Glaucome is the second most common cause of blindness in the United States, and the leading cause of blindness among African-Americans.1 Glaucome 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 glaucoma3 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.5,5,12–14

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 studies25–28 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 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

<table>
<thead>
<tr>
<th>Subject ID</th>
<th>Diagnosis</th>
<th>Sex</th>
<th>Age, years</th>
<th>BVA, logMAR</th>
<th>BCS, log Unit</th>
<th>Stereoaucity, Arc seconds</th>
<th>MD, dB</th>
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<tr>
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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, stereoaucity 900° was used as a surrogate for zero stereoaucity.

Although 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 size of the visual span. A similar finding was also reported in the study of Crossland et al.33 Correlated changes in reading speed and the size of the visual span were also found in the reading development of English-speaking children37 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 stereoaucity 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 Stereoaucity 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 otherocular 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 ±
Slow Reading and Shrinking Visual Span in Glaucoma

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 extensions47,48; 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/m². 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).

Procedures

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 studies24,37 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); stereocuity (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 0.45° will be presented for 200 ms at one of 54 test locations in a grid on a white background (10 cd/m²).

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, stereocuity, 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, stereocuity, 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 stereocuity 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 179.41 ± 6.23 (log unit) was 1.62 ± 0.09 logMAR (or 20/16 Snellen equivalent) for age-similar normal controls. The mean binocular contrast sensitivity (in log unit) was 1.62 ± 0.09 logMAR (or 20/16 Snellen equivalent) 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 stereocuity 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. 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 12.02 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 2.5 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), stereocuity (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 stereocuity (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
between the size of the visual span and reading speed (\(R\) predictor determining the reading speed of glaucoma patients. Being held constant, the visual span size becomes the best 0.70, \(P\) speed (all other factors had no significant independent effect on reading could be accounted for by the size of the visual span (\(R^2 = 0.49, P = 0.001\)). 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 0.05) 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, there was a significant correlation 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
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 ($R = 0.37, P = 0.15$); stereoaucity ($R = 0.15, P = 0.56$); 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. 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. reported that glaucoma patients tended to engage much less reading activity compared to 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), our objective evaluation of out-load reading rate further support the view that reading difficulties are present even in relatively moderate stages of glaucoma. Our results also showed that even moderate stages of glaucoma are associated with noticeable deficits in stereoaucity (179° for glaucoma versus 47° for normal cohorts) and binocular contrast sensitivity (1.62 vs. 1.95 log unit). Poor binocular function (indicated by poor stereoaucity) in glaucoma patients was also reported in previous studies. 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. 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, stereoaucity, 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), 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. When the required field of view is not met, reading speed becomes noticeably slower. 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.
difficulties are associated with various factors that include visual span.\textsuperscript{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, including short texts,\textsuperscript{4} it has been shown that individuals with glaucoma appear to have more difficulties with long passage reading. Ramulu et al.\textsuperscript{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.\textsuperscript{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.\textsuperscript{57–61} 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.\textsuperscript{57–61} Particularly, the same flashcard reading speed was shown to be significantly correlated with developmental changes in the size of visual span.\textsuperscript{57–61} 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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References

Slow Reading and Shrinking Visual Span in Glaucoma


