing readers showed no difference between the full and the largest window condition, there was a significant interaction, and the model of the deaf readers indicated that they showed a significant decrease in reading rate from the full condition to the largest window size condition (see Figure 6). This result suggests that while deaf and hearing readers may use rightward lexical information from a similar area of the text, deaf readers may use a greater amount of lexical information to the left of fixation, and it is this leftward lexical information that contributes to their observed reading efficiency with normal text.

Saccade Length

Effects of Rightward Window Size Manipulation. There was no significant effect of group. Hearing readers showed significantly longer saccades in each window comparison, contrary to our predictions. There were no significant interactions between group and any of these comparisons, and the model of only the deaf readers also showed increases at each of the window size comparisons (see Figure 7A). This suggests that deaf and hearing readers both use nearby rightward lexical information to plan saccades, and they do so in similar ways.

Table 7

Results of Linear Mixed Effects Models Testing the Effect of Group in the Full Condition, the Leftward Span (Difference Between the Largest Window Size and the Full Condition) for the Hearing Group, the Interaction Between Group and the Leftward Span, and the Leftward Span for the Deaf Group in Experiment 2

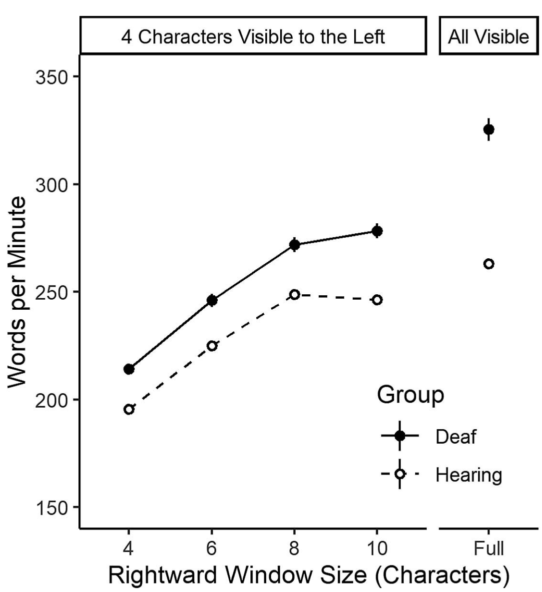
	Reading rate (wpm)				Mean saccade length (character)				Mean fixation duration (ms)			
Predictor	Est.	*SE*	*t*	*p*	Est.	*SE*	*t*	*p*	Est.	*SE*	*t*	*p*
Full model (hearing reader as baseline)												
(Intercept)	261.96	14.37	18.23	<.001*	10.64	0.35	71.42	<.001*	221.46	3.74	59.29	<.001*
Group: deaf versus hearing (full condition only)	65.00	20.73	3.14	.002*	1.05	0.05	0.88	.377	−0.00	5.67	−0.00	1.000
Window: 10 versus full (hearing only)	−16.03	10.36	−1.55	.122	0.97	0.02	−1.55	.121	4.78	2.14	2.23	.026*
Group × Window: 10 versus full	−33.63	10.80	−3.12	.002*	0.93	0.02	−3.05	.002*	4.37	2.77	1.58	.115
Deaf readers only												
(Intercept)	326.97	22.58	14.48	<.001*	11.18	0.44	61.90	<.001*	221.44	5.94	37.27	<.001*
Window: 10 versus full	−49.70	14.39	−3.45	.001*	0.90	0.01	−7.18	<.001*	9.18	3.02	3.04	.002*

Note. Est. = estimated; *SE* = standard error.
* $p < .05$.

Effect of the Full Versus Largest Window Manipulation (Effects of Leftward Span). There was no significant effect of group in the full condition, suggesting that when lexical information was not restricted, deaf and hearing readers make saccades of similar lengths. Hearing readers did not show a significant change in saccade length from the full condition to the largest window size condition, suggesting they do not use leftward lexical information to make "where" saccade decisions. There was a significant interaction between group, and the model of the deaf group showed a significant decrease in saccade length from the full condition to the largest window condition (see Figure 7A), suggesting that leftward lexical information impacts saccade length, a measure more aligned with "where" decisions, but only for deaf readers.

Figure 6

Reading Rates (Words per Minute) of Deaf and Hearing Groups at Each Window Size in Experiment 2



Note. Error bars represent ±1 SEM. SEM = standard error of the mean.

Fixation Duration

Effects of Rightward Window Size Manipulation. There was no significant effect of group. Hearing readers made shorter fixation durations with increasing window sizes up to eight characters. There were no significant interactions between group and any of the window size comparisons, and the model of the deaf group only showed the same pattern as the hearing group. These findings suggest that the extent of the rightward word identification spans and its impact on "when" decisions is similar between deaf and hearing readers.

Effect of the Full Versus Largest Window Manipulation (Effects of Leftward Span). There was no significant effect of group in the full condition, suggesting that when lexical information was not restricted, deaf and hearing readers make fixations of similar durations. Hearing readers showed a significant increase in fixation duration between the full condition and the largest window size condition, indicating that they use leftward lexical information to determine their "when" saccade decisions. The interaction with group was not significant, and the model of only deaf readers showed a statistically significant increase in fixation duration for the largest window size condition compared to the full condition (see Figure 7B).

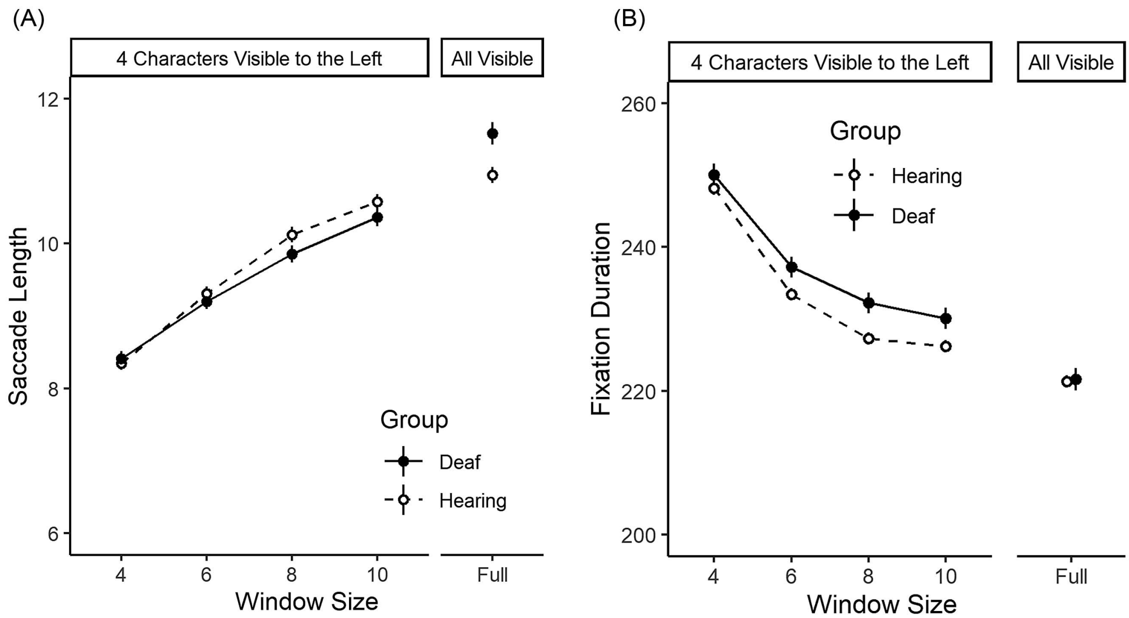
Summary of Experiment 2

The size of the rightward word identification span for hearing readers was, as expected, eight characters to the right of fixation as reading rate significantly increased up to, but not beyond, this window size. In contrast to our predictions, the measure of saccade length showed increases with larger window sizes than the other measures. As in Experiment 1, for the comparison between the largest window size and the full condition, hearing readers showed no changes in reading rate or saccade length but a numerically small (although statistically significant) decrease in fixation duration when the full text was available. Overall, these data suggest that hearing readers' word identification span does not extend past four characters to the left (the leftward extent of all of our window conditions).

The size of the rightward word identification span of deaf readers was also eight characters, in contrast to our predictions. Therefore, it is possible that deaf readers' larger reading spans are not specifically

Figure 7

Forward Saccade Length (Panel A) and Average Fixation Duration (Panel B) of Deaf and Hearing Groups at Each Window Size in Experiment 2



Note. Error bars represent ±1 SEM. SEM = standard error of the mean.

tied to either word identification spans or to perceptual spans (as tested in Experiment 1), but rather require the integration of information obtained in both types of spans (Bélanger et al., 2012, 2018; see General Discussion). However, the deaf readers were more sensitive to the availability of leftward lexical information. All of the dependent variables were affected by the availability of leftward lexical information for deaf readers: Reading rates and average saccade lengths increased, and average fixation durations decreased in the full condition compared to the largest window size.

Overall, these findings suggest that deaf and hearing readers may have rightward word identification spans of similar extents, up to eight characters, which may potentially be a consequence of the ability to extract linguistic information parafoveally, leading to shorter fixation durations once they land on the targeted word. Although deaf readers do not seem to differ from hearing readers in terms of their rightward word identification spans, they appear to rely more heavily on leftward lexical information.

General Discussion

The primary goals of this study were to systematically disentangle the perceptual and word identification spans, to determine whether they are related to different types of saccade decisions (i.e., "when" vs. "where"), and to compare the sizes of the spans for deaf and hearing readers to identify the source of deaf readers' previously reported larger reading spans. In addition, we investigated the contribution of leftward perceptual and linguistic information to the reading processes for hearing and deaf readers. Overall, we found similar rightward span estimates to prior research for hearing readers; the perceptual span extends out to somewhere between 10 and 14 characters, and the word identification span extends out to eight characters. However, contrary to our predictions, we did not find a clean dissociation of these two spans mapping onto different saccade decisions, as both of the studies showed fairly similar impacts of the manipulations on "where" decisions (i.e., saccade length) and "when" decisions (i.e., fixation duration). With respect to group differences, although we found overall more efficient reading for deaf compared to hearing readers, we did not find differences in the extent of either of the rightward spans for the two groups. Therefore, it may be the case that deaf readers are more efficient readers, but in order for them to take advantage of information further to the right of fixation, they need to be able to integrate visuospatial and lexical information. In addition, deaf readers' increased speed may derive from more efficient foveal processing, which was not manipulated in the present study. We did find dramatic differences in the impact of the availability of leftward information whereby deaf readers benefited much more than hearing readers, suggesting they may distribute attention to the left of fixation to a greater extent than hearing readers, and this seems to be true for both perceptual and linguistic information.

Deaf Readers' Enhanced Spans Require Integration of Perceptual and Linguistic Information

Contra findings from prior studies that manipulated both spans simultaneously (Bélanger et al., 2012, 2018), the estimated sizes of our dissociated spans were the same for deaf readers compared to reading-level matched hearing readers. Because we followed much of the same procedure and participant inclusion criteria as Bélanger et al. (2012), we suspect these differences across studies are due to the fact that deaf readers' enhanced reading spans are only manifested when they can perceive both visuospatial and linguistic information in the parafovea. This may explain why prior studies have consistently found that skipping rates are higher for deaf readers (Bélanger et al., 2013; Bélanger & Rayner, 2013; Cooley et al., 2023; Traxler et al., 2021; see Belanger & Rayner, 2015), and in the full conditions in our study deaf readers skipped words significantly more often than hearing readers (44% vs. 38%, respectively; both *p*s < .005).[11] In contrast, more dissociable measures show less consistent findings: Shorter fixation durations are only statistically significant in some studies (Traxler et al., 2021) but not others (Bélanger et al., 2012, 2013; Bélanger & Rayner, 2013; Stringer et al., 2024; Yan et al., 2015), and trends showing longer saccades are only found in some studies (Bélanger et al., 2012; Stringer et al., 2024) but not others (Bélanger et al., 2018). As discussed in the introduction, the measure of word skipping represents a sort of hybrid of "when" and "where" decisions in that it indicates that the reader intended to move their eyes past the word in space and intended to spend no time directly fixating it. It may be that the ability to integrate the two types of information needed to make each of those decisions specifically benefits a behavior—like word skipping—that integrates those sources of information. Similarly, in the full condition in both of our experiments, deaf readers had neither longer saccades nor shorter fixation durations, but they did have significantly faster reading rates, which may be a hybrid measure more like skipping rate.

Deaf Readers' Overall Reading Efficiency and Larger Leftward Spans

Despite not finding numerically larger spans for deaf readers, we did find that they were overall more efficient readers, replicating several previous studies (Bélanger et al., 2012, 2018; Bélanger & Rayner, 2015). Deaf readers read approximately 66 words per minute faster in the full conditions in both experiments than hearing readers, and they read faster even when perceptual or lexical information was restricted (i.e., in the window conditions). These data suggest that, along the lines of the word processing efficiency hypothesis (Bélanger & Rayner, 2015), deaf readers are able to extract information from the text more quickly during a single fixation within the foveal region (which was always visible in our study). It is unlikely that the small differences in age and education in our deaf readers account for their large differences in reading rate because age effects on reading rate stabilize by the time readers enter college and all of our participants (deaf or hearing) were college educated. Although reading rate increases with age and years in school in the beginning of the lifespan (i.e., from first grade through college; Taylor, 1965; Spichtig et al., 2016), differences among college readers are small (i.e., 10–16 wpm increase from first to third or fourth year; Masterson & Hayes, 2004; Brown et al., 1993), and there are no significant reading rate differences among college-educated readers between 36 and 75 years (Aberson & Bouwhuis, 1997; see Brysbaert, 2019). Our deaf readers were all skilled and college educated, and therefore it is not clear whether these findings would generalize to all deaf readers. However, it is difficult to make any strong conclusions about the reading processes in deaf readers who are not native or early signers (an inclusionary criterion for our study) because language deprivation has a profound negative impact on literacy and academic performance (Hall et al., 2019; Humphries et al., 2012, 2022).

Some of the contribution to deaf readers' reading efficiency in the full conditions may derive from their larger leftward spans. The data from Experiment 2 align with recent findings that deaf readers take in more lexical information to the left of fixation than their hearing counterparts (Stringer et al., 2024), and the data from Experiment 1 extend this finding and support the hypothesis that deaf readers also take in perceptual information from a larger area. In contrast, the leftward spans of hearing readers do not seem to extend past four characters to the left of fixation (Rayner et al., 2014; Veldre & Andrews, 2014). These findings suggest that deaf readers attend to information more symmetrically around fixation compared to hearing readers. They may use this attention either to engage in lexical processing over an extended period of time (i.e., while the word is to the left of fixation) or to engage in late confirmatory processes (i.e., to verify comprehension of text that has already been read or assumed/predicted). This increased attention to information that has already been processed likely helps deaf readers to read faster, plan longer forward saccades, and integrate words into the sentence without needing to make regressions (see Bélanger et al., 2012, 2013). In fact, in the full conditions in our study, deaf readers regressed significantly less often than hearing readers (9% vs. 12%, respectively; both *p*s < .01).[12] Furthermore, the results of the present study suggest that deaf readers attend to both perceptual and linguistic information in order to engage in processing of leftward information, so they may be using linguistic properties of the text and word boundary information together to continue word identification after the eye has moved past the text. Thus, word length, in addition to the identities of the letters themselves, is important to continued word identification or to the late confirmatory processes that take place after deaf readers move their eyes past a word.

Lack of Dissociation of the Two Spans and Implications for When Versus Where Decisions

Although it has often been claimed that the perceptual span extends out 14–15 characters to the right while the smaller the word identification span extends only 7–8 characters (Rayner, 1975, 1998, 2014; Rayner et al., 1982), these estimates may not align with the definitions of these spans presented here. Although prior studies finding the 14–15 character size have claimed this represents the perceptual span (McConkie & Rayner, 1975; Rayner et al., 1980, 1981; Rayner & Bertera, 1979; Rayner, 1986), the manipulations used combined masking of both perceptual and linguistic information. Therefore, this estimate represents some kind of combined reading span, rather than one representing the use of primarily perceptual information. Very few studies have measured the perceptual span (i.e., masking the spaces in between words but leaving lexical information outside of the moving window; Pollatsek & Rayner, 1982), and none have provided a specific estimate of this span. Therefore, we suggest that the perceptual span (i.e., the area within which readers take in visuospatial features of the

[11] In Experiment 1, there was no significant difference between the full condition and the largest window size for either group, but in Experiment 2, there was a significant difference for the deaf group ($p < .005$), whereby they skipped less when lexical information was masked, but there was no difference for the hearing group, leading to a significant interaction ($p < .05$).

[12] Although numerically there were more regressions in the largest window size condition compared to the full condition, this comparison was not significant for either group, nor were there significant interactions for either experiment (all *p*s > .14).

text) extends only 10–14 characters to the right of fixation. In addition, most prior studies test a young adult college population, in contrast to our study that included a large number of matriculated community-dwelling individuals. The reading habits of students in college and adults no longer in school may differ and may slightly change the strategies they use to read. However, we made sure to recruit both deaf and hearing participants from outside of the college student population to ensure that this does not qualify our comparison between groups within our study.

While it may be the case that oculomotor control can be dissociated into autonomous systems that control "when" and "where" decisions independently (Findlay & Walker, 1999), reading may be a specialized task that requires perceptual and linguistic information to be integrated in order to maximize efficiency. It appears that the perceptual span and word identification spans are dissociable in the sense that they are able to be independently manipulated (see also Morris et al., 1990) and encompass different extents of the text (i.e., between 10 and 14 characters for perceptual and eight characters for linguistic information). Therefore, if researchers want to specifically investigate parafoveal perceptual processing in reading, they should use a paradigm that manipulates the spaces between the words (e.g., our manipulation in Experiment 1), and if they want to specifically investigate parafoveal linguistic processing in reading, they should use a paradigm that manipulates the letter identities (e.g., our manipulation in Experiment 2). However, it seems that readers use perceptual and linguistic information together in such a deeply integrated way that these spans are not dissociable in practice, in the sense that readers actively use them together to engage with the text. Therefore, when investigating reading efficiency across populations, we suggest that the easiest way to observe differences would be to use the combined span (i.e., mask both letters and spaces outside the visible window; e.g., Bélanger et al., 2012, 2018).

Conclusion

In this study, we independently assessed the perceptual span and word identification span and determined that they both influence "where" and "when" decisions of eye movement control in reading. Comparisons between the spans for deaf and hearing readers revealed that, when manipulated independently, deaf readers do not have wider rightward spans—their previously reported wider spans possibly rely on integration of perceptual and linguistic information—but they do utilize information to the left of fixation significantly more than their hearing counterparts. Our results confirm that deaf signers read more efficiently than reading-matched hearing readers and challenge the assumed dissociation between type of reading span and type of saccade decision.

Constraints on Generality

We expect our conclusions to generalize beyond the populations tested for several reasons. First, the sample we tested includes not only college students, which are typically studied in psychology, but also community-dwelling adults beyond college age. Although past research has found that the size of the reading spans change throughout development (Häikiö et al., 2009; Rayner, 1986; Sperlich et al., 2015, 2016) and the advanced lifespan (Rayner et al., 2009; Risse & Kliegl, 2011), our novel findings with respect to the dissociations of the spans and the need to integrate both of them to read efficiently are likely to generalize across age as well. Furthermore, our comparisons of two populations that differ in both their linguistic and perceptual experiences but nevertheless have similarly sized perceptual and word identification spans (when matched on age and reading level) suggest that our conclusions are robust to these group differences.

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