Glaucoma

Severity of Vision Loss Interacts With Word-Specific Features to Impact Out-Loud Reading in Glaucoma

Priya M. Mathews,[1] Gary S. Rubin,[2] Michael McCloskey,[3] Sherveen Salek,[1] and Pradeep Y. Ramulu[1]

[1]Wilmer Eye Institute, Johns Hopkins University, Baltimore, Maryland, United States
[2]UCL Institute of Ophthalmology, NIHR Moorfields Biomedical Research Centre, London, United Kingdom
[3]Department of Cognitive Science, Johns Hopkins University, Baltimore, Maryland, United States

Correspondence: Pradeep Y. Ramulu, 1800 Orleans Street, Maumenee B110, Baltimore, MD 21287, USA; pramulu1@jhmi.edu.

Submitted: August 13, 2014
Accepted: January 16, 2015

Citation: Mathews PM, Rubin GS, McCloskey M, Salek S, Ramulu PY. Severity of vision loss interacts with word-specific features to impact out-loud reading in glaucoma. *Invest Ophthalmol Vis Sci*. 2015;56:1537–1545. DOI:10.1167/iovs.15-15462

Purpose. To assess the impact of glaucoma-related vision loss on measures of out-loud reading, including time to say individual words, interval time between consecutive words, lexical errors, skipped words, and repetitions.

Methods. Glaucoma subjects ($n = 63$) with bilateral visual field loss and glaucoma suspect controls ($n = 57$) were recorded while reading a standardized passage out loud. A masked evaluator determined the start and end of each recorded word and identified reading errors.

Results. Glaucoma subjects demonstrated longer durations to recite individual words (265 vs. 243 ms, $P < 0.001$), longer intervals between words (154 vs. 124 ms, $P < 0.001$), and longer word/post-word interval complexes (the time spanned by the word and the interval following the word; 419 vs. 367 ms, $P < 0.001$) than controls. In multivariable analyses, each 0.1 decrement in log contrast sensitivity (logCS) was associated with a 15.0 ms longer word/post-interval complex (95% confidence interval [CI] = 9.6–20.4; $P < 0.001$). Contrast sensitivity was found to significantly interact with word length, word frequency, and word location at the end of a line with regards to word/post-word interval complex duration ($P < 0.05$ for all). Glaucoma severity was also associated with more lexical errors (Odds ratio = 1.20 for every 0.1 logCS decrement; 95% CI = 1.02–1.39, $P < 0.05$), but not with more skipped or repeated words.

Conclusions. Glaucoma patients with greater vision loss make more lexical errors, are slower in reciting longer and less frequently used words, and more slowly transition to new lines of text. These problem areas may require special attention when designing methods to rehabilitate reading in patients with glaucoma.

Keywords: glaucoma, reading, contrast sensitivity

Investigative Ophthalmology & Visual Science

Reading is a highly valued ability in the elderly and is essential to many daily activities. Older adults with decreased vision report difficulty reading, affecting their ability to function at work and home,[1] and several ophthalmologic conditions associated with reading difficulty have been shown to significantly impact vision-related quality of life.[2–5] Two-thirds of patients seeking low vision rehabilitation services cite reading as a primary complaint.[6] As a result, vision rehabilitation programs must emphasize reading performance as a key outcome, and should understand the best ways to optimize reading rehabilitation with different types of vision loss.[7,8]

Reading difficulty has most traditionally been associated with disease affecting visual acuity, though recent literature suggests that significant reading difficulties can also be experienced in glaucoma, where visual acuity is relatively maintained while contrast sensitivity (CS) and peripheral vision are impaired. Reading is one of the most common complaints among glaucoma patients, and appears to be affected over a range of glaucoma severity.[9,10] Several objective reading tests have been used to demonstrate reading difficulty in the glaucoma population, showing slower out-loud and sustained silent reading speeds in glaucoma patients compared with controls.[11–14]

Several hypotheses have been proposed to explain the effect of glaucoma disease on reading speed. One possible explanation is peripheral vision loss (i.e., visual field [VF] loss due to glaucoma) causing difficulty in finding the start of the next line, which may result in an overall decreased reading speed.[15] Another study demonstrated that glaucoma patients are more sensitive to reduced text contrast, which could also account for the significant decrease in average reading speed when compared with visually healthy controls.[16] Glaucoma patients may also have more difficulty while reading text with a small print size.[17] Although previous studies have shown that patients with glaucoma have a slower overall reading rate than those with normal vision,[11,12] specific word or text features that might produce reading difficulty as a result of glaucoma-related vision loss have not been explored or identified. Identifying text elements causing the most difficulty for glaucoma patients would suggest the underlying mechanism driving slower reading speed, and allow for more focused reading rehabilitation in these patients.

In this study, we aimed to determine if specific word features (such as number of letters, frequency in the English language, or the location of a word at the end of a line) posed particular challenges to patients with glaucoma-related vision

www.iovs.org | ISSN: 1552-5783

loss. To do so, we evaluated glaucoma patients and glaucoma suspect controls reading an International Reading Speed Text (IReST) passage aloud, and performed a detailed examination of voice recordings to determine the length of time to say each individual word and the duration of intervals between successive words. We hypothesized that the interaction between glaucoma severity and word-specific features would be reflected in the time required to say words with challenging features. Lastly, we evaluated the association of glaucoma severity and the incidence of out-loud reading errors (i.e., skipping, repeating, or misidentifying a word).

Methods

The study protocol was approved by the Johns Hopkins University institutional review board and in accordance with the Declaration of Helsinki. Study participants signed written informed consent and completed procedures between July 2009 and April 2011.

Study Subjects

Patients aged 50 years or older were recruited from the Wilmer Eye Institute Glaucoma Clinic. Patients were eligible for enrollment if they were able to communicate in English, reported being literate, and had VF testing at the Glaucoma Clinic within the past 12 months (on a HFA2 machine; Carl Zeiss Meditec Inc., Dublin, CA, USA). Visual field testing was performed in both eyes over the central 24° using a size III stimulus and the Swedish interactive thresholding algorithm (SITA) standard testing program. Visual field severity was defined by the higher (less negative) mean deviation (MD) between the two eyes.[18] Individuals with any ocular laser procedure performed in the prior week, ocular surgery in the past 2 months, or suspicion of vision loss from reasons other than glaucoma during chart review were excluded from the study as previously described.[19]

Two study groups were recruited: individuals who were being followed for possible glaucoma (glaucoma suspect controls), and patients with a known history of glaucoma with documented bilateral VF loss (glaucoma subjects). Controls had ocular hypertension, or other reasons for suspected glaucoma, and met the following criteria: (1) VF MD better than −3 dB at least in 1 eye and better than −4 dB in both eyes on the SITA standard 24-2 test, (2) Glaucoma Hemifield Test (GHT) result of “Within Normal Limits,” “Borderline,” or “General Reduction of Sensitivity” in both eyes, and (3) presenting visual acuity of 20/40 or better in both eyes on the Early Treatment Diabetic Retinopathy Study (ETDRS) chart. Glaucoma subjects had a known diagnosis of POAG, primary angle closure glaucoma, pseudoexfoliation glaucoma, or pigment dispersion glaucoma and also demonstrated: (1) a better-eye visual acuity of at least 20/40, (2) a VF MD worse than −3 dB in both eyes, and (3) a Glaucoma Hemifield Test result of “Outside Normal Limits,” “Borderline,” or “Generalized Reduction of Sensitivity” in both eyes, with at least one eye being “Outside Normal Limits.” Detailed description of the study groups is presented elsewhere.[19]

Evaluation of Reading

All study subjects were recorded while reading an IReST passage (Flesh-Kincaid grade level of 5.2, 77 words in total, 7.7 words/line, 4.3 characters/word) aloud, before any VF test or eye examination.[12,14,19] The same passage was used for all subjects, presented in black text against white background, 12-point Times New Roman font, with 1.5 line spacing, on a 5 × 8 inch paper.[12,19] Subjects were given the same instructions by the tester: to wear their habitual reading correction if needed and hold the reading material, printed on matte paper, at the distance most comfortable for them. Room lighting was provided by overhead fluorescent lamps and was standardized to ensure uniform lighting on pages without shadows (between 400 and 600 lux at page level). Subjects were permitted to take any length of time necessary to read the passage out-loud.

Measurement of Vision and Covariates

Presenting visual acuity was assessed binocularly and converted into the negative logMAR units.[20] Binocular reading acuity was obtained from MNRead acuity chart, as previously described.[12] Contrast sensitivity was measured as the number of letters read correctly on the Pelli-Robson Chart and transformed to a logarithmic scale (logCS).[21] The presence of significant lenticular changes or posterior capsular opacification was assessed for each eye after pupillary dilation as previously described.[22]

Chart review and standardized questionnaires were used to collect information about age, race/ethnicity, education, and history of glaucoma surgery. Depressive symptoms were assessed using part D of the General Health Questionnaire, with a positive response to any question indicating the presence of depressive symptoms.[23] The Mini-Mental State Exam (MMSE) was used to evaluate cognitive ability.[24]

Extraction of Word-Specific Reading Data

Audio recordings of the read IReST passage were imported into Wave Editor Version 1.5.5 (Audiofile Engineering, Minneapolis, MN, USA) and analyzed by an evaluator masked to glaucoma status and severity to determine the beginning and end time of each word. The spectogram was viewed while listening to the reading in order to mark the exact start and finish time to say each word. The marker times were imported into a separate database to calculate the exact time required to say each word, as well as the interval time between consecutive words. All reading errors were identified and noted, including skipping a word, repeating a word, or making a lexical error (defined as a misidentification or significant mispronunciation of a word). If a word was repeated, the length of time to say that particular word was calculated by averaging all repetitions. If a word was mispronounced or misidentified, the preceding interval would be the time between the end of the preceding word and the start of the incorrect word.

Description of Word-Level Features

In order to properly examine the interaction between glaucoma severity and word-level features, it was necessary to know where word-specific features alone demonstrated their impact. For example, if words were said while upcoming words were being viewed, then the impact of a challenging word (i.e., a word requiring a longer time to read) would be seen in the word(s) or interval(s) prior to the challenging word. On the other hand, if reading a challenging word caused additional contemplation/uncertainty even after the word was read, then the impact of a challenging word may be seen in the following word(s) or interval(s). Therefore, the relationship between challenging word features and the following outcomes were computed: (1) duration of time to say the word whose features were analyzed (word time), (2) duration of interval immediately following this word (post-word interval), (3) word time + post-word interval, and (4) preword interval + word time + post-word interval. The specific challenging word features examined

Table 1. Characteristics of Study Participants by Glaucoma Status

	Glaucoma Subjects, $n = 63$	Controls, $n = 57$	
	Mean (SD)	Mean (SD)	*P* Value
Demographics			
Age, y*	71.5	67.2	<0.01
Female Sex, %	63.2	57.1	0.50
African-American race, %	20.6	19.3	0.86
Education, y	15.2	15.5	0.47
Employed, %	41.2	45.6	0.63
Vision			
Visual field MD (better eye)	−8.9 (6.8)	0.2 (1.0)	<0.001
Better-eye Acuity, mean logMAR	0.09 (0.11)	0.00 (0.11)	<0.001
Binocular Reading Acuity, mean logMAR	−0.01 (0.14)	−0.05 (0.11)	0.07
Binocular log CS	1.67 (0.19)	1.93 (0.13)	<0.001
Sig. cataract/PCO†, %	11.1	7.0	0.44
Health			
MMSE score	27.4 (1.4)	27.7 (1.5)	0.25
Depressive symptoms, %	7.9	7.0	0.85

Sig., significant.
* Indicates median values. Mean values shown for all other continuous variables.
† In one or both eyes.

included: (1) word size (defined as number of letters in word), (2) word frequency (represented as logarithm of frequency of word per million words in common English language according to online Celex database), and (3) location of the word in the text (i.e., beginning of line versus not beginning of line, or end of a line versus not the end of the line).[25]

Statistical Methods and Programming

Group differences were analyzed using the Student's *t*-tests for continuous variables and χ^2 tests for categorical variables. Generalized estimating equations (GEE) models in which each word read by each individual was taken as a separate observation were used for all univariate and multivariate analyses.

Predictors of the timed outcomes (e.g., word time, post-word interval time) were evaluated using univariate, bivariate (age-adjusted), and multivariate linear regression models. Covariates were included in multivariate models if they demonstrated a significant impact on word time ($P < 0.1$) in age-adjusted models or if they had been previously shown to impact reading speed (sex, race, educational level, and MMSE score).[11] Word features affecting time to read aloud in univariate analyses, such as word size, word frequency, and location in text (e.g., last word of line), were also included in multivariate models. Next, interactions between glaucoma severity (measured as both visual field mean deviation and logCS in the better eye) and word/text features (word size, word frequency, and location in text) on word+post-word interval time outcomes were incorporated into multivariate GEE models. Finally, separate multivariate logistic models were used to determine the association between glaucoma severity (again as both VF MD and logCS) and probability of skipping, repeating, or misidentifying a word. Data analyses were performed with STATA version 12 (STATA Corp., College Station, TX, USA) and figures were produced by R 2.15.1 (R Development Core Team; R Foundation for Statistical Computing, Vienna, Austria).

Results

One hundred twenty individuals (63 glaucoma subjects and 57 controls) completed all study procedures and were included for analysis. Glaucoma patients were older than controls (71.5 vs. 67.2 years, P <0.01), but were not significantly different with regards to sex, race, education level, employment status, cognitive ability, or depressive symptoms ($P > 0.2$ for all, Table 1). Glaucoma patients had more severe better-eye VF loss, worse-better eye visual acuity, and lower CS compared with controls ($P < 0.001$). The glaucoma patients had a range of VF loss between −30.2 to −2.2 dB, and a range of logCS between 1.05 and 2 (correlation factor of 0.6 between VF MD and CS). The groups did not differ significantly in the proportion of cataract/posterior capsular opacification (PCO).

Initial analyses were performed to see where the impact of word-specific features lay (i.e., on duration of the current word, the interval before/after the word, or more distant words/intervals). Univariate linear regression models using generalized equation models demonstrated that word size and word frequency strongly impacted the duration required to say the corresponding word (i.e. the word whose features were being analyzed) and the interval after the corresponding word (Figs. 1 and 2). Words at the end of a line of text required longer durations to read, with longer durations also required to say the first word of the next line (Fig. 3). Based upon these analyses, the impact of word-specific features were analyzed in models in which the time between starting the corresponding word (i.e., the word whose features were analyzed) and starting the following word was taken as the primary outcome variable. This time is referred to as the word/post-word interval complex.

Glaucoma subjects had a longer average word/post-word interval complex compared with controls (419 vs. 367 ms), and longer durations were found both for words less than 7 letters in length (389 vs. 339 ms) and greater than 7 letters in length (715 vs. 646 ms; $P < 0.001$ for all, Table 2). When the word/post-word interval complex was broken down into individual components, glaucoma patients took longer to say individual words (265 vs. 243 ms) and also had longer durations of silence between successive words (154 vs. 124 ms; $P < 0.001$ for both). Additionally, glaucoma subjects had a longer average gap after the last word of a line as compared with controls (183 vs. 130 ms). The percentage of individuals skipping a word, repeating a word, making a lexical error, or making any type of error at least once did not differ by glaucoma status ($P > 0.05$, Table 2).

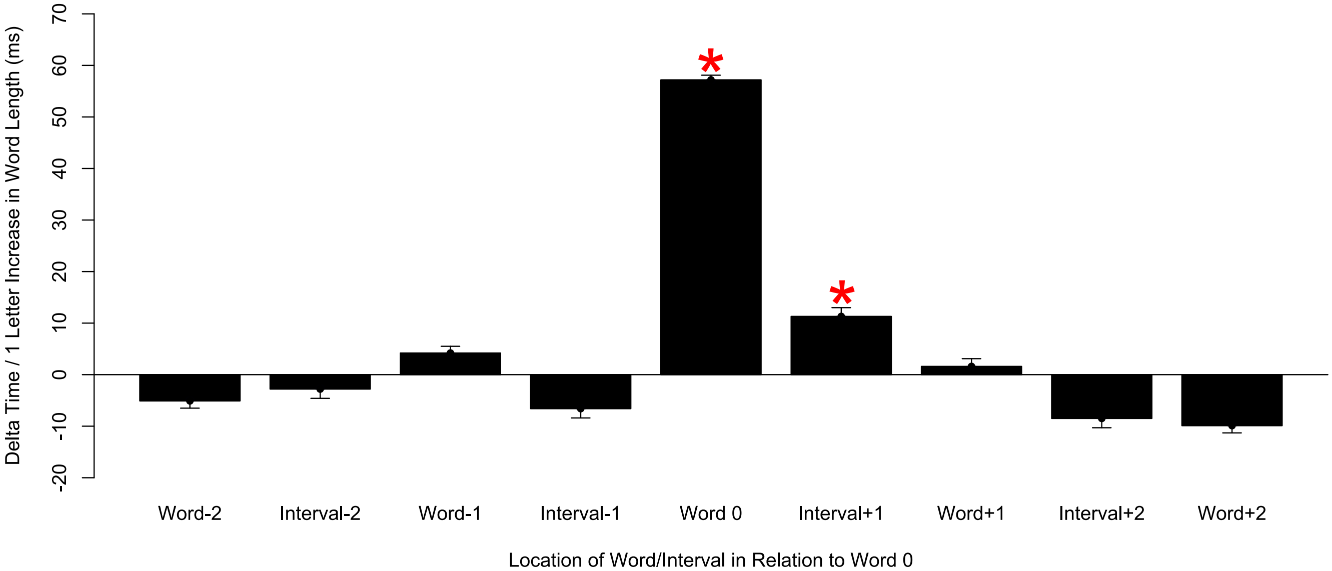

FIGURE 1. Impact of word length on various word and interval durations. Word 0 is the word whose length is being analyzed. The next two words in the text are shown as word+1 and +2, and the previous two words in the text are word–1 and –2. Times for 'words' refers to durations to read the word out-loud and for 'intervals' refers to durations between one word to the next word. Delta time refers to the difference in these outcomes based on each additional letter of Word 0 (positive values represent longer durations/intervals). Results demonstrate that longer words require extra time to say the word whose length is being analyzed as well as the interval following this word.

Predictors of Word/Post-Word Interval Complex Duration: Multivariate Analysis

Multivariate GEE models were used to evaluate the impact of vision, word-specific features and demographic/cognitive features on word/post-word interval durations. Statistical analysis was performed using both CS and VF MD as the primary metrics of glaucoma disease severity. Both measures of visual function yielded significant results ($P < 0.05$), however CS had a greater strength of association compared with VF MD as judged by a greater corresponding Z-score (lower P value) derived from the multivariable GEE model. Therefore, results depicted in the tables reflect the statistical analysis using CS as the primary metric of glaucoma. Worse CS was associated with a longer word/post-word interval complex duration (+15.0 ms per 0.1 decrement in log CS; 95% confidence interval [CI] = 9.6–20.4; $P < 0.001$; Table 3). Greater word/post-word interval duration was also associated with increased word size (+26.1 ms per 1 letter increase; 95% CI = 23.2–29.0; $P < 0.001$) and decreased word frequency (–47.1 ms per 10-fold lower frequency of use; 95% CI = –49.4 to –44.9; $P < 0.001$). Word/post-word interval durations were also significantly longer for the last word on a line (along with the interval between this word and the first word of the next line) as compared with word/post-word interval complexes not at the end of a line (+49.6 ms; 95% CI = 36.2–63.0; $P < 0.001$). Participants with a lower MMSE score had a longer word/post-interval complex

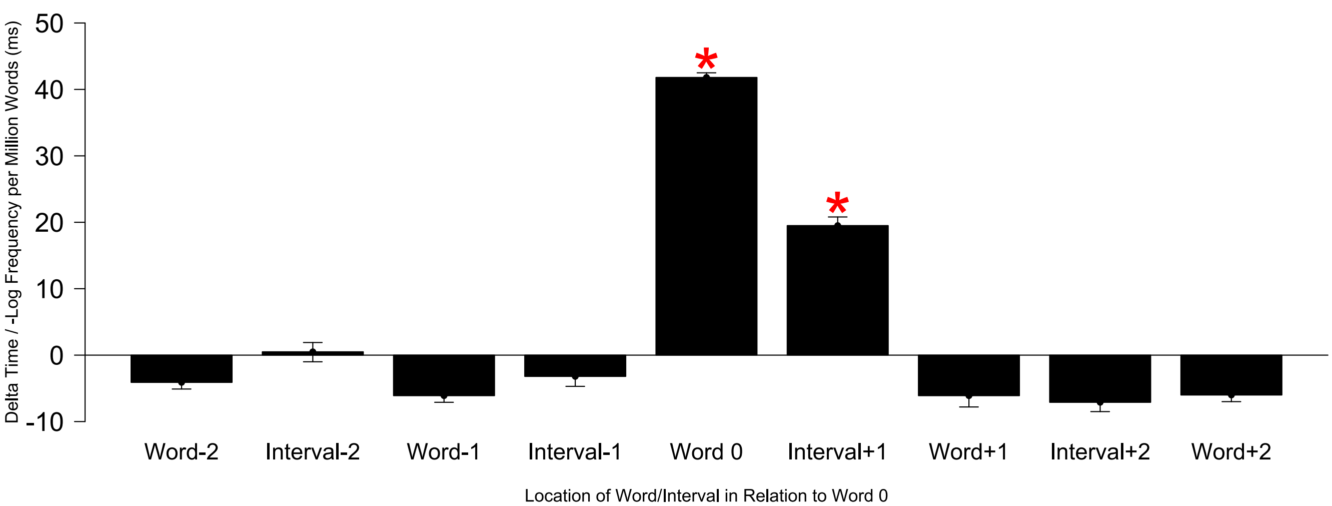

FIGURE 2. Impact of word frequency on various word and interval durations. Word 0 is the word whose frequency is being analyzed. The next two words in the text are shown as word+1 and +2, and the previous two words in the text are word–1 and –2. Times for 'words' refers to duration to read the words out-loud and for 'intervals' refers to durations between one word to the next word. Delta time refers to the difference in these outcomes based on every 10-fold decrease in frequency of word 0 (positive values represent longer durations/intervals). Results demonstrate that less frequently used words require extra time to say the word whose frequency is being analyzed as well as the interval following this word.

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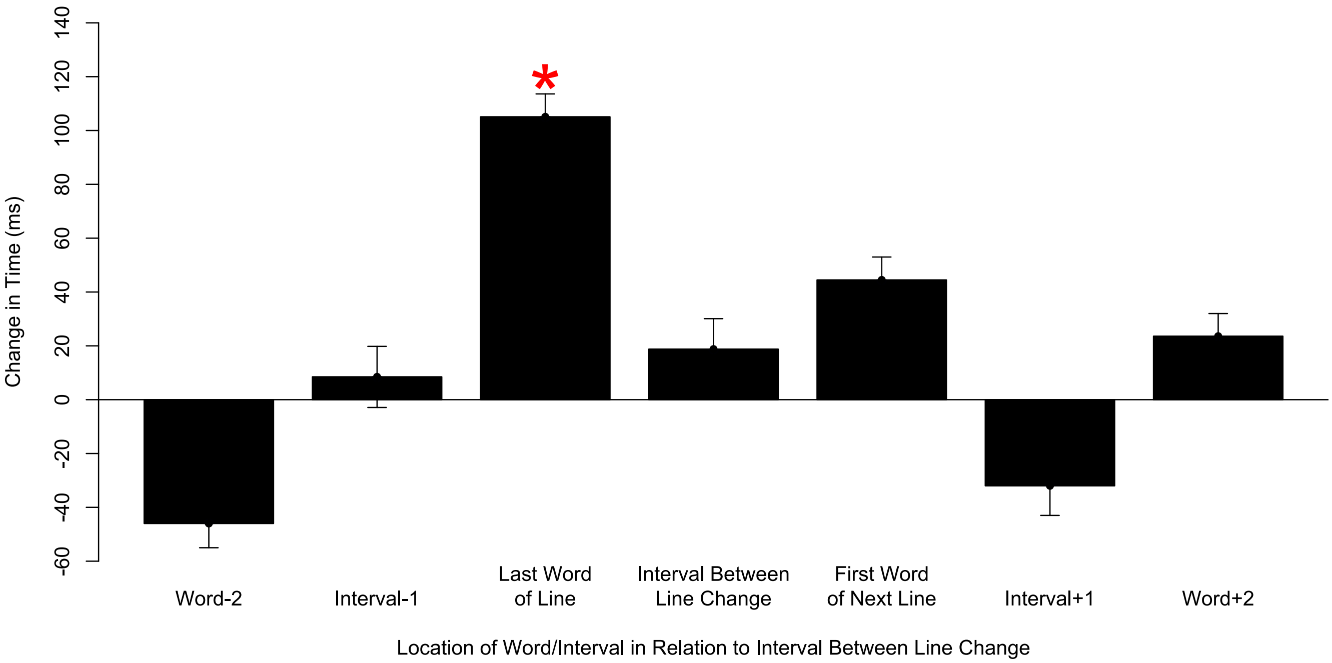

FIGURE 3. Impact of word location within a line on various word and interval durations. Word and interval parameters are defined with regards to a line transition. "Last word of line" refers to the last word of the line, while word–2 refers to the word preceding the last word of a line. "First Word of Next Line" refers to the first word of the new line, while word+2 refers to the second word of the new line. Interval–1 refers to the interval between word–2 and the last word of the line, while interval+1 refers to the interval between the first word of the next line and word+2. Results demonstrate that longer durations are required to say the last word of a line and the first word of a new line, and the word-to-word interval corresponding to the line change is also longer compared with durations when 'word 0' (word of interest) is not located at the end of the line.

duration ($P < 0.001$), while no association was found with age, sex, race, or educational level ($P > 0.05$ for all). Similar results were observed when other verbal units were taken as the primary outcome (word time only, post-interval only, preword interval+word+post-word interval complex).

The impact of the interactions between glaucoma severity and word features on word/post-word interval durations were analyzed in separate multivariate GEE models including CS (to determine glaucoma severity), word feature of interest (word size, word frequency, and word location), the interaction term (CS × word feature), and all relevant nonvisual metrics (age, sex, race, education, MMSE, word size, word frequency). The worst CS was associated with slower reading (longer word/post-word interval complex reading times) for words that were longer, less frequently used, or found at the end of a line of text ($P < 0.05$ for all; Table 4). All interactions remained significant in sensitivity analyses in which only glaucoma subjects with VF loss were included ($P < 0.05$ or all).

TABLE 2. Reading Metrics by Glaucoma Status

	Glaucoma Subjects, $n = 63$	Controls, $n = 57$	
	Mean (SD)	Mean (SD)	*P* Value
Duration of word/post-word interval complex (ms)			
Average, including all words	419 (338)	367 (276)	<0.001
Word size <7 letters	389 (324)	339 (258)	<0.001
Word size ≥7 letters	715 (324)	646 (286)	<0.001
Duration to recite word out-loud (ms)			
Average, including all words	265 (160)	243 (148)	<0.001
First word of line	306 (183)	286 (176)	0.05
Last word of line	364 (174)	334 (160)	0.003
Duration of interval following word (ms)			
Average, including all words	154 (250)	124 (191)	<0.001
After last word on line	183 (311)	130 (175)	<0.001
Description of errors			
# of individuals with ≥1 error total (%)	42 (67)	35 (61)	0.55
# of individuals with ≥1 repeat (%)	25 (40)	24 (42)	0.79
# of individuals with ≥1 lexical error (%)	15 (24)	7 (12)	0.10
# of individuals with ≥1 skipped word (%)	13 (21)	20 (35)	0.08

Mean values shown for all continuous variables.

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TABLE 3. Predictors of Word/Post-Word Interval Complex Duration, Multivariate Analysis

Variable	Interval	Word/Post-Word Interval Complex, ms β (95% CI) n = 120
Vision		
CS, better eye	0.1 logCS worse	**15.0 (9.6–20.4)***
Nonvisual†		
Word characteristics		
Word size	1 letter	**26.1 (23.2–29.0)***
Word frequency‡	10 fold less common	**47.1 (44.9–49.4)***
Last word of line	vs. not last word of line	**49.6 (36.2–63.0)***
Demographics		
Age	5 y older	−0.7 (−6.5 to 5.0)
Male	vs. Female	−15.5 (−37.1 to 6.1)
African-American	vs. not African-American	17.4 (−10.4 to 45.1)
Education	4 y less	15.1 (−5.1 to 35.3)
MMSE	5 points lower	**102.0 (64.1–139.9)***

* $P < 0.001$.
† The impact of nonvisual variables taken from a single model including the degree of better eye contrast sensitivity and all nonvisual metrics shown.
‡ Represented by negative log of word frequency per million words used in common English language.

Predictors of Out-Loud Reading Errors: Multivariate Analysis

In multivariate GEE logistic models, more severe glaucoma was associated with an increased likelihood of making a lexical error (odds ratio [OR] = 1.20 per 0.1 decrement log CS; 95% CI = 1.02–1.39; $P < 0.05$, Table 5), but was not associated with an increased likelihood of skipping a word, repeating a word, or making any error ($P > 0.05$ for all). A lower level of education was also associated with increased likelihood of making a lexical error (OR = 2.68 per 4 years less of education; 95% CI = 1.51–4.74; $P < 0.001$). No other tested variable, including word size or word frequency, was associated with making a lexical error or any other type of error evaluated in this study.

TABLE 5. Predictors of Making a Lexical Error (or Word Misidentification), Multivariate Analysis

Variable	Interval	Likelihood of Lexical Error* Odds Ratio (95% CI) n = 120
Glaucoma severity		
CS, better eye	0.1 logCS worse	**1.20 (1.02–1.39)†**
Word characteristics		
Word size	1 letter	1.02 (0.85–1.23)
Word frequency§	10-fold less common	0.87 (0.74–1.02)
Demographics		
Age	10-y older	0.96 (1.02–1.39)
Male	vs. Female	1.00 (0.50–2.00)
African-American	vs. not African-American	1.87 (0.94–3.69)
Education	4 y less	**2.68 (1.51–4.74)‡**
MMSE	5 points lower	1.02 (0.33–3.13)

* Lexical error defined as a mispronunciation or misidentification of written word.
† $P < 0.05$.
‡ $P < 0.01$.
§ Represented by negative log of word frequency per million words used in common English language.

TABLE 4. Significant Interactions between Glaucoma Severity and Word Features on Word/Post-Word Interval Complex Duration, Multivariate Analysis

Variable	Interval	Word/Post-Word Interval Complex, ms β (95% CI) n = 120
Glaucoma and word Size‡		
CS, better eye	0.1 logCS worse	6.8 (−0.4 to 13.9)
Word size	1 letter longer	**62.2 (42.5–81.8)†**
CS • word size	**1.9 (0.8–3.0)†**	
Glaucoma and word frequency‡§		
CS, better eye	0.1 logCS worse	**23.5 (15.8–31.1)†**
word frequency	10-fold less common	**70.7 (55.4–86.0)†**
CS • word frequency	**1.3 (0.5–2.1)***	
Glaucoma & last word of line‡		
CS, better eye	0.1 logCS worse	**13.1 (7.6–18.6)†**
Last word of line	vs. not last word	**352.7 (230.7–474.6)†**
CS • last word of line	**15.7 (9.1–22.4)†**	

* $P < 0.05$.
† $P < 0.001$.
‡ The impact of each interaction derived from a separate model including contrast sensitivity (the visual metric), the word feature of interest, the interaction term (contrast sensitivity x word feature), and all relevant nonvisual metrics (age, sex, race, education, MMSE, word size, word frequency). Worse contrast sensitivity was associated with slower reading (longer word/post-word interval complex reading times) for words that were longer, less frequently used, or found at the end of a line of text.
§ Represented by negative log of word frequency per million words used in common English language.

Discussion

Greater word length, less frequent word use in daily language, and word location at the end of a line of text all slow reading speed to a greater extent as severity of glaucoma-related vision loss increases. Additionally, more advanced glaucoma is associated with a greater likelihood of making a lexical error while reading out-loud. The number of people with glaucoma around the world is projected to increase, suggesting that disability resulting from the disease will increase as well.[26,27] Performance in reading is strongly associated with subjective visual ability, and reading is a major component of vision-related quality of life.[28–30] Our findings provide insight to the multiple factors that may contribute to reading difficulty in the glaucoma population, and which should be considered when optimizing reading rehabilitation for glaucoma patients, particularly those with advanced disease. Although our study focuses on individuals with glaucoma, these findings may apply to other forms of visual impairment as well.

The differing impact of decreased CS with various text features is best understood by comparing the expected reading speed decrement, defined as the difference in reading speed between individuals with normal vision and otherwise-similar individuals with significantly decreased CS from glaucoma (assumed to have an average logCS = 1.80 and 1.35, respectively, in this exercise) for passages with different text features. The reading speed decrement associated with this level of glaucoma would be expected to be 9 wpm greater for a passage with an average word length of 8 letters/word as opposed to a passage with an average word length of 5 letters/word assuming a reading speed of 180 wpm for both passages amongst the individuals with normal vision. On the other hand, the reading speed decrement associated with glaucoma would be expected to be only 2 wpm greater for a passage with an average lexical frequency of 1:10,000 as opposed to a passage with an average lexical frequency of 1:1000. Likewise, the reading speed decrement associated with glaucoma would be 2 wpm greater for a 100 word passage spread out over 6 lines of text (requiring 5 line changes) as opposed to a 100 word passage spread out over 11 lines of text (requiring 10 line changes). These results suggest that word length has the most clinically significant interaction with CS, with less significant interactions present for lexical frequency and word location. It is also important to note that word length, word frequency, and word location at the end of a line also decrease reading speed in all patients (including those with normal CS), and the slower reading speed resulting from these word features independent of CS were often much larger than the slower reading speed due to the interaction between worse contrast sensitivity and the word features (particularly for word length).

Previous studies have suggested several mechanisms to explain decreased reading speed in glaucoma patients, but these mechanisms have not been demonstrated with objective evidence.[11] A questionnaire-based study suggested that peripheral field loss in glaucoma patients may produce difficulty finding the next line of text,[15] which in turn could slow reading speed. Our study supports this hypothesis, showing that patients with more severe VF loss take more time to say the last word of the line and transition to the next line than patients with less severe disease, though the magnitude of this effect was small. Additionally, CS demonstrated a stronger impact on the end-of-line transitioning than did VF loss, suggesting that central VF loss captured by decreased CS may be more critical to transitioning from the end of one line to starting the next line rather than peripheral vision in glaucoma patients. Although our results are consistent with previous studies showing that peripheral vision loss is associated with difficulty reading, our findings suggest that contrast sensitivity changes may have a more significant greater impact on reading in the glaucoma population.

Our study also demonstrated that reading speed was slower for longer words, and that word length strongly interacted with glaucoma severity with regards to reading speed. Very similar findings were demonstrated in a prior study by Legge et al.,[31] in which reading speed was found to be increasingly dependent on word length as the text contrast decreased (thus, moving text contrast closer to the CS threshold). The authors suggested that the reader was forced to make smaller advances while reading low contrast text due to the limitation in the number of characters recognized in one glance. Our study suggests that a reduced visual span may also be found in glaucoma or other diseases resulting in decreased contrast sensitivity, which would explain the observed slower reading of longer words.

Both contrast sensitivity and severity of VF loss were found to interact with word length and word frequency to produce slower reading speed ($P < 0.05$). However, greater statistical significance was noted when CS was used as a metric for vision loss, suggesting that slower reading of longer and less frequently used words is more the result of CS loss, which reflects damage to the very central field of vision, rather than peripheral vision loss. Turano and Rubin[32] reported that peripheral vision was less important than central vision when reading a coherent complete sentence, though the specific relationships of these visual metrics to specific word features was not examined. Contrast sensitivity has been less commonly used to capture glaucoma severity than VF loss in studies evaluating quality of life and function, but may be more relevant than VF loss when evaluating some aspects of reading difficulty.[33] Our work highlights that significant changes, which drive functional impairment are occurring in the central VF of patients with glaucoma. Indeed, recent papers have demonstrated that glaucoma is associated with macular retinal ganglion cell/inner plexiform layer thinning, thus providing a physical correlate to explain contrast sensitivity deficiencies shown here to have functional consequences.[34,35]

Our findings are best understood within a model in which reading is taken to be a series of educated guesses as to each word's identity. Challenging word features primarily affected the interval of time following, and not before, the difficult word, suggesting that individuals stalled after difficult words because they were uncertain whether their guess was correct. Individuals with greater vision loss appear to require a greater time to make their educated guesses, particularly when the text becomes more difficult/complex (i.e., when words are longer, less commonly used, or at the end of the line). In order to maintain reading speed, patients with more severe vision loss may also accept a lower level of accuracy in their guessing, as suggested by the greater frequency of lexical errors found in subjects with more severe vision loss.

The present study extends upon prior work[11,12] demonstrating specific text features, which potentially explain why glaucoma patients have difficulty in reading, rather than simply demonstrating a difference in overall reading speed. Given the therapeutic options available for glaucoma today, we cannot reverse visual impairment due to glaucoma. However, we can change how words are presented to alleviate some degree of difficulty. Our findings suggest general principles that may be useful in optimizing reading speed in individuals with advanced glaucoma, and may apply to other ocular diseases as well. First, short simple words should be used when possible to prevent reading difficulty associated with long or complex words. Additionally, strategies that minimize the number of line transitions in glaucoma patients by methods such as rapid serial visual presentation (RSVP) or viewing of pages in landscape mode may be beneficial.[36] Alternately, electronic readers may be programmed to allow readers to scroll text horizontally by swiping across the screen. Patients with other eye diseases have been trained to optimize the use of their peripheral vision to reading words located outside the central field of vision, which could potentially be applied in glaucoma patients to improve the ease of line transitions and overall reading speed as well.[37,38] Finally Crossland and Rubin[39] emphasized the importance of high contrast text for low vision patients with reduced CS, and the present study extends this to patients with glaucoma.

There are several limitations in our study. Some people may aim for a higher level of comprehension than others, which may affect their speed. By not testing for comprehension, we allow for greater variability in this respect. We did not capture eye movements while the subjects were recorded reading aloud, so we do not know precisely what fixation/saccade patterns resulted in poor readers with glaucoma. Prior studies have found that the size and/or accuracy of saccades in glaucoma patients are associated with lower reading speed, though it is not clear whether these differences in eye movements play a causative role in slower reading, or whether they simply reflect a need to make smaller eye movements as a result of visual decline. (Burton R, et al. *IOVS* 2012;53:ARVO E-Abstract 175) Additionally, although our results are statistically significant, the magnitude of the interactions were relatively small for lexical frequency and line changes as described above, and therefore the degree of disability attributable to poor CS in the context these specific text features should not be overstated. Finally, our findings pertain to only one reading task, but other reading tasks such as reading the newspaper, bills, notes, and so on, may result in a greater or less significant degree of impairment compared with the passage used in our study.[40]

In summary, our findings suggest that patients with more advanced vision loss due to glaucoma have more difficulty with certain word-specific features while reading out-loud, including words that are longer, less frequently used, and located at the end of the line. These findings should be used to guide which interventions should be applied to patients with advanced glaucoma-related visual loss. Future research should also aim to identify particular areas of difficulty for patients with other patterns of vision loss, which may lead optimize reading rehabilitation efforts.

Acknowledgments

Supported by grants from the Research to Prevent Blindness Robert and Helen Schaub Special Scholar Award (New York, NY, USA), American Glaucoma Society/Glaucoma Research Foundation Career Development Award (San Francisco, CA, USA), and National Eye Institute Grant EY018595 (Bethesda, MD, USA).

Disclosure: **P.M. Mathews**, None; **G.S. Rubin**, None; **M. McCloskey**, None; **S. Salek**, None; **P.Y. Ramulu**, None

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