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Perceptual span in individuals with aphasia

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Abstract

Background: Perceptual span refers to the field of effective vision during reading comprehension. It is determined by many factors, including reading proficiency. No studies have investigated the perceptual span in people with reading comprehension impairments due to aphasia.

Aims: The present study examined whether perceptual span is smaller in individuals with aphasia than controls.

Methods and Procedures: The task was a gaze-contingent moving windows paradigm during silent reading using an eye tracker. Data from 11 individuals with aphasia and 15 neurotypical controls were analyzed.

Outcomes and Results: Perceptual span in individuals with aphasia was the fixated word plus one word to the right of fixation, whereas perceptual span in controls was the fixated word plus two words to the right of fixation.

Conclusion: Individuals with aphasia have a smaller perceptual span than controls, which likely reflects increased effort during reading comprehension.

Keywords

Perceptual span; aphasia; reading comprehension; eye tracking; sentence comprehension

Introduction

Reading comprehension impairments are common in individuals with aphasia (IWA). In a survey of long term needs after stroke, 23% of respondents reported reading difficulties, compared to 34% with speech difficulties (McKevitt et al. 2011). These results suggest that a large proportion of individuals with aphasia also have ongoing difficulty with reading. Reading difficulty can affect both the abilities to read aloud or silent reading comprehension. Most investigations of reading in aphasia focus on single word, oral reading (e.g., Ablinger, Huber, & Radach, 2014; Cherney, 2015). Significantly less is known about silent reading comprehension, particularly at the sentence and text levels. The present study focused on silent reading comprehension, using an eye-tracking methodology.

Eye-tracking during reading provides a sensitive means of observing how IWA read for comprehension. This method captures the first time an individual fixates on a word as well as regressive eye movements to earlier parts of the text and repeated fixations to reread material (e.g., Rayner 1998). Eye-tracking has been used to examine eye movements of individuals with acquired alexia when orally reading single words (e.g., Ablinger et al., 2014; Schattka, Radach, & Huber, 2010). One consistent finding is that people with acquired alexia make more eye fixations and reread words more frequently than non-brain-damaged controls. Similarly, eye tracking studies of silent reading comprehension have reported more fixations and rereading in IWA than controls (Chesneau et al., 2007; Hsu et al., 2014; Knilans & DeDe, 2014).

Recent work has used eye-tracking to examine how lexical variables (e.g., word length & frequency) and sentence variables (e.g., syntactic complexity and predictability) affect sentence level reading comprehension (e.g., DeDe, 2017; Huck, Thompson, Cruice, & Marshall, 2017a; 2017b; Kim & Bolger, 2012; Knilans & DeDe, 2015).¹ This work has shown that lexical effects such as word frequency and word length are similar or exaggerated in individuals with aphasia compared to controls (e.g., DeDe, 2017; Huck et al., 2017a; 2017b; Kim & Bolger, 2012). There is also eye tracking evidence that individuals with aphasia show delayed and possibly reduced effects of syntactic complexity and sentence level predictability in on-line reading comprehension (e.g., Huck et al., 2017b; Knilans & DeDe, 2015).

A common thread in studies of sentence and text comprehension is that individuals with aphasia read less accurately and more slowly than non-brain-damaged populations (also see Chesneau et al., 2007; Hsu et al., 2014). There are many different reasons why IWA may read more slowly, including delayed lexical or syntactic processing. Another related reason that IWA might read more slowly is if they obtain less visual information on each fixation, that is, if they have a smaller perceptual span. The present study investigated whether perceptual span, or the field of effective vision, during reading is smaller in IWA than non-brain-damaged controls.

Readers fixate on most words when silently reading a sentence. Fixations are short time periods between saccadic eye movements, during which our eyes process visual stimuli (Rayner, 1998). However, even when fixating on a word, we are generally conscious of other words in the sentence. Perceptual span refers to the number of words or characters that are processed on a given fixation (McConkie & Rayner, 1975). In proficient, English speaking adult readers aged 18 to 30, perceptual span is approximately three to four characters to the left of fixation and 14 to 15 characters to the right of fixation (cf. McConkie & Rayner, 1976; Rayner, 1998). In practical terms, this translates to the fixated word, plus two words to the right. Readers tend to fixate in the middle of first half of a word (e.g., a reader might focus on the letter “c” in “because”). Thus, characters to the left of fixation may be part of the same word.

¹Some studies have used self-paced reading to examine reading comprehension in individuals with aphasia. Here, we focus on studies that use eye tracking because of work suggesting that the two methods may not provide consistent patterns of results (e.g., DeDe, 2013 and Knilans & DeDe, 2015).

The perceptual span includes visual information in both the center of the field of vision (fovea) and the immediately adjacent portion of the retina (the parafovea). However, not all letters or words that fall within the perceptual span are processed to the same degree. Readers use information seven to eight characters to the right of fixation for word recognition (Rayner, 1998). This means that readers may begin processing words before fixating on them directly, at least under some circumstances (Rayner, 1998). This early processing is known as parafoveal preview benefit, because it allows for more efficient processing of the visual stimulus (word). Beyond seven to eight characters, information processing is limited to general impressions of letter shape and word length (McKonkie & Rayner, 1975; McKonkie & Zola, 1987). Word length information is important because knowing the length of upcoming words allows better planning of saccadic eye movements. Thus, a smaller perceptual span could influence both the time spent reading individual words and the accuracy of planning eye movements during reading.

There is a lot of evidence that perceptual span is not determined by the reader's visual acuity or other aspects of visual-perceptual processes (Henderson & Ferreira, 1990; Mielliet, O'Donnell, & Sereno, 2009). For example, cross-linguistic data demonstrate that linguistic features influence perceptual span. Perceptual span is smaller in languages such as Chinese (2 to 2½ characters), where single characters represent words (Inhoff & Liu, 1998). Perceptual span is asymmetrical to the left (i.e., 3–4 characters to the right and 14–15 characters to the left) in Hebrew, where text is read right to left (Pollatsek, Bolozky, Well, & Rayner, 1981).

Perceptual span also varies with reading ability. Both novice readers (Häikiö et al., 2009; Rayner, 1986) and readers with dyslexia (Rayner et al., 1989) show smaller perceptual spans than proficient, college age adults. For example, Häikiö et al. (2009) showed that second graders were able to identify approximately five letters to the right of fixation, whereas sixth graders and adult readers identified nine characters. Within the second graders, faster readers showed somewhat larger perceptual spans (5–6 characters) than slower readers (3–4 characters). These data suggest that as reading proficiency improves, readers are able to allocate fewer processing resources to foveally fixated words. As a result, more proficient readers both allocate attention to and begin word recognition processes for lexical items outside the fovea, leading to a larger perceptual span (cf. Engbert, Nuthmann, Richter, & Kliegl, 2005; Kliegl, Grabner, Rolfs, & Engbert, 2004; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 2003 for computational models of how words are processed parafoveally). These types of data also suggest that the relationship between perceptual and reading ability is bidirectional. We return to this point in the discussion section.

In sum, perceptual span may be constrained by acuity in the foveal and parafoveal regions, but the processing demand exerted by material in the fovea is a primary determinant of perceptual span (Rayner, Slattery, & Belangier, 2010). When readers are less proficient or when text is more informationally dense, perceptual span is smaller. Taken together, these results suggest that perceptual span is determined by reading ability, though the relationship may also be bidirectional (Frey & Bosse, 2018).

There are also age-related changes in eye movements, which is relevant since most IWA are older than fifty years of age. Older adults tend to make more and longer fixations than younger adults (Kliegl, Grabner, Rolfs, & Engbert, 2004; Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006). Studies of perceptual span in older adults have reported some conflicting results. Rayner and colleagues (2009) reported that perceptual span was smaller and more symmetrical in older than younger adults: one word to the right and one word to the left of the fixated word. In contrast, Risse and Kliegl (2011) reported that perceptual span in older and younger adults was quite similar. The studies differ with respect to methods and materials, which makes the results difficult to compare. However, if it is the case that older adults require increased time and effort to recognize words during reading, then a smaller perceptual span would not be unexpected. Rayner and colleagues (2009) suggested that older adults may show a more symmetrical perceptual span because they have less efficient processing of parafoveal information, leading to increased reliance on foveal information to the left and right of fixation.

Although it is well known that IWA have impairments of reading comprehension, it is unclear how or if their perceptual span is affected. Thus, the present study investigated perceptual span in IWA and non-brain-damaged controls. Understanding the size of the perceptual span provides a window into understanding other aspects of reading in IWA, such as reduced skipping rates and the extent to which they benefit from parafoveal preview (cf. Rayner, 1998) when reading silently for comprehension. Given that IWA typically read more slowly and less accurately than non-brain-damaged controls, IWA were predicted to show smaller perceptual spans.

Methods

Participants

Fifteen IWA (9 males, mean age=59.9 years, range 42 – 70) following left hemisphere damage and fifteen non-brain-damaged controls (7 males, mean age=63.1 years, range 53 – 70) completed the study. In addition to the fifteen who completed the experiment, four IWA were unable to complete the study due to difficulty with the eye tracker (e.g., bifocal glasses, difficulty with calibration). Data from four of the 15 IWA who completed the study were later excluded because they were missing 25% or more of the observations (due to track loss and long reading times). Controls had more years of education than the individuals with aphasia (IWA: mean=13.5 years, controls: mean=15.7 years). The participants reported normal or corrected-to-normal vision and denied significant visual impairments. Control participants denied any history of neurological disease, language disorder, or reading impairment. All controls were screened for dementia using the Montreal Cognitive Assessment (Nasreddine et al., 2005), with a cut off of 26/30 points. Two controls did not pass based on this criterion, but were included because they also completed the Mini-Mental State Examination and earned at least 29/30 points (Folstein, Folstein, & McHugh, 1975).

IWA were at least one year post-onset of a stroke and were diagnosed with aphasia by a licensed speech language pathologist. All participants with aphasia were screened for neglect using a letter cancellation task. Table 1 presents background testing results for the participants with aphasia. Six were diagnosed with anomic aphasia, four with Broca's

aphasia, four with conduction aphasia, and one with transcortical motor aphasia. All participants completed the Boston Naming Test (Kaplan, Goodglass, & Weintraub, 2001) to document the presence of anomia. Western Aphasia Battery (WAB) Aphasia Quotients (AQ) (Kertesz, 2006) were available for all but two participants, and are given in Table 1. One participant (P15) was not aphasic by WAB, but was included based on her BNT performance and on the presence of significant anomia in connected speech.

To be included in the study, participants with aphasia had to demonstrate adequate single word comprehension in both the auditory and written modality. All participants had single word auditory comprehension within two standard deviations of the mean when compared to age matched controls on the Peabody Picture Vocabulary Test (Dunn & Dunn, 2007). In addition, all earned at least 97% accuracy on the written word picture matching subtest from the Psycholinguistic Assessment of Language (Caplan, 1992). All participants also completed the reading section of the Western Aphasia Battery (Kertesz, 2006). WAB total reading scores ranged from 43 to 94, and all participants demonstrated strong single word reading.

In addition, the Shipley vocabulary test (Shipley, Gruber, Martin, & Klein, 2009) was administered to provide a measure of how well the participants understood more complex vocabulary. The Shipley is a 40-word multiple choice vocabulary test that has been normed on neurotypical adults aged 20 to 90 years (in increments of 10 years). It begins with relatively simple words (e.g., talk, couch) and then progresses to very complex words (e.g., peregrinate, quotidian). Results of the Shipley demonstrate that seven of the eleven participants with aphasia performed within two standard deviations of normative sample, pointing to some word level reading impairments in the other four participants with aphasia.

Apparatus

Eye movements were recorded using a SR Research Eyelink 1000 eye tracker with a sampling rate of 1000 Hz. The Eyelink 1000 consists of a control unit, infrared camera, and display computer. Participants were seated with their chin on a headrest to minimize head movements, and were approximately 65 cm from the display monitor. Stimuli (sentences and visual screens) were presented in black courier new, 14-point font on a white background. The display was a 20-inch monitor with a resolution of 1024 by 768 pixels and a refresh rate of 150 Hz. The eye tracker has a spatial resolution of .01 degree, meaning that it has a very high degree of precision in measuring eye movements (SR Research, Toronto, Ontario, Canada). Given these parameters, approximately 2.8 characters fell within 1 degree of visual angle in the experiment.

Calibration and validation of the camera's measurement were completed using protocols established by SR Research for the Eyelink 1000 (EyeLink 1000 User Manual, version 1.5.2). The purpose of calibration is to map eye gaze in response to known target locations. The first step requires that the participant fixate on a series of three targets displayed on one line in the center of the screen. Following calibration, the camera's measurements were validated by comparing the distance between known fixation positions and the camera's measurement. The program calculates the measurement error as the difference between the

actual location and where the camera recorded the fixation. Acceptable error rates were less than .3 degrees of visual angle.

Visual Screening Tasks

Participants completed three visual screening tasks, which were designed to ensure that they could perceive and identify letters on the computer screen in the center of the visual field and in the parafoveal region to the left and right of fixation. Visual screens were programmed and presented using Experiment Builder Software (SR Research). Calibration and validation were completed before each task and throughout the task as necessary (e.g., if the camera did not recognize when participants were fixating on the target that initiated each trial). Sample trials are presented in Figure 1.

Letter Identity: This task ensured that participants could recognize letters on the screen in the font used in the moving windows task. A fixation point appeared on the screen. Next, a letter appeared on the screen for 1500 ms. After the letter disappeared, the participant was presented with three choices (the target, e.g., C and two visually similar foils, e.g., G and O) and pressed a button to identify the correct choice. Multiple-choice responses were used to minimize the possibility that expressive aphasia would lead to errors.

Field Cut: This task examined whether participants could identify a target to the left or right of a fixation. Trials proceeded as follows. First, a fixation cross appeared on the screen. Next, a ring of X's appeared around the fixation cross, with one "O". After 1500 ms, the ring of letters disappeared, and the participant used a number pad to indicate the location of the "O". The letters were arranged in a circle at the following coordinates: 512, 335; 547, 349; 561, 384; 547, 419; 512, 433; 477, 419; 463, 384; and 477, 349. This distance corresponds to approximately 5 characters (1.8 degree of visual angle) from the central fixation point. Participants were instructed to look at the cross and not move their eyes. Trials on which the eye tracker detected an eye movement were recycled. Thus, the task tried to determine whether the participant could detect a target without moving their eyes. There were four practice trials to familiarize participants with the procedure.

Movement: The purpose of this task was to examine whether IWA could detect characters to the left and right of fixation as quickly and accurately as controls. Trials proceeded as follows. A fixation cross appeared on the screen, followed by the letter X. When participants detected the X, they moved their eye gaze (i.e., a saccade) and fixated on the X until they heard a tone. After the tone, they looked back to the fixation cross. X's could appear anywhere around the fixation point, to prevent the participants from predicting where the X would be. In the critical trials, the X appeared on the same line as the fixation point (i.e., same x coordinate), but to the left or right of fixation (i.e., a different y coordinate). These X's occurred at 1.5, 2.4, and 3.3 degrees of visual angle from the fixation point. This corresponds to approximately 5 to 9 characters, or 1 to 2 words (given an average word length of 4.3; see below). There was a total of 60 trials.

The critical measures were (1) fixation time, defined as the time to fixate on X (relative to when the X appeared on the screen) and (2) fixation error, defined as the distance (in degree

of visual angle) from the center of the interest area containing the X to the measured location of the participant's fixation. To reduce the possibility that participants used multiple, shorter saccadic movements to fixate on the X, we coded only the first fixation in the direction of the X that occurred after the X appeared. Thus, if participants made multiple saccadic eye movements towards the X, only the first one would be counted (which would result in a larger fixation error).

The critical question for the movement task was whether individuals with aphasia showed a pattern consistent with a right visual field cut. This would be exemplified by slower response times or larger fixation errors for targets on the right versus left of the fixation cross, or by progressively longer response times or greater fixation error as targets were further to the right from the fixation cross.

Perceptual Span Task

During the experimental task, participants' eye movements were recorded while they read sentences and responded to yes/no comprehension questions about them. Each sentence was preceded by a calibration target in the center of the screen, followed by a fixation box on the left side of the screen. The fixation box was gaze-contingent, meaning that it would not disappear until the participant fixated on it for 300 ms. The purpose of the fixation box was to ensure that the first fixation would be at the beginning of the sentence. The camera was recalibrated following the practice sentences, every 25 trials, or whenever there was significant difficulty triggering the fixation box.

After the fixation box disappeared, the target sentence appeared on the screen at the vertical midline. The participant pressed a button on a button box interfaced with the computer to indicate when they were finished reading the sentence. Participants were allowed 30 seconds to read each sentence. If they did not finish within 20 seconds, the trial automatically ended. The time limit was imposed to limit the length of the task and to reduce possible effects of fatigue associated with spending more than 30 seconds per sentence. Also, it was unclear how to interpret reading times greater than 30 seconds, and whether longer reading times reflect reading processes per se or other cognitive processes. Each sentence was followed by a yes/no question to ensure that participants were reading for comprehension. A sample comprehension question is presented in table 2. Each list was preceded by a set of 10 practice items, which included all five conditions, to familiarize participants with the task.

Target sentences were presented in a gaze-contingent moving windows paradigm. The task is called "moving windows" because the sentence is covered in X's except for a "window" centered around the reader's fixation point. The purpose is to control how much information the reader has access to on each fixation. The "window" moves as the reader moves his/her gaze to each word in the sentence. Eyetrack software (<https://blogs.umass.edu/eyelab/software/>) ensured that the windows moved in synchrony with the eyes and that display changes occurred within 6 to 12 ms.

There were 3 different window sizes. In each of these conditions, one word to the left of the fixated word was visible, as well as no word (one word, or 1W), one word (W+1), or two

words (W+2) to the right of the fixated word (cf. Rayner et al., 1982). There was also a no-window condition, which acted as a baseline.

In the 1W condition, the reader could see the word they were fixating on (“word N”) and one to the left of it, but all other words were replaced by X’s. As the reader moved to the next word (Word N+1), Word N would be replaced by X’s and Word N+1 was revealed. In the “W+1” condition, the reader would be able to see the word they were fixated on, one word to the left, and one word to the right. All other words would be covered in X’s. In the “W+2” condition, the reader could see the word they were fixated on, one word to the left, and two words to the right. Figure 2 shows what the participant would see on sequential fixations in the 1W and W+2 conditions. The four study conditions are summarized in table 2.

Materials

The stimuli were 80 sentences modified from those used by Rayner et al. (2009). Sentences were modified so that they all had Subject-Verb-Object word order, contained 8 to 10 words, and were 34 to 65 characters in length. There was an average of 4.3 characters per word (standard deviation = .47). The sentences were then divided into sets of 20 sentences. Neither number of words nor number of characters differed between sets of sentences (F ’s < 1). Frequency of open class nouns and verbs in each sentence was determined using the SUBTLEXus database (Brysbaert & New, 2009). Frequency of these words did not differ across the sets of sentences (F < 1).

Next, four lists of experimental stimuli were created. All sentences occurred in all lists, but each sentence occurred in a different condition in each list. Thus, all sentences occurred in all conditions across lists and there were 20 items in each condition within each list. The design was a Latin Square in which each participant read one list. Lists were pseudorandomized for each participant, with the constraint that the same condition not occur on more than two consecutive trials.

Results

Visual Screens

Due to a programming error, only seven of the control participants completed the visual screening tests. However, none of these participants reported any visual impairments. All IWA completed the visual screening tests.

Letter Identity Task: Controls correctly identified 98% of the letters (range 90% to 100%). IWA correctly identified 89.6% of the letters (range 60% to 100%). Although there was some variation, all participants were above chance, indicating that they accurately perceived letters on the computer monitor.

Field Cut Task: Controls identified the correct location for 98.7% of the targets (range = 80% to 100%). IWA were 96.3% correct in identifying the correct location (range 67% to 100%). The two most important locations were four characters to the right and left of fixation, on the same line as the experimental sentences. Accuracy for the targets four

characters to the right of fixation was 97.1% (range 80% to 100%) for controls and 98.2% (range 80% to 100%) for IWA. Accuracy for the targets four characters to the left of fixation was 97.1% for controls (range 80% to 100%) and 100% for IWA.

Movement Task: Figure 3 presents the mean time that it took participants to fixate on the X (panel A) and the degree of error between the center of the X and the participants' actual fixation location, as measured by the eye tracker (panel B). In general, the IWA fixated on the targets more slowly than the controls. This measure includes both the time to detect the target and the time to fixate on it. Controls' fixation times ranged from 290 to 335 ms, depending on the location of the target. In contrast, IWA's fixation times ranged from approximately 321 to 473 ms. However, there was no clear difference between fixation times for targets to the left versus right of fixation, suggesting that visual field cuts were not affecting the results. The two groups differed less with respect to the accuracy of their fixations. The controls' fixation error ranged from .50 to .73 degrees of visual angle, whereas the IWA's fixation errors ranged from .48 to .67 degrees of visual angle. Perhaps more importantly, the groups' fixation error did not differ by more than .08 degrees of visual angle for any location, and there was no consistent pattern with respect to one group being more or less accurate than the other.

Perceptual Span Task

Data were screened as follows. Fixations shorter than 80 ms were merged with adjacent fixations and fixations longer than 1000 ms were excluded (cf. Abbott, 2011). The upper cut off for total reading times was 12000 ms. Finally, trials were omitted if there were more than 10 blinks. Data were analyzed using the R statistical package version 3.5.2 using the lmerTest package. Linear mixed effect (lme) models were fit to the reading time data separately for each group, with condition as the fixed effect. The models included random intercepts for participants and items, and random slope for participants by condition. Random slopes for items were not included because the maximal models failed to converge. The models converged, and returned the same results, when the random slope was included for either participants or items. Here, random slopes are reported for the participants because the effect of condition was deemed more likely to vary as a function of individual variability than item variability. Results of the lme models are presented in Table 3. Means and standard deviations are presented in Figure 4.

To determine the perceptual span, reading rate (words per minute), number of fixations, and average duration of each fixation for the no window condition were compared to reading times for other conditions. If the X's only replace characters outside of the perceptual span, they should not disrupt reading and so reading measures should not statistically differ from the full sentence condition. On the other hand, if the X's fall within the perceptual span, then reading should be slowed relative to the full sentence condition. Thus, perceptual span is the smallest window size at which there is no difference in reading times compared to the full sentence condition.

Words per Minute: Compared to the no-window condition, the controls read significantly fewer words per minute in the 1W, $\beta = -110.4$, 95% CI $[-122, -99]$, W+1, $\beta = -37.0$, 95%

CI [-48, -25], and W+2, $\beta = -18.1$ 95% CI [-30, -6]. The IWA's reading rate was significantly slower in the 1W, $\beta = -11.8$, 95% CI [-22, -1], condition compared to the no-window condition. However, none of the other comparisons were significant. This suggests that reading times for the W+1, $\beta = -2.7$, 95% CI [-13, 7.6], and W+2, $\beta = 0.1$, 95% CI [-10, 10], conditions were statistically equivalent to the no-window condition.

Number of Fixations: Controls made significantly more fixations in the 1W, $\beta = 1.9$, 95% CI [1.6, 2.3], and W+1, $\beta = 0.5$, 95% CI [0.2, 0.9], conditions compared to the no-window condition. There was no significant difference in the number of fixations in the no-window and W+2, $\beta = 0.2$, 95% CI [-0.1, 0.6] conditions.

IWA made significantly more fixations in the 1W condition than the no-window condition, $\beta = 1.7$, 95% CI [0.4, 2.9]. The W+1, $\beta = 0.9$, 95% CI [-.32, 2.2], and W+2, $\beta = -0.7$, 95% CI [-2, 0.6], conditions did not differ statistically from the no-window condition.

Mean Fixation Duration: Mean fixation duration was calculated by dividing total reading times by the number of fixations. The controls' mean fixation duration was longer in the 1W, $\beta = 43.6$, 95% CI [39, 48], W+1, $\beta = 4.2$, 95% CI [0.4, 2.9], and W+2, $\beta = 5.7$, 95% CI [0.4, 2.9], conditions compared to the no-window condition.

For IWA, mean fixation duration differed significantly in the 1W and no-window condition, $\beta = 13.1$, 95% CI [3, 23]. There were no significant differences between the no-window and W+1, $\beta = 4.2$, 95% CI [-6, 14], or W+2, $\beta = 5.7$, 95% CI [-4, 16], conditions.

Accuracy Data: Accuracy data were analyzed in logistic mixed effect models with random intercepts by participants and items. Models that contained random slopes did not converge. Results are presented in Table 4. Neither group showed significant differences in accuracy as a function of condition. Controls answered 97.3% of questions correctly in the no-window condition, 97.9% in the 1W condition, 97.1% in the W+1 condition, and 96.2% in the W+2 condition. IWA answered 75.7% of questions correctly in the no-window condition, 77.3% in the 1W condition, 74.7% in the W+1 condition, and 78.3% in the W+2 condition.

Post-Hoc Correlational Analyses: A correlational analysis was run to explore whether aphasia severity was associated with perceptual span. First, the difference in reading rate between the 1W and W+1 conditions was calculated for IWA. This difference score was a proxy for the cost (in reading rate) associated with being able to see only the fixated word, as compared to seeing one word to the right of fixation. The correlation for this difference score with WAB Aphasia Quotient was .61 ($p=.06$), and with WAB Reading Quotient was .52 ($p=.10$).

Discussion

The present study investigated whether IWA have a smaller perceptual span than non-brain-damaged controls. The results suggest that perceptual span is very reduced in IWA. Perceptual span in IWA was the word they were looking at plus one word to the right. The

logic is as follows. When the participant could not see any words to the right of fixation (1W condition), reading rate was significantly slower than it was in the no-window, baseline condition. However, reading rate did not differ from the no-window condition when at least one word to the right of fixation was visible (the W+1 condition). That is, if the IWA were able to perceive at least the fixated word and one word to the right of it, their reading rate was statistically indistinguishable from the full sentence condition. Similarly, IWA made more fixations on sentences when they could only see one word at a time. However, when they could see one or more words to the right of fixation (*W+1 or W+2* conditions), their reading was not distinguishable from the full sentence condition.

In contrast, the results suggest that the perceptual span for the controls was at least the word they were looking at plus two words to the right. In all the moving window conditions, reading rate and mean fixation duration were significantly slower than they were in the no-window, baseline condition. Controls made more fixations on sentences in the 1W and W+1 conditions than they did in the no-window condition. However, when they could see two words to the right of fixation (*W+2* condition), the number of fixations was not distinguishable from the full sentence condition. Taken together, these results suggest that the neurotypical group's perceptual span was at least two words to the right of fixation. However, the reading rate and average fixation duration data suggest that it could be larger given that W+2 was the largest window examined. Thus, perceptual span was considerably smaller in the IWA than control group.

Rayner and others have argued that perceptual span reflects the processing demand of information in the fovea (e.g., Henderson & Ferreira, 1990; Inhoff & Liu, 1998; Rayner, 1998). Thus, the present data are consistent with the view that both word recognition and syntactic processing were effortful for the IWA in the study. These data are also consistent with previous studies, which showed greatly reduced skipping rates in IWA compared to controls for content words (DeDe, 2017; Huck, 2017a). The common explanation for skipping words is that the reader is able to process the word without fixating on it, often because it is short (number of letters) and/or highly predictable in context. IWA may be less able to generate predictions about upcoming words in a sentence (e.g., predicting "the" after a transitive verb) due to slowed processing speed and reduced perceptual span, leading to overall slower reading comprehension. This does not mean that IWA are unable to generate any predictions about words in sentences (e.g., DeDe, 2012; Huck 2017a), but they may generate predictions more slowly than neurotypical individuals.

The relationship between reading speed and perceptual span is likely bidirectional (Frey & Bosse, 2018). That is, lexical or syntactic impairments may cause IWA to read more slowly. These impairments mean that text in the fovea exert greater processing demands on the reader, resulting in a reduced perceptual span. One consequence might be reduced parafoveal preview benefit, leading to more or longer fixations on words that more skilled readers could skip. Thus, reading impairments may contribute to a reduced perceptual span, which leads to further reduction in reading speed. This bidirectional cycle could result in the very slow reading times observed in many people with aphasia.

An alternative possibility is that visual field cuts reduced access to information in the right parafoveal region. Visual fields were not evaluated by optometry, meaning that this interpretation cannot be ruled out. Future research is required to fully explore this possibility. However, the visual screening tests were included to minimize the likelihood that visual perceptual ability would influence the measurement of perceptual span. The critical results were that (1) IWA may take longer to fixate on targets, but (2) they detect targets up to 3.3 degrees of visual angle to the right and left of fixation, and (3) they fixate on targets as accurately as controls. In particular, the finding that individuals with aphasia were able to perceive and fixate on targets one to two words to the right of fixation suggests that visual impairments alone do not account for the reduced perceptual span.

A potentially relevant data point is the positive correlation between WAB Aphasia and Reading Quotient scores and the magnitude of the reading rate decline from the 1W to W+1 condition. These correlations were non-significant, likely due to the small sample size. Thus, the results are to be interpreted with caution. However, the positive correlations are compatible with the idea that aphasia severity is associated with the size of the perceptual span, and with the idea that more mildly impaired individuals would typically derive more benefit from a larger window size.

Although clinicians are unlikely to measure perceptual span, these results are potentially interesting to clinicians as they shed further light on the underlying cause of slow reading times in IWA. In addition, perceptual span might prove to be sensitive to changes in reading comprehension ability in treatment research studies involving IWA. The expectation would be that as reading improves, the perceptual span should expand. Future research might also explore the relationship between perceptual span and syntactic effects such as predictability and word frequency, as well as examining the extent to which IWA benefit from parafoveal preview.

The present study has a number of limitations, including a relatively small number of participants and the lack of a formal assessment of the visual fields. The small number of participants might affect the generalizability of the data to a larger sample, and also likely underlies the non-significant correlations. Future work with large sample sizes would address these issues. Another issue was that the results may have been influenced by a greater number of blinks. Given the IWA's long reading times, only trials with more than 10 blinks were omitted. Previous studies of older and younger adults have allowed fewer blinks, but that was not realistic given the longer reading times in the present study. It is unclear how the inclusion of blinks would change the overall pattern of results, but it is possible that the total reading times were somewhat inflated by the inclusion of blinks.

In summary, the present study suggested that the field of useful visual information, or perceptual span, is smaller in individuals with aphasia (IWA) compared to non-brain-damaged controls. IWA's perceptual span was the fixated word plus one word to the right. Visual screening tasks make it unlikely that visual perceptual abilities account for these results. The reduction in perceptual span is consistent with the view that IWA take longer to access individual words, resulting in reduced processing of upcoming words in the text.

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Figure 1:
Example of Visual Screening Tasks. Note that figures are not to scale. Grey circles indicate the location of the participants' eye gaze when eye gaze is critical. Each tile represents a successive screen seen by participants.

Panel A: Sample of W1 condition

The g^{*}irl xxxx xx xxx xxxxxx xxxx xxxxxxxx.
 xxx girl we^{*}nt xx xxx xxxxxx xxxx xxxxxxxx.
 The xxxx went t^{*}o xxx xxxxxx xxxx xxxxxxxx.
 The xxxx xxxx to t^{*}he xxxxxx xxxx xxxxxxxx.
 The xxxx xxxx xx the st^{*}ore xxxx xxxxxxxx.
 xxx girl we^{*}nt xx xxx xxxxxx xxxx xxxxxxxx.
 The xxxx xxxx xx xxx store last^{*} xxxxxxxx.

* Indicates location of eye gaze in sequential fixations. Each line shows what the participant would see if they were to fixate on that word with the asterisk.

Panel B: Sample of W+2 condition

The g^{*}irl went to xxx xxxxxx xxxx xxxxxxxx.
 xxx girl we^{*}nt to the xxxxxx xxxx xxxxxxxx.
 xxx xxxx went t^{*}o the store xxxx xxxxxxxx.
 xxx xxxx xxxx to t^{*}he store last xxxxxxxx.
 xxx xxxx xxxx xx the st^{*}ore last Tuesday.

Figure 2:
 Example of Gaze Contingent Moving Window Display for W1 and W+2.

Figure 3:
Movement Task Data. Error bars show the standard error.

Figure 4:
Reading time data by Condition. Error bars show standard errors.

Table 1:

Participant Information

Participant	Age	Aphasia Type	WAB AQ	WAB Reading	Shipley	PPVT*	Boston Naming	PAL WPM
P01	58	Anomic	80.2	79	27 [‡]	96	46	32
**P02	69	Conduction	53.6	71	22 [‡]	91	0	32
**P03	68	Anomic	n/a	78	33 [‡]	101	56	32
P05	70	Broca	65.1	58	21 [‡]	91	41	32
P06	58	Broca	59.5	46	15	79	24	32
P08	42	Anomic	n/a	93	25 [‡]	98	51	32
P09	63	Conduction	90.2	94	31 [‡]	96	34	32
P10	70	Broca	52.7	60	17	91	8	32
**P11	63	Conduction	72.0	79	30 [‡]	83	29	32
P12	54	Anomic	90.3	90	35 [‡]	98	56	32
P13	48	Conduction	77.0	43	9	79	16	30
P15	61	Anomic	94.3	92	30 [‡]	88	46	31
**P17	68	Transcortical Motor	64.9	56	18	85	30	32
P18	52	Broca	84.8	47	12	83	31	31
P19	55	Anomic	88.8	81	23 [‡]	89	45	31

* Standard Score

** Participants excluded because more than 25% of the observations were missing on the perceptual span task.

[‡] Participants who scored within two standard deviations of the mean compared to age matched controls.

Abbreviations: WAB AQ is Western Aphasia Battery Aphasia Quotient, PPVT = Peabody Picture Vocabulary Test, WPM is word picture matching.

Table 2:

Condition Names and Numbers. Word N is the fixated word, “girl” in the example. Note that the participant can always see one word to the left of the fixated word.

Condition #	Condition Name	Example Sentence
1	Full sentence	The girl went to the store last Tuesday.
2	1W	The girl xxxx xx xxx xxxxx xxxx xxxxxxxx.
3	W+1	The girl went xx xxx xxxxx xxxx xxxxxxxx.
4	W+2	The girl went to xxx xxxxx xxxx xxxxxxxx.
Comp Q	Did the boy go to the store?	

Table 3:

Results of Reading Time Measures. The comparison condition is always the no-window condition. The β for the intercept is the mean of the comparison condition.

Fixed Effects	Reading Rate			Number of Fixations			Mean Fixation Duration		
	β	SE	<i>t</i>	β	SE	<i>t</i>	β	SE	<i>t</i>
People with Aphasia									
1W	-11.8	5.3	*-2.23	1.7	0.6	*2.57	13.1	5.1	*2.6
W+1	-2.7	5.3	-0.52	0.9	0.6	1.45	4.2	5.1	0.82
W+2	0.1	5.3	0.01	-0.7	0.6	-1.08	5.7	5.0	1.13
Intercept	118.0	11.9	*11.8	22.1	1.7	*12.8	258.3	13.1	*19.72
Non-brain-damaged Controls									
1W	-110.4	6.0	*-18.4	1.9	0.2	*10.2	43.6	2.3	*18.46
W+1	-37.0	6.0	*-6.2	0.5	0.2	*2.83	8.4	2.4	*3.56
W+2	-18.1	6.0	*-3.03	0.2	0.2	1.23	5.9	2.4	*2.49
Intercept	327.2	14.0	*23.38	8.8	0.4	*21.32	212.5	4.7	*45.1

Table 4:

Results of analyses of accuracy data. The comparison condition is always the no-window condition. The β for the intercept is the mean of the comparison condition.

Fixed Effects	<u>Individuals with Aphasia</u>			<u>Controls</u>		
	β	<i>SE</i>	<i>z</i>	β	<i>SE</i>	<i>z</i>
1W	0.15	0.21	0.69	0.34	0.54	0.63
W+1	-0.05	0.21	-0.25	-0.03	0.49	-0.06
W+2	0.20	0.21	0.95	-0.41	0.47	-0.88
Intercept	1.44	0.29	*5.05	4.54	0.52	*8.75