Research Article

Effects of Lexical Variables on Silent Reading Comprehension in Individuals With Aphasia: Evidence From Eye Tracking

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Purpose: Previous eye-tracking research has suggested that individuals with aphasia (IWA) do not assign syntactic structure on their first pass through a sentence during silent reading comprehension. The purpose of the present study was to investigate the time course with which lexical variables affect silent reading comprehension in IWA. Three lexical variables were investigated: word frequency, word class, and word length.

Methods: IWA and control participants without brain damage participated in the experiment. Participants read sentences while a camera tracked their eye movements.

Results: IWA showed effects of word class, word length, and word frequency that were similar to or greater than those observed in controls.

Conclusions: IWA showed sensitivity to lexical variables on the first pass through the sentence. The results are consistent with the view that IWA focus on lexical access on their first pass through a sentence and then work to build syntactic structure on subsequent passes. In addition, IWA showed very long rereading times and low skipping rates overall, which may contribute to some of the group differences in reading comprehension.

Most studies about sentence comprehension impairments in individuals with aphasia (IWA) focus on auditory comprehension (e.g., Caplan, Waters, DeDe, Michaud, & Reddy, 2007; Knilans & DeDe, 2015; Shapiro, 1997; Thompson & Choy, 2009). However, reading is an important means of accessing information (e.g., via the Internet) and a common leisure activity (e.g., reading books or magazines). The purpose of the present study was to examine how lexical variables affect silent reading comprehension using eye tracking.¹

DeDe (2012, 2013) investigated whether lexical and syntactic variables had similar effects on reading and listening comprehension in IWA and control participants without brain damage. DeDe (2012) focused on a lexical effect, word frequency. Both IWA and controls showed longer listening times for low- versus high-frequency words in self-paced listening, but the frequency effects were greater in IWA than controls. In self-paced reading, the results were mixed. Some IWA showed larger frequency effects

than controls, whereas others showed reverse frequency effects (i.e., longer reading times for high- than low-frequency words). Note that none of the IWA showed significant reverse frequency effects in the listening task. These data suggest that IWA are sensitive to word frequency but that the nature of the effect might differ from controls and that there may be differences between reading and listening. DeDe (2013) focused on effects of syntactic complexity and found very similar patterns of self-paced reading and listening times for object and subject cleft sentences. Both IWA and controls showed effects of syntactic complexity, that is, longer reading and listening times for the verb in object cleft sentences compared with the verb in subject cleft sentences. Thus, IWA seemed to show somewhat different effects of lexical variables than controls in reading comprehension, but syntactic processing seemed similar between groups and modalities. On the basis of these two studies, DeDe (2013) suggested that lexical processing might be more vulnerable to modality effects because word recognition depended on the surface form of the word (written vs. spoken) to a greater extent than syntactic processing.

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¹Throughout this article, references to *eye tracking* refer to the paradigm in which eye movements are measured during silent reading comprehension at the sentence level. Exceptions are specified as appropriate.

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However, a more recent study suggested that IWA and controls show different patterns of syntactic complexity in sentence reading. Knilans and DeDe (2015) investigated how IWA read object and subject cleft sentences using an eye-tracking paradigm. In eye tracking during reading, participants read a sentence on a computer screen while a camera recorded their eye movements. In contrast to previous studies of auditory comprehension and reading comprehension using self-paced reading, IWA appeared to process the sentences differently than controls. Specifically, IWA showed effects of syntactic complexity only when rereading sentences, rather than on the first pass through the sentence. In contrast, unimpaired adults show effects of syntactic complexity on their first pass through the sentence. Knilans and DeDe (2015) suggested that IWA might focus on lexical retrieval on the first pass through the sentence, so that they can use all available information to help build a syntactic representation during rereading. However, this contrasts with DeDe (2013), who suggested that syntactic processing was very similar in reading and listening and that lexical processing showed modality-specific effects.

One possibility is that task differences account for the results. Eye tracking during reading is more ecologically valid than self-paced reading because participants can revisit and reread words within the sentences when desired. In self-paced reading, participants are unable to reread words in the sentence. Thus, eye tracking during silent reading may more closely mirror how IWA read outside of experimental settings than self-paced reading. In addition, eye tracking while reading can distinguish readers' first pass through a sentence from subsequent passes (i.e., rereading). This is important because it can reveal potential differences in both the magnitude and time course of lexical effects in IWA and unimpaired adults. Little is known about how manipulations of word-level psycholinguistic variables affect IWA's eye movements during reading comprehension. The present study investigated whether three lexical variables—word frequency, word length, and word class—affect IWA's eye movements on their first pass through a sentence during silent reading comprehension.

The effect of word frequency on lexical access has been well studied in both unimpaired individuals and IWA. There is a lot of evidence that unimpaired individuals require more time to recognize and produce low- versus high-frequency words (e.g., Brysbaert, Lange, & Van Wijnendaele, 2000; Ferreira, Henderson, Anes, Weeks, & McFarlane, 1996; Gerhand & Barry, 1999; Just, Carpenter, & Wooley, 1982; Morrison & Ellis, 1995; Turner, Valentine, & Ellis, 1998). With respect to eye tracking during reading, unimpaired older and younger adults show longer first fixation times, gaze duration times, and total reading times for low-frequency than high-frequency words (e.g., Inhoff & Rayner, 1986; Kliegl, Grabner, Rolfs, & Engbert, 2004; Rayner & Duffy, 1986; Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006; Rayner, Sereno, & Raney, 1996). There is also evidence that frequency effects are larger in older adults than in younger adults (e.g., Kliegl et al., 2004; Rayner et al., 2006).

Word-frequency effects have been reported in IWA in many different tasks, including naming, lexical decision, and self-paced reading and listening (e.g., Bose, van Lieshout, & Square, 2007; DeDe, 2012; Gerratt & Jones, 1987; Kittredge, Dell, Verkuilen, & Schwartz, 2008; Nozari, Kittredge, Dell, & Schwartz, 2010; Varley, Whiteside, & Luff, 1999). A few studies have used eye tracking to examine word-frequency effects in individuals with acquired dyslexia. Schattka, Radach, and Huber (2010) demonstrated that some individuals with acquired dyslexia show effects of word familiarity, a proxy for word frequency, on refixation time (calculated as gaze duration – first fixation duration) and total reading time in an oral reading task. More directly relevant is Johnson and Rayner's (2007) case study, which focused on silent reading comprehension (also cf. Rayner & Johnson, 2005). Their letter-by-letter reader showed larger effects of word frequency than unimpaired individuals in total reading times and total number of fixations. However, Johnson and Rayner (2007) did not report eye-tracking measures that reflect the first pass through a sentence (e.g., gaze duration), so it is unclear whether the effect of word frequency emerged on the first pass through a sentence or only in subsequent passes. Taken together, these studies suggest that IWA are sensitive to word frequency. The question in the present study is whether word-frequency effects emerge in the first pass through the sentence during silent reading comprehension.

Similar to word frequency, converging data from many tasks suggest that IWA are sensitive to word length. The word-length effect is that long words take more time to process than short words. This effect is not consistently found in first fixation times, but gaze duration and rereading times are typically slower for long compared with short words (Hyönä & Olson, 1995; Kliegl et al., 2004; McConkie, Kerr, Reddix, Zola, & Jacobs, 1989; Rayner & McConkie, 1976). Shorter words are also more likely to be skipped (Rayner, 1998; Rayner & McConkie, 1976; Vitu, O'Regan, Inhoff, & Topolski, 1995). In one study, unimpaired individuals showed skipping rates of about 50% for three-letter words and 10% for seven-letter words (Vitu et al., 1995). Kliegl et al. (2004) compared word-length effects in older and younger adults and did not report age differences in reading durations or skipping rates.

IWA show length effects on confrontation naming (e.g., Nickels & Howard, 1995), repetition (e.g., McCarthy & Warrington, 1984), and oral reading tasks (e.g., Behrmann, Shomstein, Black, & Barton, 2001; Friedman & Kohn, 1990; Schattka et al., 2010). For example, Schattka et al. (2010) reported significantly longer refixation and total reading durations for medium (seven- to eight-letter) versus long (11- to 12-letter) words during an oral reading task. These types of data suggest that IWA will show word-length effects during silent reading comprehension, but it is unclear whether length effects in IWA and unimpaired adults will be of the same magnitude or emerge on the same time course.

Word class is another important determinant of eye movements during silent reading. Studies focused on

younger adults have shown that closed-class words such as determiners and conjunctions are skipped more frequently than open-class words of the same length. Carpenter and Just (1983) reported skipping rates of 60% for *the* and 71% for *and*. In contrast, three-letter content words were skipped 43% of the time. More recently, this finding has been replicated in studies focusing on the determiner *the* (Angele & Rayner, 2013; Drieghe, Brysbaert, Desmet, & De Baecke, 2004).

The effects of word class on skipping rates for IWA have not been investigated in silent reading comprehension. There is evidence that at least some IWA process closed-class words differently than individuals without brain damage, which could lead to differences in skipping rates (e.g., Friederici, 1985; Grossman, Carey, Zurif, & Diller, 1986; Rosenberg, Zurif, Brownell, Garrett, & Bradley, 1985; Swinney, Zurif, & Cutler, 1980). In one study, participants were instructed to cross out letters in written paragraphs (Rosenberg et al., 1985). Unimpaired individuals and individuals with Wernicke's aphasia were more likely to skip target letters in closed- than open-class words. For example, they missed the *t* in *but* more often than in *bat*. In contrast, individuals with agrammatic Broca's aphasia did not distinguish open- and closed-class words. Studies using event-related brain potentials suggest individuals with Broca's aphasia show absent or reduced effects of grammatical class when compared with unimpaired individuals (ter Keurs, Brown, & Hagoort, 2002; ter Keurs, Brown, Hagoort, & Stegeman, 1999; also cf. Park, McNeil, & Doyle, 2002). These types of data suggest that IWA, particularly those with Broca's aphasia, may skip closed-class words less often than controls. However, other studies suggest that individuals with agrammatic Broca's aphasia are sensitive to the presence of at least some types of closed-class words (DeDe, 2013; Dickey, Milman, & Thompson, 2008). Thus, it is unclear whether IWA will show normal effects of word class on skipping rates.

The Present Study

In a study using eye tracking during silent reading comprehension, Knilans and DeDe (2015) reported that effects of syntactic complexity emerged only when IWA were rereading sentences. They suggested that IWA might focus on lexical access, rather than syntactic structure building, in their first pass through sentences. The present study used eye tracking during silent reading to examine whether word frequency, word length, and word class influence IWA's eye movements on the first pass through a sentence. These lexical variables were chosen because their effects are well established in studies of unimpaired readers. Previous studies suggest that IWA are sensitive to word frequency and word length, so the question is whether IWA show sensitivity to these lexical manipulations on their first pass through the sentence. Predictions regarding word class are more complicated. The results will be consistent with Knilans and DeDe's (2015) claim if IWA are sensitive to word class on the first pass through the sentence,

as evidenced by higher skipping rates for determiners than nouns.

An alternative hypothesis is that, in contrast to Knilans and DeDe's (2015) hypothesis, both syntactic and lexical effects have a delayed effect during silent reading comprehension in IWA. In this scenario, effects of word frequency or word length in the present study would be observed in rereading times but not first fixation or gaze duration times. Lexical effects may persist in rereading times, so the critical question is whether the lexical effects emerge in the first pass through the sentence or only in rereading times.

Method

Participants

The Institutional Review Board of the University of Arizona approved this study. Nine IWA (three women, six men; $M = 55.9$ years, range = 34–69) and eight age-matched unimpaired controls (one woman, seven men; $M = 57$ years, range = 48–65) participated.² The controls had more years of education than IWA, $t = 2.3$, $p = .04$ (IWA: $M = 14.0$, range = 12–18; controls: $M = 16.9$, range = 12–19). The participants reported normal or corrected-to-normal vision and denied significant visual impairments. All IWA completed a letter cancellation task to screen for visuospatial neglect. Unimpaired participants denied any history of neurological disease, language disorder, or reading impairment. All controls were screened for dementia using the Mini-Mental State Examination, with a cutoff of 28 of 30 points (Folstein, Folstein, & McHugh, 1975).

IWA were at least 1 year after onset of aphasia and had documented speech-language impairments on the basis of testing by a licensed speech-language pathologist or by a master's student supervised by a licensed speech-language pathologist. The presence of anomia, which is a feature common to all aphasia types, was confirmed using the Boston Naming Test (Kaplan, Goodglass, & Weintraub, 2001). All IWA scored at least two standard deviations below the mean for age-matched controls on the Boston Naming Test. Single-word comprehension was tested using the Peabody Picture Vocabulary Test–Fourth Edition (Form A; Dunn & Dunn, 2007), in order to ensure participants had a minimal level of comprehension to perform the eye-tracking task. All IWA performed within two standard deviations of the mean for age-matched controls on the Peabody Picture Vocabulary Test. Participants also completed the Written Word Picture Matching subtest from the Psycholinguistic Assessment of Language (PAL; Caplan, 1992), to ensure that single-word reading ability was relatively preserved. All of the IWA except P10 achieved greater than 90% correct on the PAL written picture-matching test. P10 discontinued testing because of an unrelated illness and was unable to return to complete the PAL subtest. Syndrome classification was based on results of the Boston Diagnostic

²Data from the same set of participants are reported in Knilans and DeDe (2015), which focused on effects of syntactic complexity.

Aphasia Exam–Short Form (Goodglass, Kaplan, & Barresi, 2000) or the Western Aphasia Battery–Revised (Kertesz, 2006). Background information about the IWA, including test results, is presented in Table 1.

There is some evidence that individuals with agrammatism (or Broca’s aphasia, depending on the study) show atypical effects of word class (e.g., Rosenberg et al., 1985; ter Keurs et al., 1999; ter Keurs et al., 2002). For this reason, additional testing was used to identify symptoms of agrammatism in the IWA. The Northwestern Naming Battery (Thompson, Lukic, King, Mesulam, & Winetraub, 2012) was used to calculate the ratio of verbs to nouns in confrontation naming. The Sentence Comprehension and Production Priming subtests of the Northwestern Assessment of Verbs and Sentences (Cho-Reyes & Thompson, 2012) measured comprehension and production of canonical (e.g., actives, subject relatives) and noncanonical (e.g., passives, object relatives) sentences. Responses were scored as correct or incorrect according to the procedures outlined in the test manuals. These tasks were used to calculate the ratio of noncanonical to canonical sentences that were correctly understood and produced. The three ratios were averaged to determine the agrammatism ratio. Participants with average agrammatism ratios less than 0.80 were considered to be agrammatic (i.e., P02, P04, P06, P08, P09). This criterion was based on data showing that individuals with agrammatic aphasia typically have ratios less than 0.80, whereas individuals with anomic aphasia tend to have ratios greater than 0.80 (Cho-Reyes & Thompson, 2012; Thompson et al., 2012). Results are presented in Table 2.

Stimuli

Participants read a total of 224 sentences. Of these, 120 syntactically simple sentences were included in the present study. These included 27 transitive sentences, 27 intransitive sentences, 24 subject clefts, and 42 sentences such as those in Examples 1 and 2, which contained high- and low-frequency words. The remaining sentences were syntactically complex (e.g., object clefts and sentences with direct object/sentential complement ambiguities). The complex

sentences were included as fillers and were part of other experiments. The complex sentences were excluded to minimize the possibility that sentence difficulty would influence the results. Sentences ranged from nine to 14 words.

Word Frequency

Twenty-one sentence pairs contained high- and low-frequency words (see Examples 1 and 2). They were a subset of those originally developed by Juhasz, Liversedge, White, and Rayner (2006). DeDe (2012) used these stimuli in a study of frequency effects in IWA. The high-frequency words ($n = 21$) had an average occurrence of 143 words per million, and the low-frequency words ($n = 21$) had an average occurrence of 1.35 words per million (on the basis of CELEX; Baayen, Piepenbrock, & Gulikers, 1995). Juhasz and colleagues matched the items with respect to orthographic neighborhood frequency, number of letters, and lack of predictability in the sentence context. The sentences had various syntactic structures, but all had canonical word order.

1. Ralph rested in the **village** before he started on his trip. (High frequency)
2. Ralph rested in the **hammock** before he started on his trip. (Low frequency)
3. Comprehension question: Did Ralph rest after his trip?

Word Length

All nouns, verbs, and adjectives were extracted from the sentences and coded for length. This analysis included all 120 syntactically simple sentences. The analysis of length focused on high-frequency three- ($n = 190$), four- ($n = 202$), five- ($n = 155$), six- ($n = 161$), seven- ($n = 154$), and eight- ($n = 65$) character words. Each word length contained a mix of nouns, verbs, and adjectives, but the number of items in each word class differed among the lengths. There were fewer eight-letter words because of the inverse relationship between word frequency and word length. Word length is positively correlated with word frequency, with longer words

Table 1. Participant demographic and test performance data.

Participant ID	Age (years)	Education (years)	Gender	Aphasia type	Etiology	Boston Naming Test (maximum = 60)	Peabody Picture Vocab. Test ^a	Written Word Pic. Matching
P02	52	12	M	Anomic	CVA	50	97	0.97
P03	39	14	M	Anomic	CVA	51	99	0.97
P09	57	12	F	Anomic	CVA	46	96	1.00
P10	60	13	F	Anomic	CVA	48	94	N/A
P04	56	12	F	Broca	CVA	22	80	1.00
P06	68	15	M	Broca	CVA	29	99	1.00
P08	68	12	M	Broca	CVA	8	89	0.97
P12	34	12	M	Broca	Gunshot wound	5	72	0.94
P11	69	18	M	Conduction	CVA	0	91	1.00

Note. CVA = cerebral vascular accident.

^aStandard score, all within 2 SD of mean for age-matched controls.

Table 2. Accuracy by stimulus type and relevant ratios on the Northwestern Assessment of Verbs and Sentences (NAVS) and Northwestern Naming Battery.

Participant ID	NAVS: Production			NAVS: Comprehension			Northwestern Naming Battery			Agrammatism ratio ^a
	Canonical	Noncanonical	Ratio	Canonical	Noncanonical	Ratio	Nouns	Verbs	Ratio	
P02	13	3	0.23	13	15	1.15	16	16	1.00	0.79
P03	15	12	0.80	13	12	0.92	16	16	1.00	0.91
P09	13	1	0.08	14	6	0.43	16	15	0.94	0.48
P10	14	7	0.50	14	14	1.00	16	15	0.94	0.81
P04 ^b	0	0	0.00	11	7	0.64	13	12	0.92	0.78
P06	3	0	0.00	13	9	0.69	14	11	0.79	0.49
P08 ^b	0	0	0.00	13	13	1.00	6	3	0.50	0.75
P12 ^b	0	0	0.00	10	7	0.70	5	5	1.00	0.85
P11 ^b	0	0	0.00	9	10	1.11	10	8	0.80	0.96

Note. The maximum score for the canonical and noncanonical sentences was 15 for the NAVS Production and Comprehension subtests. The maximum score for the Northwestern Naming Battery was 16.

^aAgrammatism ratio was calculated by averaging the three ratios. ^bParticipant could not complete the NAVS Production subtest. This ratio was excluded from the agrammatism ratio for these participants. Ratios < 0.80 were considered to indicate agrammatism (see text for further details). Participants in boldface were classified as agrammatic.

being lower in frequency. To minimize the impact of this confound, only high-frequency words were included. For the purpose of this analysis, *high frequency* was defined as having a value of at least four on the seven-point Zipf scale (van Heuven, Mandera, Keuleers, & Brysbaert, 2014). Zipf scores are logarithmic word frequency scores, which control for the size of the database from which the raw scores were obtained. According to van Heuven et al. (2014), Zipf scores greater than four correspond to high-frequency words. Words were excluded if they occurred in the first or last position of the sentence.

Word Class

The analysis of word class focused on the determiner *the* because skipping rates of *the* have been demonstrated in multiple studies (e.g., Angele & Rayner, 2013; Carpenter & Just, 1983; Drieghe et al., 2004). Skipping rates for *the* were compared with skipping rates for three-letter nouns. Words (including determiners) were excluded if they occurred in the first or last position of the sentence. The three-letter nouns were *car*, *gun*, *man*, *boy*, *dog*, and *cat*. Each of these words occurred in at least 10 stimuli across the 120 syntactically simple sentences. Although the nouns were lower in frequency than *the*, they were all high frequency (Zipf value ≥ 4.5 , log frequency ≥ 3.1). Frequency and Zipf values for the items are presented in Table 3.

Procedures

The stimuli were divided into two lists so that similar sentences (e.g., sentences with high- and low-frequency nouns) were separated. All participants read both lists in different testing sessions, which were at least 7 days apart to minimize practice effects. The order of list presentation was counterbalanced across participants. Both lists began with 10 practice items to familiarize participants with the procedure, followed by 112 experimental items. There were

breaks after 25%, 50%, and 75% of the items or whenever the participant requested a break.

The experimental task was eye tracking during silent reading. Eye movements were recorded using an EyeLink1000 eye tracker (SR Research, Toronto, Ontario, Canada), using a desktop-mounted camera. Eye movements were sampled at a rate of 1000 Hz, from the right eye. Participants were seated approximately 65 cm from the display monitor, with the camera positioned immediately in front of the screen. Sentences were presented in Courier New, 14-point font in a single line of text. Text was presented in black on a white background. The display was a 20-in monitor with a resolution of 1,024 by 768 pixels. The eye tracker has a spatial resolution of 0.01°, meaning that it has a very high degree of precision in measuring eye movements (SR Research). Given these parameters, approximately 2.8 characters fell within 1° of visual angle in the experiment.

During eye tracking, participants sat in a height-adjustable chair and rested their head on chin and forehead rests to minimize movement. Calibration and validation were completed using protocols established by SR Research (2005) for the EyeLink 1000. The camera was calibrated by

Table 3. Frequency of stimuli for effects of word class.

Word	Frequency	Zipf	Length
<i>the</i>	3.9	7.5	3
<i>cat</i>	3.1	4.8	3
<i>gun</i>	3.5	5.3	3
<i>dog</i>	3.5	5.3	3
<i>car</i>	3.7	5.7	3
<i>boy</i>	3.8	5.7	3
<i>man</i>	3.9	6.3	3

Note. Frequencies are log-transformed values (Lg10CD) from SUBTLEXus (Brysbaert & New, 2009).

having the participant look at three targets displayed on one line in the center of the screen (at the position where the experimental sentences were displayed). The purpose of calibration is to map eye gaze in response to known target locations. Following calibration, the camera's measurements were validated by comparing the distance between known fixation positions and the camera's measurement. That is, participants were instructed to fixate on targets on the computer screen, and the program calculated the difference between the actual location and where the camera recorded the fixation. The difference between the actual location and the measured location is the measurement error. For the purposes of this study, acceptable error rates were less than 0.3° of visual angle. The camera was recalibrated following the practice sentences, at each break, and during the experiment as needed.

Individual trials proceeded as follows. First, a target like the ones used during calibration appeared at the center of the screen. When the participant fixated on the target, the experimenter pressed a key to initiate the trial. The purpose of this first target was to evaluate whether the camera's calibration had "drifted" over time. This might occur if the participant made small head movements or other positional adjustments. Second, a small gray box appeared at the left of the screen. It disappeared when the participant had fixated on the box for 300 ms. The box was located at the beginning of the sentence, ensuring that the participant's first fixation would be at the beginning (rather than middle) of the sentence. Together, the drift correction target and gray box served as a check on calibration. If participants had difficulty triggering these targets, the camera was recalibrated. Next, the sentence appeared on the screen. The entire sentence was visible until the participant indicated that he or she had finished reading the sentence by pressing a button on a button box interfaced with the computer. A yes/no comprehension question then appeared on the screen, and the participant pressed a button to indicate the response. A sample comprehension question is given in Example 3 above.

Design and Analysis

The dependent measures of interest were first fixation duration, gaze duration, skipping rate, and rereading time. To understand these measures, consider Example 4. The subscripted numbers represent a participant's successive eye fixations while reading the sentence. In the example, the reader fixates on *girl* first, followed by *The*, and so on. There are two fixations on *girl*, one on the first pass through the sentence and one on the second pass through the sentence. There are also two successive fixations on *mountain* (noted as Fixations 5 and 6), which would likely occur on different letters of the word. For example, the reader might fixate on the *u* and then the *i* before moving to the next word.

4. The₂ girl_{1, 9} went₃ to the₄ mountain_{5, 6} with her₇ mother_{8, 10}.

Both first fixation and gaze duration are obtained on the first pass through the sentence. Gaze duration is the total duration of all fixations on a word before moving the eyes to another word. In Example 4, first fixation duration for *mountain* would be the duration of Fixation 5, and gaze duration would be the sum of Fixations 5 and 6. First fixation durations are in some sense a cleaner measure of first-pass processing than gaze duration because the former includes only one fixation. Nonetheless, gaze duration is considered to be a first-pass measure because it encompasses fixations on the target word before the eye moves to the left or right of the target (Clifton, Staub, & Rayner, 2007). Some words are skipped on the first pass through the sentence (e.g., *to*). Skipping rates indicate whether readers fixate on a given word on their first pass through the sentence. Words are more likely to be skipped when they are short, highly predictable in context, or function words (for review, see Drieghe, Rayner, & Pollatsek, 2005; Rayner, 1998). Participants also reread words after making regressive or progressive eye movements; rereading time for *girl* would be the duration of Fixation 9.

Although many other reading measures are available, these were chosen because they were likely to be sensitive to effects of the lexical variables and to distinguish the first pass through the sentence (first fixation duration, gaze duration, skipping rate) from subsequent passes (rereading times). Total reading times, which are the sum of all fixations in a region, were not reported because they conflate first-pass reading times with rereading times.

Fixations were defined using the manufacturer's default settings, which use algorithms to identify saccades and blinks and define fixations as the time between saccades (SR Research, 2005). Fixations interrupted by blinks are treated as separate fixations. Before data analysis, fixations shorter than 80 ms were merged with adjacent fixations. Gaze duration and rereading duration were based on fixations only; saccades were excluded from the measures (cf. Rayner, 1998, for discussion). Gaze duration was calculated using the Get Reading Measures application available through SR Research.

Data were analyzed both including and excluding items whose comprehension questions were incorrectly answered. The results did not differ, so here we report analyses including all items. In addition, outliers that were three standard deviations above or below the mean were replaced with the upper or lower value. Finally, items were excluded if the participant blinked while reading a critical word in the sentence. This resulted in removal of 11% of the observations.

Unless otherwise noted, reading time measures were analyzed with linear mixed effect (LME) models using the lme4 package in R (R Core Team, 2008). LME models were estimated separately for the four dependent measures (first fixation duration, gaze duration, skipping rate, rereading duration) and for each lexical variable (word length, class, and frequency). Similar to analyses of variance, LME models provide a way to estimate main effects and interactions associated with fixed factors (here, lexical variables

and group). LME models have the advantage of allowing participants and items to be treated as random factors within one analysis (cf. Baayen, Davidson, & Bates, 2008; Jaeger, 2008). In addition, experimental manipulations such as frequency can be treated as continuous rather than categorical variables. All models included random intercepts for participants and items. Random slopes were tested for the lexical variables (length, frequency, and word class). LME models of word length and word frequency included random slopes for these variables, whereas random slopes associated with word class were removed because they accounted for too little variance in the model.

Model selection proceeded as follows. For each dependent measure, the first LME model contained the main effects of group (IWA vs. controls) and lexical variable (frequency, length, or class) and the interaction of these variables. Control variables were also included. For example, frequency of the critical words in the analyses of word length and word class was included as a covariate, in order to minimize the effects of this confounding variable on the variables of interest. Variables were treatment-coded, with the control condition serving as the reference variable. The reference variable for the factor group was the group of participants without brain damage. The reference variable for the factor word class was three-letter nouns. Next, nonsignificant parameters were removed iteratively, and the resulting models were compared using log-likelihood χ^2 tests with a criterion of $p < .05$. A significant result indicates that the larger model (i.e., the one with more parameters) provides a significantly better model fit to the data than the smaller model. The best approach to the calculation of degrees of freedom is not clear for parameters in LME models; for this reason, p values were calculated using Markov Chain Monte Carlo simulations (cf. Baayen et al., 2008). Finally, significant interactions in the LME models were further explored using pairwise t tests in R,³ with p values adjusted with a Holm correction for multiple comparisons. The alpha level for the adjusted p values was set at .05.

Results

Accuracy

Overall, the IWA correctly answered 76.2% of the comprehension questions, and controls correctly answered 95.2% of the comprehension questions. IWA correctly answered 76.2% of questions in the high-frequency condition and 78.0% in the low-frequency condition. The controls correctly answered 98.0% of questions in the high-frequency condition and 95.4% in the low-frequency condition.

³Note that the pairwise t -test function in R does not provide t statistics or unadjusted p values. Hence, only Holm-adjusted p values are reported. Holm's adjustment essentially involves a sequential application of the Bonferroni correction (in which p values are multiplied by the number of comparisons), using an algorithm based on the p values and the number of comparisons.

Word Frequency

Table 4 contains the estimate, standard error, t value, and p value for each factor in the best-fitting model for word frequency for each dependent variable. Figure 1 presents the means and standard errors for all reading times, and Panel A of Figure 2 presents data for skipping rates. For ease of presentation, means and standard errors are reported for high- and low-frequency words as defined in the Method section. However, frequency was treated as a continuous variable in the LME analyses.

First Fixation Durations

The best-fitting model showed main effects of frequency and group, reflecting longer first fixations by IWA and for low-frequency words. Although the interaction was significant, the t tests revealed no significant differences of interest (adjusted $ps > .5$).

Gaze Duration

The best-fitting model contained both main effects of frequency and group and the interaction between frequency and group. Although both groups showed significant effects of frequency, the effect was greater in the IWA than controls (adjusted $ps < .001$).

Rereading Time

The best-fitting model contained both main effects and the interaction between group and frequency, but the main effect of frequency was not significant (see Table 4). Post hoc t tests revealed that the effect of frequency was significant in both groups but larger in the IWA (adjusted $ps < .001$).

Probability of Skipping

The best-fitting model contained main effects of group and frequency but no interaction between the two parameters. Numerically, controls skipped high-frequency words

Table 4. Results of best-fitting linear mixed effect models for frequency effects.

Parameter	Estimate	Standard error	t value	p value
First fixation duration				
Frequency	-3.7	1.5	-2.5	.02
Group	54.6	19.5	2.8	.01
Frequency $\times$ Group	-5.4	2.3	-2.3	.02
Gaze duration				
Frequency	-6.7	3.2	-2.1	.04
Group	320.3	34.1	9.4	<.0001
Frequency $\times$ Group	-42.4	4.4	-9.6	<.0001
Rereading times				
Frequency	4.1	5.7	0.7	.47
Group	770.8	55.2	14.0	<.001
Frequency $\times$ Group	-73.1	7.9	-9.2	<.001
Skipping rate				
Frequency	0.3	0.1	4.3	<.0001
Group	-2.2	0.3	-6.9	<.0001
Frequency $\times$ Group	Parameter excluded in best-fitting model			

Figure 1. Effects of word frequency on reading times for individuals with aphasia (IWA) and controls. Error bars depict the standard error.

more often than low-frequency words, and IWA showed low skipping rates for both conditions.

Summary

Like controls, IWA spent more time reading low-frequency words than high-frequency words. The effects tended to be larger in IWA, with differential group effects emerging in gaze duration times and persisting throughout reading times for the sentence.

Word Length

Table 5 contains the parameter estimates, standard errors, *t* values, and *p* values for the best-fitting model for each dependent variable. Figure 3 presents the means and standard errors for the reading time data; skipping rates are presented in Panel B of Figure 2. Given the large number of pairwise comparisons, results of *t* tests for significant interactions are presented in Table 6.

First Fixation Duration

Neither the main effect of length nor the main effect of group was significant, but the interaction between group and length was. The *t* tests showed that IWA made significantly shorter first fixation durations on three-letter words than all other word lengths, with no other significant effects of length for IWA or controls.

Gaze Duration

The main effect of group was not significant, but the main effect of length and the interaction between group and length were significant. The interaction emerged because IWA showed significant effects of length for more of the pairwise comparisons than controls (see Table 6).

Rereading Time

The main effects of group and length were significant, as was the interaction between group and length. Similar to gaze duration, the IWA showed more pairwise effects of length than the controls.

Probability of Skipping

IWA skipped fewer words than controls, and both groups were more likely to skip shorter (three- to four-letter) than longer (six- to eight-letter) words. The interaction was not significant.

Summary

Like controls, IWA read shorter words more quickly than longer words and were more likely to skip relatively short words. The effect of word length was significantly greater in IWA than controls on the first pass through the sentence, as indicated by first fixation and gaze duration times. Skipping rates were lower in IWA than controls.

Word Class

Previous research has focused on the probability of skipping open- versus closed-class words rather than other reading time measures. For this reason, only skipping rates are reported here. Results for the full group of IWA versus controls are presented in Table 7, and means/standard errors are in Panel C of Figure 3. IWA skipped fewer words than controls, and both groups were more likely to skip *the* than high-frequency, three-letter nouns. The interaction between word class and group was marginally significant ($p = .05$). Inspection of the post hoc tests showed that IWA skipped nouns significantly less

Figure 2. Effects of word frequency, word length, and word class on skipping rates for individuals with aphasia (IWA) and controls. Error bars depict the standard error. (A) Word frequency. (B) Word length. (C) Word class.

often than controls ($M = 0.39$ for controls vs. 0.20 for IWA, $p = .03$) and skipped *the* significantly less often than controls ($M = 0.54$ for controls vs. 0.48 for IWA, $p = .002$).

Agrammatism

Some studies have reported that individuals with agrammatism are less likely to skip closed-class words than controls or individuals with other aphasia types. To address this question, data from the five individuals with agrammatism were compared with controls. The results were similar to those reported for the full group. Results of the LME analyses are in Table 7. Individuals with agrammatism skipped the determiner *the* 45% of the time (standard error = 22%) and three-letter nouns 11% of the time (standard error = 14%). The main effects of both group and word class were significant, and the interaction showed a weak trend toward significance ($p = .09$). Numerically, it seemed like the individuals with agrammatism were less likely to skip nouns than controls (and the full group of IWA) but that skipping rates for *the* were similar between the groups.

Summary

Like controls, IWA were more likely to skip closed-class words than open-class words. IWA skipped both nouns and *the* less often than controls.

Discussion

The present study investigated whether lexical variables affect IWA's reading times on their first pass through a sentence or if lexical effects emerge only in rereading times. The results were clearly consistent with Knilans and DeDe's (2015) prediction that IWA would show lexical effects on their first pass through a sentence. Effects of word frequency and word length were also observed in rereading times, but the critical finding was that all three lexical variables influenced reading behavior on the first pass through the sentence. We will consider each of the lexical variables in turn.

With respect to word frequency, both IWA and controls showed small but significant effects of word frequency in first fixation durations. It is somewhat surprising that the small differences in Figure 1 represent significant differences, but it is important to recall that frequency was treated as a continuous variable in the LME analyses and a categorical variable in the post hoc t tests. In fact, the post hoc t tests revealed no significant differences in the first fixation durations. The difference between the LME and t -test results is likely an artifact of the two analytic approaches, with the LME models being more sensitive to frequency effects because frequency was treated as a continuous rather than dichotomous variable (cf. Tily, Fedorenko, & Gibson, 2010). Regardless, the LME models from first fixation durations and the LME models and post hoc tests for the gaze durations indicate that effects of word frequency were greater in IWA than controls on the first pass through the sentence. The IWA continued to show larger frequency effects than controls in rereading times. The controls showed numerically longer rereading times for low- compared with high-frequency words, but the difference was not significant. Skipping rates were somewhat different, due to

Table 5. Results of best-fitting linear mixed effect models for length effects.

Parameter	Estimate	Standard error	t value	p value
First fixation duration				
Length	0.0	0.1	0.4	.66
Group	13.5	15.4	0.9	.39
Length × Group	2.3	0.9	2.6	.01
Gaze duration				
Length	5.3	1.4	3.6	<.001
Group	19.5	24.5	0.8	.43
Length × Group	21.4	1.6	13.2	<.0001
Rereading time				
Length	9.1	2.9	3.2	.001
Group	157.7	42.9	3.7	.001
Length × Group	41.4	3.2	13.0	<.0001
Skipping rate				
Length	−0.3	0.02	−20.2	<.0001
Group	−1.7	0.4	−4.3	<.0001
Length × Group	Parameter excluded in best-fitting model			

overall lower skipping rates in IWA. We return to this point below. The present results extend Johnson and Rayner's (2007) finding of larger word-frequency effects in IWA from a single case study to a group of IWA and show that group differences are present in both the first pass through the sentence and in rereading times.

The frequency results were inconsistent with DeDe's (2012) self-paced reading data, where there were not significant differences in the magnitude of word-frequency effects in IWA and controls. DeDe's (2012) results likely reflected reverse frequency effects in some of the IWA. The present study did not replicate the reverse frequency effects, suggesting that they are not a consistent characteristic of reading in IWA. The present results are consistent with DeDe's (2012) observation that frequency effects were greater in IWA than controls in the group analysis of self-paced listening data. It is possible that the difference between self-paced reading and eye tracking during reading reflect task differences. Eye tracking during reading allows the participant to reread words, whereas self-paced tasks do not allow participants to revisit sentence segments. Eye tracking has greater ecological validity than self-paced reading, because it more closely resembles reading outside of laboratory settings. Some of the IWA in DeDe (2012) may have had difficulty adjusting their reading patterns in the self-paced reading task, resulting in reverse frequency tasks. Thus, it is likely that the present eye-tracking data represent how IWA read better than the results of self-paced tasks.

Next, consider the effects of word length. Not surprisingly, IWA had longer reading times than controls across word lengths. In addition, the IWA seemed to be more sensitive to word length than controls. The main differences were that IWA showed effects of length for more of the contrasts than controls and that IWA were less likely to skip relatively short words ($\leq$ five letters) than controls. The group differences were relatively weak in the first

Figure 3. Effects of word length on reading times for individuals with aphasia and controls. Error bars depict the standard error. (A) Controls. (B) Individuals with aphasia (IWA).

Panel A: Controls

Panel B: Individuals With Aphasia

fixation durations, but they were observed in gaze durations and rereading times. This finding is consistent with the results from Schattka et al. (2010) and Behrmann et al. (2001) from oral reading tasks and extends the results to a different task (silent reading comprehension). The present results also show that group differences in word-length effects are present in the first pass through the sentence as well as in rereading times.

An anonymous reviewer pointed out that reliance on nonlexical (grapheme-to-phoneme) reading routes might account for more marked length effects in the IWA. This is an interesting observation, although it is worth noting that the nonlexical route does not necessarily lead to reading comprehension unless the word is read aloud. That is, there is no direct link from the indirect reading route to the semantic system. This line of inquiry is related to the nature of the relationship between performance on oral

Table 6. Pairwise comparisons for the interaction between group and length for gaze duration, rereading times, and probability of skipping.

Item	Individuals with aphasia					Controls				
First fixation duration										
Length	3	4	5	6	7	3	4	5	6	7
4	<.0001					ns				
5	<.0001	ns				ns	ns			
6	<.0001	ns	ns			ns	ns	ns		
7	<.0001	ns	ns	ns		ns	ns	ns	ns	
8	<.0001	ns	ns	ns	ns	ns	ns	ns	ns	ns
Gaze duration										
Length	3	4	5	6	7	3	4	5	6	7
4	<.0001					ns				
5	<.0001	.001				.02	ns			
6	<.0001	<.0001	ns			.14	<.0001	.07		
7	<.0001	<.0001	.001	.04		<.0001	<.0001	.02	.02	
8	<.0001	<.0001	<.0001	<.0001	ns	<.0001	<.0001	.02	.01	ns
Rereading times										
Length	3	4	5	6	7	3	4	5	6	7
4	ns					ns				
5	<.0001	.001				.01	ns			
6	<.0001	<.0001	< .01			.001	.05	ns		
7	<.0001	<.0001	.01	ns		<.0001	.001	.10	ns	
8	<.0001	<.0001	< .01	ns	ns	<.0001	<.0001	< .01	.01	.16
Probability of skipping										
Length	3	4	5	6	7	3	4	5	6	7
4	ns					.02				
5	<.0001	< .01				<.0001	<.0001			
6	<.0001	.001	ns			<.0001	<.0001	.01		
7	<.0001	< .01	ns	ns		<.0001	<.0001	<.0001	.09	
8	<.0001	< .01	ns	ns	ns	<.0001	<.0001	<.0001	< .01	.17

Note. ns denotes $p > .20$. Given the large number of comparisons (30 for each dependent variable), it is worth noting that most of the significant effects survive a Bonferroni correction, which would use a cutoff of .0017.

reading tasks and silent reading comprehension. Some studies of college age adults without brain damage suggest that aspects of prosody influence reading comprehension (e.g., Steinhauer & Friederici, 2001, but cf. Staub, Grant, Clifton, & Rayner, 2009). The present study was not designed to investigate whether performance on oral reading tasks correlates with silent reading comprehension. Future studies might include measures of sublexical written language processing and oral reading ability to evaluate whether length effects can be related to reliance on the non-lexical reading route.

The final lexical variable under consideration was word class. Both IWA and controls showed higher skipping

rates for determiners than similarly high-frequency nouns. The interaction between group and word class was significant, but IWA skipped fewer nouns and determiners when compared with controls. Numerically, the difference in skipping rates between IWA and controls was larger for nouns (19% difference) than determiners (6% difference). Taken together, these data suggest that IWA and controls show similar effects of word class on skipping rates while reading and that word class exerts an effect on reading on the first pass through the sentence.

The effects of word class are relevant to the larger issue of how IWA process open- and closed-class words. In the current study, the skipping rate for closed-class words was similar to controls in both the full group of IWA and a subset identified as having agrammatism. Given the small number of individuals with agrammatism, these results should be interpreted cautiously. Nonetheless, the results are consistent with previous studies reporting that IWA are sensitive to the presence of closed-class words (DeDe, 2013; Dickey et al., 2008). Other studies have suggested that individuals with agrammatic Broca's aphasia do not differentiate between open- and closed-class words in the same ways as controls. One possibility is that IWA show different effects of word class depending on the types of closed-class words tested (e.g., determiners vs. conjunctions). This would account for the discrepant results because the previous studies (Rosenberg et al., 1985; ter Keurs et al.,

Table 7. Results of best-fitting linear mixed effect model for word class effects on skipping rates.

Item	Estimate	Standard error	t value	p value
IWA (including those with and without agrammatism) vs. controls				
Word class	0.6	0.2	3.3	.001
Group	-1.2	0.5	-2.3	.02
Class × Group	0.9	0.5	2.0	.05
Individuals with agrammatism vs. controls				
Word class	0.6	0.2	3.2	.001
Group	-1.8	0.8	-2.1	.03
Class × Group	1.3	0.8	1.7	.09

1999, 2002) tested a range of closed-class words, whereas the current study focused only on *the*.

Another possibility is that effects of word class do not differ for IWA and controls on the first pass through a sentence but emerge later in processing. Rosenberg et al.'s (1985) letter cancellation task did not distinguish different processing stages. In ter Keurs et al.'s (1999, 2002) event-related potential studies, written stimuli were presented one word at a time, meaning that participants were not given a choice of whether or not to skip closed-class words. In contrast, the analysis of word class in the present study focused on the decision of whether or not to fixate on *the*. The idea that differences in processing open- and closed-class words emerge somewhat later in sentence comprehension is consistent with a study by DeDe (2013). DeDe (2013) found that IWA showed sensitivity to the presence of the complementizer *that* in sentential complements but did not rely on the complementizer to disambiguate the sentences. Although speculative, it may be that IWA initially recognize closed-class words but treat them differently in later processing stages. Further research is needed to explore these ideas, including whether the results generalize to function words other than *the* and to a larger group of IWA. Future studies may also investigate whether skipping rates vary for different types of open-class words (e.g., nouns vs. adjectives vs. verbs). Regardless, it seems clear that the IWA in this study were sensitive to word class on the first pass through the sentence.

Moving beyond the specific lexical effects, a striking difference between the overall reading behaviors of IWA and controls was that IWA had much longer reading times across all word lengths and frequencies. This is consistent with previous studies of both oral reading (e.g., Schattka et al., 2010) and reading comprehension (e.g., DeDe, 2012; Johnson & Rayner, 2007; Knilans & DeDe, 2015). First fixation durations, gaze durations, and rereading times were longer in IWA than controls, but inspection of Figures 1 and 3 suggests that group differences were greater in rereading times than in the first pass through the sentence. For example, gaze duration was roughly twice as long in IWA compared to controls, whereas rereading times were four to seven times longer in IWA compared with controls. Although not the focus of this article, it is worth noting that the controls generally showed very short rereading times. The controls showed numeric trends toward effects of frequency and length in rereading times, but these were not significant. This likely reflects the relatively short and simple sentences analyzed in this study.

More interesting are the rereading times for the IWA. The increase in rereading times was observed for both relatively easy words (high-frequency or short) and harder words (low-frequency or long). Longer reading times could reflect strategic processing, possibly a response to treatment strategies that focus on very careful processing of written material. In the absence of specific treatment data for the participants, however, this sort of explanation is speculative. Another possibility is that slowed reading times were indicative of poorer oculomotor control. This explanation

is unlikely because oculomotor control would affect both first-pass and rereading times, and rereading times were disproportionately longer than first-pass reading times. Finally, longer rereading times could be a strategy to compensate for word retrieval impairments or decreased short-term memory (DeDe, Ricca, Knilans, & Trubl, 2014; Martin, Kohen, Kalinyak-Fliszar, Soveri, & Laine, 2012). That is, participants with aphasia may spend more time rereading words in an effort to fully access their meaning. Further research is needed to explore these possibilities.

IWA were also less likely to skip open-class words than controls. For example, controls skipped high-frequency words approximately 14% of the time, compared with 1% for IWA. With respect to word length, controls skipped three-letter words 44% of the time, compared with 29% for IWA. According to Rayner and colleagues, words are skipped when they can confidently be recognized on the basis of parafoveal preview (Drieghe et al., 2005; Rayner, 1998). Unimpaired readers use parafoveal preview less efficiently when lexical access is slower, as in the case of low-frequency words (e.g., Inhoff & Rayner, 1986). Thus, IWA's lower skipping rates might indicate that they are less able to recognize words on the basis of parafoveal preview than unimpaired readers.

From a clinical perspective, these data are interesting because they suggest that longer reading times in offline tasks probably reflect longer rereading times and lower skipping rates, rather than slowed reading on the first pass through the sentence. This observation raises the question of whether time spent rereading words is an effective compensatory strategy for reading comprehension. One way to address this question would be to examine the relationship between online measures such as first-pass reading times and rereading times and offline measures such as word- and sentence-level reading comprehension and oral reading ability. Such analyses would help determine whether, for example, longer rereading times for low-frequency words are associated with better performance on measures of online and offline reading comprehension.

One limitation of the present study is the relatively small sample size and the fact that the control group had a small but significant advantage over the IWA with respect to years of education. Another limitation was that the sentences were not carefully controlled for length or syntactic structure in the analyses of word length and word class. That the predicted lexical effects were observed despite variations in sentence type and word position speaks to the robust nature of these effects. Given that the present study replicated previous findings from unimpaired individuals, it is unlikely that features of the sentence stimuli significantly influenced the results. However, it is possible that some of the group differences in effects of word length and word class would be mitigated in more carefully controlled sets of sentences.

In sum, the results were consistent with Knilans and DeDe's (2015) proposal that IWA focus on lexical access on their first pass through the sentence and then assign syntactic structure on subsequent passes. On their first pass

through the sentence, IWA in this study showed effects of word class, word length, and word frequency that were either similar to or greater than those observed in controls. IWA also demonstrated very low skipping rates and long rereading times, which may contribute to group differences in reading comprehension. Differences in IWA's lexical processing may contribute to sentence impairments at the sentence and discourse levels, even in syntactically simple sentences.

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References

- Angele, B., & Rayner, K. (2013). Processing the in the parafovea: Are articles skipped automatically? *Journal of Experimental Psychology: Learning, Memory and Cognition*, 39, 649–662.
- Baayen, R. H., Davidson, D. J., & Bates, D. M. (2008). Mixed-effects modeling with crossed random effects for subjects and items. *Journal of Memory and Language*, 59(4), 390–412.
- Baayen, R. H., Piepenbrock, R., & Gulikers, L. (1995). *The CELEX lexical database (Release 2)*. Philadelphia, PA: Linguistic Data Consortium.
- Behrmann, M., Shomstein, S. S., Black, S. E., & Barton, J. J. (2001). The eye movements of pure alexic patients during reading and nonreading tasks. *Neuropsychologia*, 39(9), 983–1002.
- Bose, A., van Lieshout, P., & Square, P. A. (2007). Word frequency and bigram frequency effects on linguistic processing and speech motor performance in individuals with aphasia and normal speakers. *Journal of Neurolinguistics*, 20(1), 65–88.
- Brysaert, M., Lange, M., & Wijnendaele, I. V. (2000). The effects of age-of-acquisition and frequency-of-occurrence in visual word recognition: Further evidence from the Dutch language. *European Journal of Cognitive Psychology*, 12, 65–85.
- Brysaert, M., & New, B. (2009). Moving beyond Kucera and Francis: A critical evaluation of current word frequency norms and the introduction of a new and improved word frequency measure for American English. *Behavior Research Methods*, 41, 977–990.
- Caplan, D. (1992). *Language: Structure, processing, and disorders*. Cambridge, MA: MIT Press.
- Caplan, D., Waters, G., DeDe, G., Michaud, J., & Reddy, A. (2007). A study of syntactic processing in aphasia I: Behavioral (psycholinguistic) aspects. *Brain and Language*, 101(2), 103–150.
- Carpenter, P. A., & Just, M. A. (1983). What your eyes do while your mind is reading. In K. Rayner (Ed.), *Eye movements in reading: Perceptual and language processes* (pp. 275–307). Hillsdale, NJ: Academic Press.
- Cho-Reyes, S., & Thompson, C. K. (2012). Verb and sentence production and comprehension in aphasia: Northwestern Assessment of Verbs and Sentences (NAVS). *Aphasiology*, 26, 1250–1277.
- Clifton, C., Staub, A., & Rayner, K. (2007). Eye movements in reading words and sentences. In R. P. G. van Gompel, M. H. Fischer, W. S. Murray, & R. L. Hill (Eds.), *Eye movements: A window on mind and brain* (pp. 341–372). Amsterdam, the Netherlands: Elsevier.
- DeDe, G. (2012). Effects of word frequency and modality on sentence comprehension impairments in people with aphasia. *American Journal of Speech-Language Pathology*, 21, S103–S114.
- DeDe, G. (2013). Reading and listening in people with aphasia: Effects of syntactic complexity. *American Journal of Speech-Language Pathology*, 22, 579–590.
- DeDe, G., Ricca, M., Knilans, J., & Trubl, B. (2014). Construct validity and reliability of working memory tasks for people with aphasia. *Aphasiology*, 28(6), 692–712.
- Dickey, M. W., Milman, L. H., & Thompson, C. K. (2008). Judgment of functional morphology in agrammatic aphasia. *Journal of Neurolinguistics*, 21, 35–65.
- Drieghe, D., Brysaert, M., Desmet, T., & De Baecke, C. (2004). Word skipping in reading: On the interplay of linguistic and visual factors. *European Journal of Cognitive Psychology*, 16, 79–103. <https://doi.org/10.1080/09541440340000141>
- Drieghe, D., Rayner, K., & Pollatsek, A. (2005). Eye movements and word skipping during reading revisited. *Journal of Experimental Psychology: Human Perception and Performance*, 31, 954–969.
- Dunn, L. M., & Dunn, L. M. (2007). *Peabody Picture Vocabulary Task—III*. Circle Pines, MN: American Guidance Service.
- Ferreira, F., Henderson, J. M., Anes, M. D., Weeks, P. A., Jr., & McFarlane, D. K. (1996). Effects of lexical frequency and syntactic complexity in spoken language comprehension: Evidence from the auditory moving windows technique. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 22, 555–568.
- Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). Mini-Mental State: A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research*, 12, 189–198.
- Friederici, A. D. (1985). Levels of processing and vocabulary types: Evidence from on-line comprehension in normals and agrammatics. *Cognition*, 19, 133–166.
- Friedman, R. B., & Kohn, S. E. (1990). Impaired activation of the phonological lexicon: Effects upon oral reading. *Brain and Language*, 38, 278–297.
- Gerhand, S., & Barry, C. (1999). Age-of-acquisition and frequency effects in speeded word naming. *Cognition*, 73, B27–B36.
- Gerratt, B., & Jones, D. (1987). Aphasic performance on a lexical decision task: Multiple meanings and word frequency. *Brain and Language*, 30, 106–115.
- Goodglass, H., Kaplan, E., & Barresi, B. (2000). *Boston Diagnostic Aphasia Examination—Third Edition*. New York, NY: Lippincott, Williams & Wilkins.
- Grossman, M., Carey, S., Zurif, E. B., & Diller, L. (1986). Form class judgments in Broca's aphasia. *Brain and Language*, 28, 114–125.
- Hyönä, J., & Olson, R. K. (1995). Eye fixation patterns among dyslexic and normal readers: Effects of word length and word frequency. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 21, 1430–1440.
- Inhoff, A. W., & Rayner, K. (1986). Parafoveal word processing during eye fixations in reading: Effects of word frequency. *Perception & Psychophysics*, 40, 431–439.
- Jaeger, T. F. (2008). Categorical data analysis: Away from ANOVAs (transformation or not) and towards logit mixed models. *Journal of Memory and Language*, 59(4), 434–446.
- Johnson, R. L., & Rayner, K. (2007). Top-down and bottom-up effects in pure alexia: Evidence from eye movements. *Neuropsychologia*, 45, 2246–2257.

- Juhász, B. J., Liversedge, S. P., White, S. J., & Rayner, K. (2006). Binocular coordination of the eyes during reading: Word frequency and case alternation affect fixation duration but not binocular disparity. *Quarterly Journal of Experimental Psychology*, 59, 1614–1641.
- Just, M. A., Carpenter, P. A., & Wooley, J. D. (1982). Paradigms and processes in reading comprehension. *Journal of Experimental Psychology: General*, 111, 228–238.
- Kaplan, E., Goodglass, H., & Weintraub, S. (2001). *Boston Naming Test*. Baltimore, MD: Lippincott, Williams & Wilkins.
- Kertesz, A. (2006). *Western Aphasia Battery-Revised (WAB-R)*. Austin, TX: Pro-Ed.
- Kittredge, A. K., Dell, G. S., Verkuilen, J., & Schwartz, M. F. (2008). Where is the effect of frequency in word production? Insights from aphasic picture-naming errors. *Cognitive Neuropsychology*, 25(4), 463–492.
- Kliegl, R., Grabner, E., Rolfs, M., & Engbert, R. (2004). Length, frequency, and predictability effects of words on eye movements in reading. *European Journal of Cognitive Psychology*, 16, 262–284.
- Knillans, J., & DeDe, G. (2015). Online sentence reading in people with aphasia: Evidence from eye tracking. *American Journal of Speech-Language Pathology*, 24, S961–S973.
- Martin, N., Kohen, F., Kalinyak-Fliszar, M., Soveri, A., & Laine, M. (2012). Effects of working memory load on processing of sounds and meanings of words in aphasia. *Aphasiology*, 26(3–4), 462–493.
- McCarthy, R., & Warrington, E. K. (1984). A two-route model of speech production. Evidence from aphasia. *Brain*, 107, 463–485.
- McConkie, G. W., Kerr, P. W., Reddix, M. D., Zola, D., & Jacobs, A. M. (1989). Eye movement control during reading: II. Frequency of refixating a word. *Perception & Psychophysics*, 46, 245–253.
- Morrison, C. M., & Ellis, A. W. (1995). Roles of word frequency and age of acquisition in word naming and lexical decision. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 21, 116–133.
- Nickels, L., & Howard, D. (1995). Aphasic naming: What matters? *Neuropsychologia*, 33, 1281–1303.
- Nozari, N., Kittredge, A. K., Dell, G. S., & Schwartz, M. F. (2010). Naming and repetition in aphasia: Steps, routes, and frequency effects. *Journal of Memory and Language*, 63, 541–559.
- Park, G. H., McNeil, M. R., & Doyle, P. J. (2002). Lexical access rate of closed-class elements during auditory sentence comprehension in adults with aphasia. *Aphasiology*, 16, 801–814.
- R Core Team. (2008). R: A Language and Environment for Statistical Computing (Version 3.2.2) [Computer software]. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from <https://www.R-project.org>
- Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, 124, 372.
- Rayner, K., & Duffy, S. A. (1986). Lexical complexity and fixation times in reading: Effects of word frequency, verb complexity, and lexical ambiguity. *Memory & Cognition*, 14, 191–201.
- Rayner, K., & Johnson, R. L. (2005). Letter-by-letter acquired dyslexia is due to serial encoding of letters. *Psychological Science*, 16, 530–534.
- Rayner, K., & McConkie, G. W. (1976). What guides a reader's eye movements? *Vision Research*, 16, 829–837.
- Rayner, K., Reichle, E., Stroud, M., Williams, C., & Pollatsek, A. (2006). The effect of word frequency, word predictability, and font difficulty on the eye movements of young and older readers. *Psychology and Aging*, 21, 448–465.
- Rayner, K., Sereno, S. C., & Raney, G. E. (1996). Eye movement control in reading: A comparison of two types of models. *Journal of Experimental Psychology: Human Perception and Performance*, 22, 1188–1200.
- Rosenberg, B., Zurif, E., Brownell, H. H., Garrett, M., & Bradley, D. (1985). Grammatical class effects in relation to normal and aphasic sentence processing. *Brain and Language*, 26, 287–303. [https://doi.org/10.1016/0093-934X\(85\)90044-6](https://doi.org/10.1016/0093-934X(85)90044-6)
- Schattka, K. I., Radach, R., & Huber, W. (2010). Eye movement correlates of acquired central dyslexia. *Neuropsychologia*, 48, 2959–2973.
- Shapiro, L. P. (1997). Tutorial: An introduction to syntax. *Journal of Speech, Language, and Hearing Research*, 40(2), 254–272.
- SR Research. (2005). EyeLink 1000 (Version 1.5.2) [Computer software]. EyeLink 1000 User Manual. Mississauga, ON, Canada: Author.
- Staub, A., Grant, M., Clifton Jr., C., & Rayner, K. (2009). Phonological typicality does not influence fixation durations in normal reading. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 35(3), 806.
- Steinhauer, K., & Friederici, A. D. (2001). Prosodic boundaries, comma rules, and brain responses: The closure positive shift in ERPs as a universal marker for prosodic phrasing in listeners and readers. *Journal of Psycholinguistic Research*, 30(3), 267–295.
- Swinney, D., Zurif, E., & Cutler, A. (1980). Effects of sentential stress and word class upon comprehension of Broca's aphasics. *Brain and Language*, 10, 132–144.
- ter Keurs, M., Brown, C., & Hagoort, H. (2002). Lexical processing of vocabulary class in patients with Broca's aphasia: An event-related brain potential study on agrammatic comprehension. *Neuropsychologia*, 40, 1547–1561.
- ter Keurs, M., Brown, C., Hagoort, H., & Stegeman, D. (1999). Electrophysiological manifestations of open- and closed-class words in patients with Broca's aphasia with agrammatic comprehension: An event-related brain potential study. *Brain*, 122, 839–854.
- Thompson, C. K., & Choy, J. J. (2009). Pronominal resolution and gap filling in agrammatic aphasia: Evidence from eye movements. *Journal of Psycholinguistic Research*, 38, 255–283.
- Thompson, C. K., Lukic, S., King, M. C., Mesulam, M. M., & Weintraub, S. (2012). Verb and noun deficits in stroke-induced and primary progressive aphasia: The Northwestern Naming Battery. *Aphasiology*, 26, 632–655.
- Tily, H., Fedorenko, E., & Gibson, E. (2010). The time-course of lexical and structural processes in sentence comprehension. *Quarterly Journal of Experimental Psychology*, 63, 910–927.
- Turner, J. E., Valentine, T., & Ellis, A. W. (1998). Contrasting effects of age of acquisition and word frequency on auditory and visual lexical decision. *Memory & Cognition*, 26, 1282–1291.
- van Heuven, W. J., Mandera, P., Keuleers, E., & Brysbaert, M. (2014). SUBTLEX-UK: A new and improved word frequency database for British English. *Quarterly Journal of Experimental Psychology*, 67, 1176–1190.
- Varley, R., Whiteside, S., & Luff, H. (1999). Apraxia of speech as a disruption of word-level schemata: Some durational evidence. *Journal of Medical Speech-Language Pathology*, 7(2), 127–132.
- Vitu, F., O'Regan, J. K., Inhoff, A. W., & Topolski, R. (1995). Mindless reading: Eye-movement characteristics are similar in scanning letter strings and reading texts. *Perception & Psychophysics*, 57, 352–364.