Slow Reading in Glaucoma: Is it due to the Shrinking Visual Span in Central Vision?

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Purpose. Glaucoma is a leading cause of blindness worldwide, characterized by progressive loss of retinal ganglion cells. Patients with bilateral glaucoma read slower than normal cohorts. Here we examined the factors that may underlie slow reading in glaucoma and determined the best predictor of reading speed in glaucoma.

Methods. A total of 38 subjects participated in this study: 17 patients with primary open-angle glaucoma (mean age = 64.71 years) and 21 age-similar normal controls (58.24 years). For each subject, we measured binocular visual acuity (BVA); binocular contrast sensitivity (BCS); stereoacuity; visual field mean deviation (MD); and the visual span (i.e., the number of letters recognizable at one glance) known to limit reading speed. The visual span was measured with a trigram letter-recognition task in which subjects identify trigrams flashed at varying letter positions left and right of the fixation. Oral reading speed was measured with short blocks of text.

Results. Even after controlling for age, glaucoma patients showed significantly slower reading speed (by 19%, $P < 0.05$) and smaller visual span (by 11 bits, $P < 0.001$) compared to normal controls. While their BVA was relatively normal (20/20 Snellen equivalent), their BCS ($P < 0.001$); stereoacuity ($P < 0.001$); and visual field MD ($P < 0.001$) showed pronounced deficits. Multiple regression analysis further revealed that reading speed in glaucoma was best predicted by the visual span.

Conclusions. Our results showed that slower reading speed in glaucoma was closely related to the shrinkage of the visual span. Our findings further support the view that the visual span plays a limiting role in reading speed.

Keywords: glaucoma, macular function, the visual span, reading speed, contrast sensitivity

Glaucoma is the second most common cause of blindness in the United States, and the leading cause of blindness among African-Americans.[1] Glaucoma is characterized by progressive retinal ganglion cell (RGC) loss and associated visual field defects. The classical view has been that glaucoma spares central vision until the end stage and thus it has little impact on central vision tasks such as reading.[2] However, growing evidence has shown that reading difficulties (slow reading or fatigue reading) are common in people with bilateral glaucoma[3] and reading performance can be compromised even in relatively early stage glaucoma.[4,5] Moreover, reading problems have been cited as a the main cause of anxiety among people with glaucoma.[5–11] In addition to self-reported measures of difficulties with reading, functional assessments of both oral and silent reading have shown that people with bilateral glaucoma have abnormal eye movements during reading and/or noticeably slower reading speed compared to age-matched healthy controls.[2,3,12–14]

Reading is essential to our everyday life and is thus a key component of vision-related quality of life.[15] Although reading difficulties have been a major complaint among glaucoma patients,[5,16–18] little is known about how glaucomatous damage undermines the perceptual process of reading in central vision. As slow and effortful reading in low vision often reflects a bottom-up, visual sensory limitation on reading, reading speed has been a functionally significant measure.[19] Thus, the current study was undertaken to understand the visual factors that may influence reading speed in glaucoma.

Previous studies on reading have shown that deficiencies of letter recognition such as acuity limit or loss of contrast sensitivity lead to a significant reduction in reading speed.[20–24] Recent studies[25–28] using spectral-domain optical coherence tomography (SD-OCT) have demonstrated even early glaucomatous injury involves the macula (i.e., the retinal area corresponding to the central 10° or 20° visual field). Such damage includes loss of retinal ganglion cells and significant shrinkage of dendritic structures and cell bodies of remaining cells in the macula. Contrast is known to be a primary parameter encoded by contrast sensitive neurons such as center-surround RGCs. Thus, it is reasonable to speculate that deficiencies of letter recognition such as loss of contrast sensitivity in glaucomatous eyes may contribute to slow reading in glaucoma. Indeed, a recent study by Burton et al.[12] has shown that a greater dependence of text contrast on reading speed in glaucoma patients compared to normal cohorts. They found the reduction in the reading speed of glaucoma patients became significantly more pronounced as text contrast decreased. The significant association between contrast sensitivity and reading speed in glaucoma was also reported in a recent study by Ramulu et al.[3]

In addition to deficiencies of single letter recognition such as acuity limit or loss of contrast sensitivity, studies have shown

Table 1. Characteristics for Study Participants

Subject ID	Diagnosis	Sex	Age, years	BVA, logMAR	BCS, log Unit	Stereoacuity, Arc seconds	MD, dB	
							OD	OS
G1	POAG	M	67	0.10	1.65	200	−2.15	−6.19
G2	POAG	M	74	0.00	1.65	40	−1.59	−2.12
G3	POAG	M	60	0.04	1.35	80	−9.55	−10.63
G4	POAG	F	66	0.02	1.65	400	−9.63	−21.27
G5	POAG	F	84	−0.06	1.50	100	−1.51	−6.94
G6	POAG	F	70	0.00	1.35	200	−16.19	−21.58
G7	POAG	F	72	0.08	1.60	400	−8.91	−3.58
G8	POAG	F	83	0.12	1.90	50	−14.50	−17.22
G9	POAG	F	55	−0.10	1.80	50	−12.20	−9.59
G10	POAG	F	46	0.24	1.35	60	−32.30	−15.14
G11	POAG	F	52	−0.10	1.80	100	0.84	−10.43
G12	POAG	F	53	−0.08	1.65	50	−0.99	−1.51
G13	POAG	F	59	0.14	1.65	null	−7.92	−22.10
G14	POAG	F	60	0.00	1.35	200	−7.19	−11.56
G15	POAG	M	71	−0.10	1.95	40	−2.95	−2.44
G16	POAG	F	65	0.04	1.65	140	−15.22	−4.22
G17	POAG	M	63	0.02	1.65	40	−0.61	−2.39
Mean (±SD)	POAG (n = 17)	F:M = 12:5	64.71 (±10.44)	0.02 (±0.09)	1.62 (±0.19)	179.41 (±218.62)	−8.39 (±8.29)	−9.94 (±7.23)
	Normal vision (n = 21)	F:M = 9:12	58.24 (±7.01)	−0.09 (±0.07)	1.93 (±0.08)	47.14 (±14.19)	0.13 (±1.74)	0.07 (±1.71)

Note that the numbers in parentheses are standard deviations (SD). OD, Right eye; OS, Left eye. Also note that for the purpose of statistical analysis, stereoacuity 900″ was used as a surrogate for zero stereoacuity.

that the visual span, the number of letters that can be reliably recognized in one glance, imposes an additional limitation on reading speed.[29] The visual span can be thought of as the size of a window in the visual field within which letters can be recognized reliably. Thus, a larger visual span likely results in a smaller number of fixations and saccades required to read, thereby leading to a faster reading (assuming that the average fixation duration remains constant). Because the size of the visual span is largely accounted for by crowding (i.e., the inability to recognize target objects in clutter),[30] it is also called the "uncrowded window."[31] Over a decade, a number of studies have demonstrated a close linkage between reading speed and the size of the visual span in both normal and clinical populations.[19,29,32–36] For example, Cheong et al.[32] showed that slow reading speed in patients with age-related macular degeneration was closely related to the shrinkage of the visual span. A similar finding was also reported in the study of Crossland et al.[36] Correlated changes in reading speed and the size of the visual span were also found in the reading development of English-speaking children[37] and French-speaking children.[38] Furthermore, various manipulation of text properties such as letter contrast and size,[39] letter spacing,[40] and the spatial-frequency content (blur) of letters[24] has also supported the critical role of the visual span in reading speed. Thus, the visual span likely captures any changes in functional field of view directly relevant to reading performance following glaucomatous damage. However, the question still remains unanswered, how glaucomatous macular damage affects the size of the visual span and whether the shrinking visual span (if any) indeed contributes to slow reading in glaucoma.

Thus, the purpose of the current study was to examine the impact of glaucomatous injury on the size of the visual span, visual acuity, contrast sensitivity, and stereoacuity and to determine which visual factors contribute significantly to slow reading in patients with glaucoma. A global measure of glaucoma severity, visual field mean deviation (MD), was considered because studies have shown that glaucomatous reading difficulties are associated with the severity of visual field loss.[3,41] Stereoacuity was also included in this study as binocular function is known to impact the performance of various everyday tasks including reading.[42–44]

The outcome of the current study is expected to help us understand how glaucoma undermines the perceptual process of reading, typically thought to be spared from glaucomatous damage. A better understanding of the factors limiting reading speed in glaucoma patients will also help us develop effective reading rehabilitation for these patients.

Methods

Participants

A total of 38 subjects participated in the current study: 17 patients with primary open-angle glaucoma (POAG; mean age: 64.71 ± 10.44 years) and 21 normally sighted subjects of similar age (mean age: 58.24 ± 7.01 years). Patients with glaucoma were recruited from the Callahan Eye Hospital Clinics at the University of Alabama at Birmingham (UAB). Normally-sighted subjects were recruited from either a local senior center or the UAB Callahan Eye Hospital (i.e., those who visit the clinic for their routine eye exam). Patients with glaucoma, whose diagnosis was confirmed through medical records, met the following inclusion criteria:

1. Glaucoma specific changes of optic nerve or nerve fiber layer defect. The presence of the glaucomatous optic nerve was defined by masked review of optic nerve head photos by glaucoma specialists using previously published criteria.[45]
2. Glaucoma specific visual field defects: a value of glaucoma hemifield test from the Humphrey Field Analyzer (HFA) must be outside normal limits.
3. No history of other ocular or neurologic disease or surgery that caused visual field loss.

Table 1 summarizes characteristics of study participants. The average mean deviation obtained from the HFA in glaucoma patients was −6.23 ± 5.47 dB for the better eye and −12.09 ±

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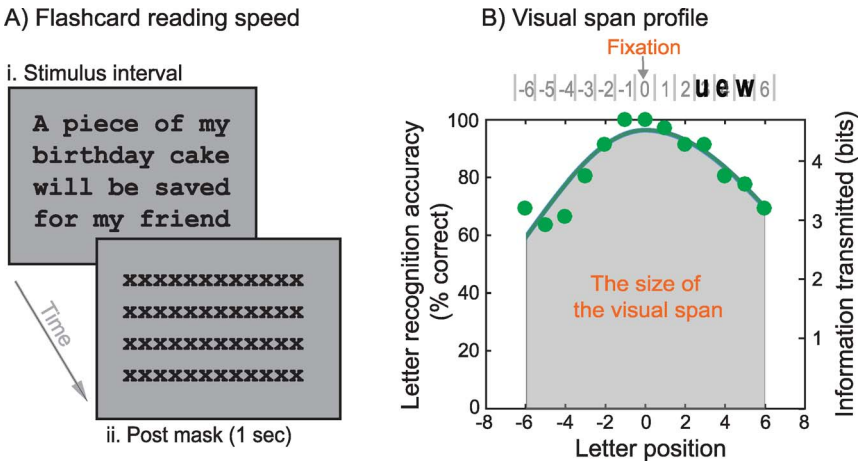

Figure 1. Schematic diagrams of task stimuli and procedure. (**A**) Task procedure for measuring flashcard reading speed. Each sentence was displayed on a screen for a given exposure duration, followed by a postmask consisting of x's. Participants were instructed to read the sentences aloud as quickly and accurately as possible. (**B**) Task procedure for measuring visual span profile. *Top*: an example of a trigram presented in a horizontal line. A trigram, a random string of three letters (e.g., "uew"), is centered at 1 of 13 positions in a horizontal line, left or right of the fixation. *Bottom*: an example of visual span profile. A visual span profile consists of letter recognition accuracy (% correct) as a function of letter position, and is fitted with a split Gaussian function. The *right vertical* scale shows a transformation from recognition accuracy to information transmitted in bits. The size of the visual span was defined as the area under the curve.

8.60 dB for the worse eye. According to the Hodapp-Anderson-Parrish glaucoma grading system,[46] the majority of our glaucoma patients were in either early or moderate stages of glaucoma (14 out of 17). Normal vision was defined as better than or equal to 0.00 logMAR (20/20 Snellen equivalent) best-corrected visual acuity in each eye with normal contrast sensitivity, with normal binocular vision, with the glaucoma hemifield test result being within normal limits, and with no history of ocular or neurologic disease other than cataract surgery. All participants were native English speakers without known cognitive or neurologic impairments, confirmed by both the Mini Mental Status Exam (MMSE; ≥25 MMSE score, for those aged 65 and older) and medical records. Proper refractive correction for the viewing distance was used. The experimental protocols followed the tenets of the Declaration of Helsinki and were approved by the internal review board at UAB. Written informed consents were obtained from all participants prior to the experiment after explanation of the nature of the study.

Stimuli and Apparatus

The 26 lowercase Courier font letters of the English Alphabet—a serif font with fixed width and normal spacing—were used for both visual span and reading speed tasks. Trigrams, random strings of three letters, were used to measure visual span profiles. All the letters were black on a uniform gray background with a contrast of 99% (Fig. 1A) and a letter size of 0.8° (in x-height) at the 57-cm viewing distance.

All stimuli were generated and controlled using a computing environment (MATLAB version 8.3 and Psychophysics Toolbox extensions[47,48]; MathWorks, Inc., Natick, MA, USA) for a commercial operating system (Windows 7; Microsoft Corp., Redmond, WA, USA) running on a PC desktop computer (Dell Precision Tower 5810; Dell, Inc., Round Rock, TX, USA). Stimuli were presented on a liquid crystal display monitor (model: Asus VG278HE; refresh rate: 144 Hz; resolution: 1920 × 1080, subtending 60° × 34° visual angle at a viewing distance of 57 cm) with the mean luminance of the monitor at 159 cd/m^2. Luminance of the display monitor was made linear using an 8-bit lookup table in conjunction with photometric readings from a luminance meter (MINOLTA LS-110; Konica Minolta, Inc., Tokyo, Japan).

Procedure

Measuring Flashcard Reading Speed. As illustrated in Figure 1A, oral reading speed was measured with short blocks of text (flashcard method). The same method and sentences were used in previous studies.[24,37] All sentences were 56 characters (including spaces) in length and formatted into four lines of 14 characters. The difficulty of the sentences was roughly 2nd to 4th grade level. These simple and standardized sentences were chosen to minimize the influences of higher-level cognitive and linguistic factors, thereby assessing the front-end visual aspects of reading. Participants were instructed to read the sentences aloud as quickly and accurately as possible. But they were allowed to complete their verbalization after the sentence disappeared from the display. The method of constant stimuli was used to present sentences at five exposure times, spanning a range of ~1.4 log units. Five sentences were tested for each exposure time and the percent correct of word recognition was computed at each exposure time. The order of five durations was randomly interleaved within a block. Psychometric functions, percent correct versus log exposure duration, were created by fitting these data with cumulative Gaussian functions.[49] The threshold exposure time, defined as the exposure time yielding 80% of words read correctly, was then converted into the number of words read correctly per minute (wpm).

Measuring Visual-Span Profiles. Visual-span profiles were measured using a trigram letter-recognition task. A more detailed procedure was described in previous studies.[29,37] In brief, trigrams were centered at 13 letter positions, including 0 (the letter position at fixation) and from 1 to 6 letter widths left and right of the 0 position (Fig. 1B), corresponding to the central 10° visual field (–5° to +5°). Each of the trigrams was presented for 200 ms and tested 12 times, in a random order. Subjects were asked to fixate between two fixation lines and to report the three letters from left to right. A letter was scored as being identified correctly only if its order within the trigram was also correct. A visual span profile consisted of percent correct letter recognition as a function of letter position left

and right of the fixation. A visual span profile was fitted with a split Gaussian function based on the recognition accuracy at each letter slot. The size of the visual span was defined as the area under the profile, and was quantified in units of bits of information transmitted.

Measuring Other Visual Functions. For each participant, binocular visual acuity (BVA; Early Treatment Diabetic Retinopathy Study charts); binocular contrast sensitivity (BCS; Pelli-Robson charts); stereoacuity (Titmus Fly SO-001 StereoTest); and monocular visual field tests were also measured. Visual field test will be performed with standard automatic perimetry (SAP) using a Swedish interactive thresholding algorithm Standard 24–2 test with a Humphrey field analyzer (HFA; Carl Zeiss Meditec, Inc.). Goldmann size III targets with a diameter of 0.43° will be presented for 200 ms at one of 54 test locations in a grid on a white background (10 cd/m^2).

All subjects had practice trials for both reading speed and visual span tasks prior to data collection. A chin-rest was used to minimize head movements. Throughout the testing sessions, subjects' compliance with central fixation was continuously ensured either via a high-speed eye tracker or a webcam. As real-world reading is typically binocular, all functional measurements except for the Humphrey visual field test were made under binocular viewing.

Data Analysis

The normality of the data was checked using the quantile-quantile plot. To examine the effect of glaucoma on each of visual functions (i.e., the size of the visual span, binocular visual acuity, binocular contrast sensitivity, stereoacuity, and visual field MD) while statistically controlling for the effect of age, we performed a separate analysis of covariance for each visual function measurement. Thus, each visual function measurement was entered as a dependent variable in the model with subject group (glaucoma versus normal vision) and age being as an independent variable and a covariate, respectively. To determine which factors influence reading speed in glaucoma patients, we performed multiple regression analysis in which the size of the visual span, binocular visual acuity, binocular contrast sensitivity, stereoacuity, and visual field MD in the better eye were entered as predictor variables in the model with reading speed being as a dependent variable. We also performed Pearson's correlation and partial correlation analyses. Statistical analyses were performed using R software (version 0.98.1091).

Results

Table 1 summarizes visual characteristics of study participants. The mean binocular visual acuity was 0.02 ± 0.09 logMAR (or 20/20 Snellen equivalent) for glaucoma patients and –0.09 ± 0.07 logMAR (or 20/16 Snellen equivalent) for age-similar normal controls. The mean binocular contrast sensitivity (in log unit) was 1.62 ± 0.19 for glaucoma patients and 1.93 ± 0.08 for age-similar normal controls. The mean stereoacuity was 179.41 ± 218.62 seconds of arc for glaucoma patients and 47.14 ± 14.19 seconds of arc for age-similar normal controls. The average mean deviation obtained from the HFA in glaucoma patients was –8.39 ± 8.29 dB for the right eye and –9.94 ± 7.23 dB for the left eye (or –6.23 ± 5.47 dB for the better eye and –12.09 ± 8.60 dB for the worse eye). The average mean deviation for age-similar normal controls was 0.13 ± 1.74 dB for the right eye and 0.07 ± 1.71 dB for the left eye. Although both subject groups have a similar age distribution, there was still a noticeable difference between the two groups (64.71 ± 10.44 years vs. 58.24 ± 7.01 years). For this reason, we statistically controlled for the effect of age (i.e., the covariate) in the subsequent statistical analyses and we confirmed that the slight age difference played no significant role in any group differences in reading speed and other visual functions assessed in this study (all $P > 0.05$).

Next, we examined the effect of glaucomatous injury on reading speed, the size of the visual span, binocular visual acuity, binocular contrast sensitivity and stereoacuity by comparing each functional measure between glaucoma patients and age-similar normal controls. Figure 2 shows the mean value of each functional measurement for both glaucoma patients (in orange color) and age-similar normal controls (in green color). Gray open circles represent individual subject's data point while red open circles indicate the data from three glaucoma patients in the advanced stage of glaucoma (the rest are in either early or moderate stage glaucoma). The two dashed lines indicate the interquartile range (IQR) and the dotted lines indicate median values. As shown in Figure 2A, glaucoma patients exhibited significantly slower reading speed (a decrease by 18.69%, $F_{[1,35]} = 5.75$, $P = 0.02$) when compared to normally-sighted subjects of similar age.

Mean visual span profiles for both glaucoma patients and age-similar normal controls are summarized in Figure 2B. The peak value of the profile in glaucoma (74%) was considerably smaller than that in age-similar normal controls (90%), resulting in a vertical downward shift of the profile. In Figure 2C, the size of the visual span was quantified as bits of information transmitted. The information values ranged from 0 bits for chance accuracy of 3.8% correct (the probability of correctly guessing one of 26 letters) to 4.7 bits for 100% accuracy. The percent correct letter recognition was converted to bits of information using letter-confusion matrices by Beckmann.[50] We found that the size of the visual span measured within the central 10° visual field was significantly smaller in glaucoma patients compared to age-similar normal controls (a decrease by 11.02 bits, $F_{[1,35]} = 25.54$, $P < 0.001$). Considering the fact that 100% correct recognition of one letter is equivalent to 4.7 bits, a reduction of 11.02 bits of the visual span in glaucoma patients means that glaucoma patients recognize 2.3 letters less than what age-similar normal controls would recognize at one glance.

As shown in Figures 2D through 2G, we also found that there was a significant difference between glaucoma patients and age-similar normal controls in binocular visual acuity ($F_{[1,35]} = 15.30$, $P < 0.001$), binocular contrast sensitivity ($F_{[1,35]} = 47.08$, $P < 0.001$), stereoacuity ($F_{[1,35]} = 7.49$, $P < 0.001$), better-eye visual field MD ($F_{[1,35]} = 28.46$, $P < 0.001$) even after controlling for age. It is also worth noting that even though the binocular visual acuity of glaucoma patients was not as good as that of age-similar normal controls, glaucoma patients' visual acuity was considered nearly normal (0.02 logMAR or 20/20 Snellen equivalent).

To examine the effects of glaucoma severity on these visual functions, we further categorized our glaucoma patients into three stages of glaucoma: early ($n = 9$); moderate ($n = 5$); and advanced ($n = 3$) glaucoma using the Hodapp-Anderson-Parrish glaucoma grading system.[46] We, however, did not find any statistically significant difference among the three groups in either reading speed, the size of the visual span, binocular contrast sensitivity, binocular visual acuity, or stereoacuity (all $P > 0.05$). It is noteworthy that while there was no significant difference across glaucoma severity within the glaucoma group, these functional deficits including reading speed and the visual span became already apparent in early or moderate glaucoma when compared to age-similar normal controls (all $P < 0.05$).

Next, in order to determine the factors that could best predict the reading speed of glaucoma patients, we performed

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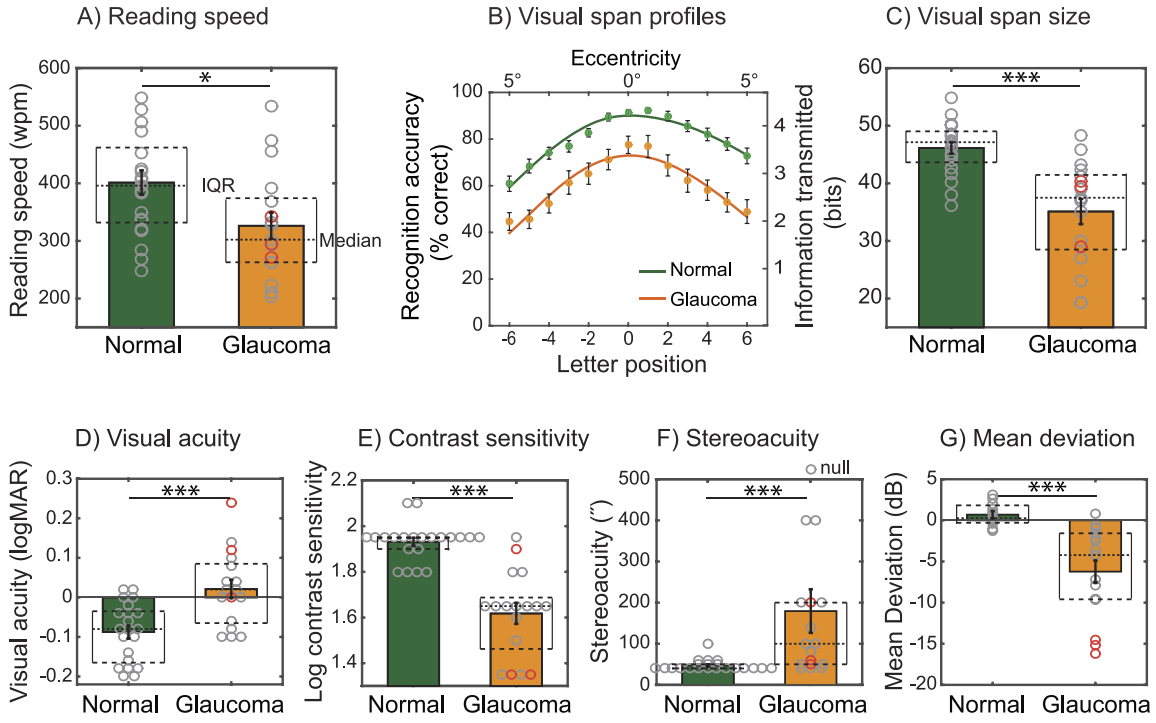

Figure 2. Slower reading speed and shrinking of the visual span in glaucoma. Note that as real-world reading is typically binocular, all the functional measurements except for the Humphrey visual field test were made under binocular viewing. Thus, the results in (**A**) through (**F**) represent binocular data, whereas the result in (**G**) represents the data from the better eye. Each panel contains data from glaucoma patients (*orange bars*; $n = 17$) and age-similar normal controls (*green bars*; $n = 21$). *Bar graphs* indicate the mean values of each result. *Error bars* represent ± 1 standard error of mean (SEM). * denotes $P < 0.05$, *** denotes $P < 0.001$. *Gray open circles* represent individual subject's data point while *red open circles* mark the data from three glaucoma patients in the advanced stage of glaucoma (the rest are in either early or moderate glaucoma). For ease of visibility in the figure, some of the circles (**D**–**F**) were laterally shifted because otherwise they overlapped with each other. The *two dashed lines* indicate the interquartile range (IQR) and the *dotted lines* indicate median values. (**A**) Flashcard reading speed. Mean reading speed (words per minute, wpm) is plotted for glaucoma patients and age-similar normal controls. (**B**) Visual span profiles. A plot of letter recognition accuracy (% correct) as a function of letter position (–6 to + 6) corresponding to the central 10° visual field (–5° to +5° visual angle) is plotted for glaucoma (*orange*) and age-similar normal controls (*green*). The data (*dots*) were fitted with a split Gaussian function to estimate the visual span profiles. The *solid lines* are the best fits of the model. (**C**) Visual span size. Mean visual span size (bits) is plotted for glaucoma and age-similar normal controls. (**D**) Binocular visual acuity (logMAR). (**E**) Binocular contrast sensitivity (in log unit). (**F**) Stereoacuity (in arc seconds). (**G**) Visual field MD (in dB) in the better eye.

a multiple regression analysis in which the size of the visual span, binocular visual acuity, binocular contrast sensitivity, stereoacuity, and visual field MD were entered as independent variables in the model with reading speed being as a dependent variable (Eq. 1).

$$\begin{aligned}\text{Glaucoma reading speed} &= \beta_0 X_{\text{Visual Acuity}} + \beta_1 X_{\text{Contrast Sensitivity}} \\ &+ \beta_2 X_{\text{Visual Span}} + \beta_3 X_{\text{Stereoacuity}} \\ &+ \beta_4 X_{\text{Visual Field MD}} + \varepsilon \end{aligned} \quad (1)$$

Our analysis revealed that the size of the visual span was the only factor that contributed significantly to the reading speed of glaucoma patients ($F_{[1,11]} = 10.39$, $P = 0.008$) while the other factors had no significant independent effect on reading speed (all $P > 0.05$). In other words, while other visual factors being held constant, the visual span size becomes the best predictor determining the reading speed of glaucoma patients.

As shown in Figure 3A, there was a significant correlation between the size of the visual span and reading speed ($R = 0.70$, $P < 0.01$) in glaucoma. The simple regression of log reading speed on the size of the visual span further showed that 50% of variance in the reading speed of glaucoma patients could be accounted for by the size of the visual span ($R^2 = 0.49$, $P < 0.01$). Our regression results showed that adding 4.7 bits to the size of the visual span (equivalent to one extra perfectly recognized letter) increases reading speed by 0.047 log units (i.e., a 12% increase in reading speed) in glaucoma patients ($\log y = 0.01x + 2.17$). It is noteworthy that the linear relationship between reading speed and the visual span remained nearly the same even when we included the data from age-similar normal controls in our regression analysis ($\log y = 0.01x + 2.21$). Legge et al.[39] showed that the slope of the regression line ranges from 0.02 to 0.04 (an average slope of 0.03) across different studies linking the size of the visual span to reading speed. Our estimated slope of 0.01 is less than the reported values. It may be due to obvious methodological differences between ours and their studies that include different age populations (older adults with/without glaucoma aged 46–84 years for our study versus young normally sighted subjects aged 18–32 years for their studies) and the modes of reading (flashcard method for ours versus rapid serial visual presentation method for theirs).

We then performed a partial correlation analysis to see if the observed correlation between reading speed and the size of the visual span still holds even after controlling for age. As shown in Figure 3B, we observed the same correlation coefficient between reading speed and the size of the visual span ($R = 0.70$, $P < 0.01$) even after removing the effect of age on reading speed and the visual span. Taken together, these results

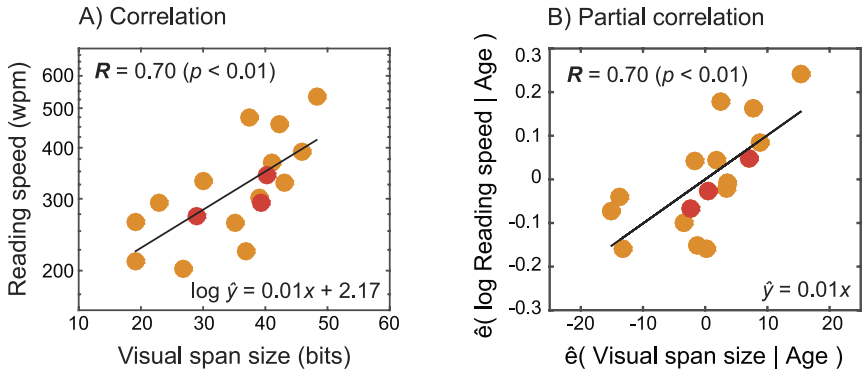

Figure 3. Relationship between reading speed and the size of the visual span in glaucoma. (**A**) Correlation between reading speed and the size of the visual span. In log-linear graph, reading speed (wpm) is plotted as a function of the size of the visual span (bits) for glaucoma patients. (**B**) Partial correlation between log reading speed (wpm) and visual span size (bits) after controlling for the effects of age on reading speed and visual span. In the partial correlation plot, $\hat{e}(y|x)$ represents the residuals from the regression of the y variable on the x variable. For both panels, each *dot* represents data for each individual subject. The data from advanced glaucoma patients were marked by *red circles* while the rest represent the data from either early or moderate glaucoma patients. The *black solid lines* represent the best linear fit to the data.

further support a significant role of the visual span in reading speed.

We, however, did not find any significant relationships between reading speed and other factors such as binocular visual acuity ($R = -0.19$, $P = 0.46$); binocular contrast sensitivity ($R = 0.37$, $P = 0.15$); stereoacuity ($R = 0.15$, $P = 0.56$); and visual field MD ($R = 0.05$, $P = 0.84$), respectively. Furthermore, the severity of glaucoma (the visual field MD in the better eye) was not significantly correlated with the size of the visual span ($R = -0.10$, $P = 0.69$).

Discussion

The ability to read is the most common priority of low vision patients in general and of those with glaucoma in particular.[51] Reading is indispensable to many daily activities, thereby affecting a person's quality of life. Contrary to the classical view that glaucoma spares central vision, individuals with glaucoma, even in relatively moderate stages of the disease, cite reading problems as one of their main difficulties. For example, Nguyen et al.[18] reported that glaucoma patients tended to engage much less reading activity compared to normal controls. This self-limiting reading behavior was associated with more severe visual field loss and contrast sensitivity, and affected various types of readings including book, newspaper and puzzle.

In this study, we showed that reading speed was significantly slower in patients with glaucoma relative to age-similar normal controls. Considering the fact that the majority of our glaucoma patients (82%) are in either early ($\leq$–6 dB in the better eye) or moderate stage of glaucoma ($\leq$–12 dB in the better eye),[46] our objective evaluation of out-loud reading rate further support the view that reading difficulties are present even in relatively moderate stages of glaucoma.[3–5,7] Our results also showed that even moderate stages of glaucoma are associated with noticeable deficits in stereoacuity (179″ for glaucoma versus 47″ for normal cohorts) and binocular contrast sensitivity (1.62 vs. 1.93 log unit). Poor binocular function (indicated by poor stereoacuity) in glaucoma patients was also reported in previous studies.[52–54] These studies showed that even in early or moderate stage of glaucoma, stereopsis, convergence, and binocular fusion are significantly more impaired in people with glaucoma, compared to glaucoma suspects or normal cohorts. Glaucoma often affects both eyes asymmetrically and this binocularly asymmetric impairment may result in the deterioration of binocular function.[55] On the other hand, our results showed that the binocular visual acuity of glaucoma patients appeared to be relatively normal (20/20 Snellen equivalent) although it was significantly different from that of age-similar normal controls (20/16 Snellen equivalent). Furthermore, we found that the size of the visual span measured in the central 10° visual field decreased by 11.02 bits for glaucoma patients, which means that glaucoma patients tend to recognize on average 2.3 letters less than what age-similar normal controls would recognize at one glance.

Then, what are the factors limiting reading speed in glaucoma? Our multiple regression analysis showed that the visual span made an independent contribution to the reading speed of glaucoma patients while the others did not. In other words, the size of the visual span was the only significant contributor to reading speed in glaucoma when binocular visual acuity, binocular contrast sensitivity, stereoacuity, and visual field MD in the better-eye were held constant. More specifically, we observed a significant correlation between the size of the visual span and reading speed ($R = 0.70$, $P < 0.01$) in glaucoma. The size of the visual span explained approximately 50% of variance in the reading speed of glaucoma patients ($R^2 = 0.49$, $P < 0.01$). Consistent with the visual-span hypothesis, our findings further provide evidence for a close linkage between reading speed and the size of the visual span. While such correlations have been reported in people with normal vision or people with central vision loss (e.g., age-related macular degeneration),[32,36] our study is the first one to demonstrate such influential role of the visual span in reading speed in people with glaucoma. While most visual information necessary for reading is obtained through the central region, parafoveal vision is known to be important for efficient reading behaviors, such as optimal saccade planning. For example, a vast literature on the processing of reading has shown that skilled readers of alphabetic writing systems obtain useful letter information across the visual field that extends 3 to 4 letters to the left of fixation and 14 to 15 letters to the right of fixation.[56] When the required field of view is not met, reading speed becomes noticeably slower.[19] Thus, in order to fully assess reading difficulties associated with glaucomatous damage, it is important to consider the spatial extent of the visual span highly relevant to reading performance.

As the size of the visual span is largely explained by visual crowding,[30] we speculate that crowding may be, at least in part, responsible for a reduction in the visual span in glaucoma. Despite various accounts of crowding, there is one common

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thread: crowding is ascribed to signals being pooled over a greater spatial extent (extensive pooling).[57–61] Previous work has shown that loss of retinal ganglion cells in glaucomatous vision is related to an increase in receptive field size, which may in turn exacerbate the crowding effect. For various stimulus conditions, Ricco's area (i.e., the area of complete spatial summation for visual stimuli) has been shown to increase even in patients with early glaucoma compared to age-matched normal controls, suggesting an increase in signal pooling in response to loss of ganglion cells and/or shrinkage of their dendritic structures and cell bodies.[62,63] An animal study indeed reported an increase of receptive fields in the superior colliculus of adult rats following experimentally induced glaucoma (sustained elevation of intraocular pressure and loss of retinal ganglion cells).[64] The increase of receptive fields was proportional to the degree of glaucomatous damage, highlighting the close linkage between the size of signal integration zones and ganglion cell damage. Although the exact neural underpinning of spatial integration in glaucoma and its impact on visual crowding remain to be answered, increasing spatial summation in glaucoma may induce changes in cortical pooling mechanisms involved in visual recognition, thereby resulting in changes in the spatial extent of crowding and the visual span.

Previous studies have shown that glaucomatous reading difficulties are associated with various factors that include print size,[5,6,41] text contrast,[12] reading duration,[3] the severity of visual field loss,[3,41] the location of scotoma,[10] the patterns of eye movements,[2] and specific word features[13] (e.g., number of letters, frequency of words, location of a word at the end of line). For example, Ramulu et al.[3] showed that reading speed measured by three different methods (i.e., out-loud MNREAD reading, out-loud IReST passage reading, sustained silent reading) was significantly slower in patients with bilateral glaucoma when compared to normal cohorts. They found that the visual acuity, contrast sensitivity, and visual field MD in the better eye were all associated with reading speed for the three reading types. Altangerel et al.[41] identified the reading of small print as one of the most visually demanding tasks for patients with glaucoma and reported a correlation between reading speed and the extent of binocular visual field loss. On the other hand, Burton et al.[12] showed that a reduction in reading speed with decreasing text contrast becomes significantly more pronounced in glaucoma patients compared to normal cohorts. Smith et al.[2] reported that glaucoma patients with poor reading performance exhibited more frequent regressive saccades. In addition to these findings, the current study provided evidence that the shrinkage of the visual span (the functional visual field directly relevant to reading) may be another major contributor to reading difficulties in glaucoma.

Unlike previous studies, the current study did not see that glaucomatous reading speed was significantly associated with either binocular visual acuity, binocular contrast sensitivity, or 24–2 visual field MD. Although speculative, it may be related to any of the reasons that follow. First, as the current study employed predominantly early or moderate stage of glaucoma (82%), it might have had low statistical power to observe the significant effects of visual acuity, contrast sensitivity, and visual field MD on reading speed. For this reason, we acknowledge that a future study should consider a wide range of glaucoma stages including glaucoma suspects and more severe stages of glaucoma to better characterize the effects of glaucomatous damage on reading ability and the size of the visual span including other visual functions. On the other hand, our results suggest that the visual span may be a more sensitive and relevant assessment tool to capture glaucomatous reading impairments when compared to visual acuity, contrast sensitivity, stereoacuity, or visual field MD. Second, unlike previous studies, the current study assessed oral reading speed with short blocks of simple and standard text (flashcard method in which a line of text occupied the central 11 degrees of the visual field), which might have underestimated particular aspects of glaucomatous reading difficulties. For example, it has been shown that individuals with glaucoma appear to have more difficulties with long passage reading: Ramulu et al.[3] found that glaucoma patients exhibit more pronounced reading deficits in sustained silent reading than out-loud reading using short text; a study by Mathews et al.[13] further demonstrated that compared to glaucoma suspect controls, glaucoma patients take a longer time changing to the next line of text during reading. Thus, it is possible that the use of short text reading might have underestimated any effect of visual field defects (mean deviation) on reading speed because visual field defects (a 24–2 visual field test) were more pronounced in the far periphery. Reading is a complex task involving various sensory, cognitive, and linguistic components. Thus, different reading measures likely tap into different aspects of the reading process.[65] In this study, we focused on the role of bottom-up, visual sensory factors in glaucoma-related reading deficits while minimizing higher-level cognitive and linguistic influences. For this reason, we adopted the flashcard method as it has been proven to examine the role of vision in reading speed.[24,37,40,66,67] Particularly, the same flashcard reading speed was shown to be significantly correlated with developmental changes in the size of visual span.[37] Nonetheless, we acknowledge that a future study should consider using other reading speed measures (e.g., sustained silent reading) to see if the observed pattern of results could be generalized to other types of reading measures. Finally, the current study relied on visual field MD (i.e., a global measure of glaucoma severity) as an overall index of glaucomatous damage. However, vision loss in different parts of the visual field likely causes different degrees of impairment in a person's reading ability. Thus, a future study should also address how the location and spatial extent of glaucomatous field defects influence reading speed in glaucoma.

Despite these limitations, the current study demonstrated that central pattern vision (within the central 10° visual field) in glaucoma is compromised than expected from age-similar normal controls: our results showed that glaucoma patients exhibit a significant reduction in the size of the visual span and corresponding decrease in reading speed. Our findings further suggest that the shrinkage in functional field of view relevant to reading task may play a limiting role in reading speed in glaucoma.

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