Higher Contrast Requirement for Letter Recognition and Macular RGC+ Layer Thinning in Glaucoma Patients and Older Adults

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PURPOSE. Growing evidence suggests the involvement of the macula even in early stages of glaucoma. However, little is known about the impact of glaucomatous macular damage on central pattern vision. Here we examine the contrast requirement for letter recognition and its relationship with retinal thickness in the macular region.

METHODS. A total of 40 participants were recruited: 13 patients with glaucoma (mean age = 65.6 ± 6.6 years), 14 age-similar normally sighted adults (59.1 ± 9.1 years), and 13 young normally sighted adults (21.0 ± 2.0 years). For each participant, letter-recognition contrast thresholds were obtained using a letter recognition task in which participants identified English letters presented at varying retinal locations across the central 12° visual field, including the fovea. The macular retinal ganglion cell plus inner plexiform (RGC+) layer thickness was also evaluated using spectral-domain optical coherence tomography (SD-OCT).

RESULTS. Compared to age-similar normal controls, glaucoma patients exhibited a significant increase in letter-recognition contrast thresholds (by 236%, $P < 0.001$) and a significant decrease in RGC+ layer thickness (by 17%, $P < 0.001$) even after controlling for age, pupil diameter, and visual acuity. Compared to normal young adults, older adults showed a significant increase in letter-recognition contrast thresholds and a significant decrease in RGC+ layer thickness. Across all subjects, the thickness of macular RGC+ layer was significantly correlated with letter-recognition contrast thresholds, even after correcting for pupil diameter and visual acuity ($r = -0.65, P < 0.001$).

CONCLUSIONS. Our results show that both glaucoma and normal aging likely bring about a thinning of the macular RGC+ layer; the macular RGC+ layer thickness appears to be associated with the contrast requirements for letter recognition in central vision.

Keywords: glaucoma, macular function, aging, letter recognition, contrast threshold, retinal layer thickness, structure-function relationship

Glaucoma is a leading cause of blindness, projected to affect 11.18 million people worldwide by 2040. It is characterized by progressive loss of retinal ganglion cells (RGCs) and associated visual field defects. Primary open-angle glaucoma (POAG), the most common form of glaucoma in the United States, affects approximately 2.2 million Americans (2% of the US population 40 years and older). Glaucoma is traditionally understood as peripheral vision loss and is thought to spare central vision until the end-stage; thus, it hardly affects central visual function. However, a growing body of evidence suggests that the macula is significantly compromised even in early stages of glaucoma (see Ref. 17 for review). For instance, studies using optical coherence tomography (OCT) have shown significant thinning of the retinal nerve fiber layer and the ganglion cell layer in the macular region, which likely reflects loss of RGCs and/or significant shrinkage of dendritic structures and cell bodies of the remaining cells. In parallel with physiological evidence, behavioral studies have shown that, even during early stages of the disease, individuals with glaucoma exhibit noticeable dysfunction in various central vision tasks such as reading and object/face recognition. Furthermore, individuals with glaucoma reported a reduced quality of life. In one survey on quality of life, patients stated that their two main priorities were “reading and seeing detail” and “outdoor mobility.” Given the view that central vision is spared from glaucomatous injury, it is rather surprising that difficulty reading has been cited as a major complaint among patients with glaucoma.

While the exact perceptual mechanism limiting central vision tasks in glaucoma remains unclear, evidence hints that reduced contrast sensitivity in glaucomatous vision likely plays a limiting role in central vision tasks such as reading. Luminance contrast refers to the difference in intensity between light and dark regions of an image. Contrast information is encoded by contrast-sensitive neurons (e.g., center-surround RGCs) along the visual pathways. The ability to detect differences in contrast is a fundamental building block of human pattern vision and thus crucial to various visual activities. For example, Rubin and Legge found that as the contrast between text and page decreases, reading speed decreases in some people with low vision. Considering the significant macular damage found in glaucomatous eyes, it is reasonable to expect a higher contrast requirement for central vision.
Contrast Requirement for Letter Recognition in Glaucoma

Methods

Participants

A total of 40 participants took part in this study: 13 patients with glaucoma (12 patients with POAG and 1 patient with preperimetric glaucoma; mean age = 65.6 ± 6.6 years); 14 age-similar older adults with normal or corrected-to-normal vision (mean age = 59.1 ± 9.1 years); and 13 young adults with normal or corrected-to-normal vision (mean age = 21.0 ± 2.0 years). The study participants were recruited from either the University of Alabama at Birmingham (UAB) Callahan Eye Hospital or the UAB campus.

For the patients with POAG, glaucoma was clinically diagnosed and confirmed through medical records. The patients with POAG in the current study met the following inclusion criteria: (1) a minimum visual acuity of 20/25 (or 0.2) in each eye; (2) a visual field defect, defined as having a value on the Humphrey Field Analyzer outside normal limits; (3) a minimum visual field loss of 5% in the affected eye; (4) a minimum visual field loss of 25% in the fellow eye; (5) no history of other ocular or neurologic disease or surgery that caused visual field loss; and (6) a minimum visual acuity of 20/25 (or 0.2) in each eye.

The average mean deviation (MD) obtained from the Humphrey Field Analyzer for glaucoma patients was −5.9 ± 8.3 dB for the better eye and −11.0 ± 8.4 dB for the worse eye. The mean MD obtained from the Humphrey Field Analyzer for normal controls was −0.6 ± 5.9 dB for the better eye and −0.6 ± 5.9 dB for the worse eye. The mean MD obtained from the Humphrey Field Analyzer for patients with POAG was −5.5 ± 8.1 dB for the better eye and −10.5 ± 8.5 dB for the worse eye. The mean MD obtained from the Humphrey Field Analyzer for normal controls was −0.6 ± 5.9 dB for the better eye and −0.6 ± 5.9 dB for the worse eye. The mean MD obtained from the Humphrey Field Analyzer for patients with POAG was −5.5 ± 8.1 dB for the better eye and −10.5 ± 8.5 dB for the worse eye.

Measuring Threshold Contrasts for Letter Recognition

Stimuli. To test letter recognition, the 26 uppercase Courier font letters of the English alphabet were used. The x-
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<th>Subject ID</th>
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<th>Age, years</th>
<th>Sex</th>
<th>Subject ID</th>
<th>Diagnosis</th>
<th>Age, years</th>
<th>Sex</th>
<th>Visual Acuity, logMAR</th>
<th>Contrast Sensitivity, log units</th>
<th>Pupil Diameter, mm</th>
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<td>56</td>
<td>F</td>
<td></td>
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<td>OS</td>
<td>0.08</td>
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<td>M</td>
<td></td>
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<td>0.04</td>
<td>OS</td>
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<td>OS</td>
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<td>F</td>
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<td></td>
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<td>OS</td>
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<td>F</td>
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<td>OS</td>
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<td>F</td>
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<tr>
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<td></td>
<td>0.08</td>
<td>OS</td>
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<td>M</td>
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<td>65.6</td>
<td>F: M=7.6</td>
<td></td>
<td></td>
<td>0.05</td>
<td>OS</td>
<td>1.50</td>
<td>5.5</td>
<td>NSC 1+ to 2+</td>
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<td>Normal Old</td>
<td>(n = 14)</td>
<td>(±0.05)</td>
<td>(±0.10)</td>
<td>(±0.23)</td>
<td>(±1.3)</td>
<td>(±1.2)</td>
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<tr>
<td>Normal Young</td>
<td>(n = 13)</td>
<td>(±0.08)</td>
<td>(±0.04)</td>
<td>(±0.12)</td>
<td>(±1.2)</td>
<td>(±1.1)</td>
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Note that the numbers in parentheses are standard deviations (SD). OD, right eye; OS, left eye; POAG, primary open-angle glaucoma; PPG, preperimetric glaucoma; NSC, nuclear sclerotic cataract; CC, cortical cataract; IOL, intraocular lenses; N/A, not available.

* Denotes an individual with dry eye.
Contrast Requirement for Letter Recognition in Glaucoma

FIGURE 1. Stimuli for the letter-recognition task and retinal OCT imaging. (A) An illustration of the stimulus configuration. A stimulus, a randomly generated letter, was presented in a gaze-contingent manner for 1 second at one of the nine locations shown here. A gaze-contingent display was used to ensure that the target letter was presented at the intended retinal location relative to the fovea. The dashed lines represent eccentricities of the target letters and were not shown in the experiment. The size of the target letter (0.8°, 0.8°, 1.1°) in relation to eccentricity was scaled considering the cortical magnification factor.44 (B) Overlay of RGC layer thickness map on a fundus photo. RGC layer thickness map (the heat map) centered on the fovea is overlaid on a fundus image. The diameter of the central, inner, and outer circles are 1, 3, and 6 mm, respectively. The diameter of the outer circle corresponds to the central 20° visual field. The inner and outer circles are divided into four quadrants each. (C) Sector map of the average RGC layer thickness. The average RGC layer thickness measurements (in micrometers) are shown for each of the nine subregions defined in (B). The center and inner circles (shaded in gray) correspond to the central 10° visual field. The thickness of the inner plexiform layer was generated in a similar manner. The RGC+ layer thickness was the sum of the inner plexiform layer and the RGC layer.

The stimuli were generated and controlled using MATLAB (version 8.3; MathWorks, Inc., Natick, MA, USA) and Psychophysics Toolbox extensions45,46 for Windows 7, 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 (Asus VS278H-E; ASUS Computer International, Fremont, CA, USA) with a refresh rate of 144 Hz and resolution of 1920×1080, subtending 60°×34° visual angle at a viewing distance of 57 cm. Stimuli were rendered with 10.8-bit gray-scale levels using the bit-stealing method.47 Luminance of the display monitor was made linear using an 8-bit look-up table in conjunction with photometric readings from a luminance meter (Minolta LS-110 Luminance Meter; Konica Minolta, Inc., Japan).

Participants’ gaze positions were monitored (monocular tracking) using an infrared video-based eye-tracker sampled at 500 Hz (EyeLink 1000 Plus/Desktop Mount, SR Research Ltd., Ottawa, Ontario, Canada) with a maximum spatial resolution of 0.01°. A stimulus was presented in a gaze-contingent manner to ensure that it appeared at the intended retinal location relative to the fovea. The tested eye was tracked while the opposite eye was covered with an eye patch. The threshold of each testing location was measured by block. One of the nine predetermined locations was randomly selected for each block. Prior to each block, subjects were cued to one of the nine locations. Subjects were instructed to fixate on a cross in the center. Chin and forehead rests were used to minimize head movements and to maintain a fixed viewing distance. Then, using a gaze-contingent display established by the high-speed eye-tracker, a target letter was flashed at the given retinal location for 1 second before being replaced by a set of the 26 letters (i.e., the answer key) presented in a clock face. A subject’s task was to determine the identity of the letter that had flashed and to select it with a mouse. Auditory feedback was given for correct answers. Letter-recognition contrast threshold was measured using a 3-down-1-up staircase procedure, which yields a target identification accuracy of 79.4%.48 Step size of the staircase was 1 dB. The final threshold was determined by taking the geometric average of the last seven staircase reversals. Prior to testing, a practice round was conducted to determine initial contrast of the letters and to familiarize participants with the task procedure.

Measuring Macular RGC+ Layer Thickness With SD-OCT

For each participant, macular retinal layer thickness was measured using SD-OCT (Spectralis; Heidelberg Engineering GmbH, Heidelberg, Germany).8,49 The measurement was made in the macula (i.e., the retinal region corresponding to the central 20° visual field). The images were generated using high-resolution volume scan made with automatic real-time mean value of 15. Macular raster scans (20°×20°) were acquired with 49 B-scans consisting of 1024 A-scans, resulting in an imaging area of approximately 6×6 mm centered on the fovea. Any scan with a quality score less than 20 dB was excluded from analysis. The thickness of each layer was read from the automatic segmentation algorithms provided by the onboard SD-OCT software (version 6.3.1.0). The RGC+ layer thickness was the sum of the ganglion cell layer and inner plexiform layer. The SD-OCT software displays the average retinal thickness and retinal volume of nine subregions of the retina, including a center circle (diameter 1 mm), an inner circle divided into four quadrants (diameter 3 mm), and an outer...
circle divided into four quadrants (diameter 6 mm). The
diameters (millimeters) of these circles were transformed to
degree units (1 mm \( \equiv 3.3^\circ \)). Figures 1B and 1C display the
locations of the nine subregions for the thickness measures.

**Data Analysis**

For both letter-recognition contrast threshold and macular
RGC+ layer thickness data, the averaged value across all retinal
locations for each considered eye was used for statistical
analyses. The normality of the data was checked using the
quantile-quantile plot. To meet the normality assumption,
logarithmically transformed letter-recognition contrast threshold-
ordered were used. We considered only one eye per participant:
the right eye for normally sighted participants or the worse eye
for glaucoma patients.

First, to address whether there are any significant differ-
ences in either the letter-recognition contrast threshold or
macular RGC+ layer thickness among different subject groups
(i.e., glaucoma, normal old, and normal young) after control-
ling for the effects of pupil diameter and visual acuity, we
performed the multivariate analysis of covariance (MANCOVA).
Here, we used subject group as an independent variable, letter-
recognition contrast threshold and macular RGC+ layer
thickness as dependent variables, and pupil diameter and
visual acuity as covariates in the model. We chose to adjust for
pupil diameter and visual acuity because iatrogenic pupils from
glaucoma medications \(^{30,31}\) or other optical characteristics (e.g.,
senile meiosis, light scattering; see the Discussion for lens
opacity) associated with the glaucomatous or aged eye could
potentially impact pattern vision. Second, to determine
whether macular RGC+ layer thickness plays a crucial role in
letter-recognition contrast threshold, we performed multiple
regression analysis in which macular RGC+ layer thickness,
visual acuity, and pupil diameter were entered as predictors
into the model, whereas the letter-recognition contrast
threshold served as the dependent variable. To further quantify
the relationship between the letter-recognition contrast
threshold and macular RGC+ layer thickness, we performed
partial correlation analyses between the two variables, after
regressing out effects of visual acuity and pupil diameter. For
our final test, we used data from both eyes of a single subject.
Here, we performed a within-subject correlation \(^{32}\) on our
glaucoma patients, comparing macular RGC+ layer thickness
and letter-recognition contrast threshold between the two
eyes. Statistical analyses were performed using the \( R \) software
(version 0.98.1091) \(^ {33}\) in combination with MATLAB (R2014b;
MathWorks, Inc.).

**RESULTS**

As described in the data analysis section, our statistical analyses
(e.g., MANCOVA) were performed on three subject groups
(i.e., glaucoma, normal old, and normal young) to correct for
multiple comparisons and control for potential confounding
variables. However, as our main goals were to compare
glaucoma and age-similar normal old adults (i.e., the effect of
glaucoma) and to compare normal old and young adults (i.e.,
the effect of normal aging), here we report the statistical
results of the effect of glaucoma and the effect of aging
separately.

**The Effects of Glaucoma: Higher Contrast Requirement for Letter Recognition and Thinner Macular RGC+ Layer Thickness in Glaucoma Patients**

In this section, we report the effects of glaucoma on the letter-
recognition contrast threshold and macular RGC+ layer
thickness. Figure 2A plots the mean letter-recognition contrast
threshold for each of the three subject groups. Gray open
circles represent an individual subject’s data point. The two
dashed lines indicate the interquartile range (IQR) and the
dotted lines indicate median values. There was a significantly
higher letter-recognition contrast threshold for glaucoma
patients compared to age-similar normal controls (by 236.0%,
\( F_{(1,23)} = 65.06, P < 0.001 \)) averaged across all testing locations
(i.e., nine locations within the central 12° visual field) after
controlling for pupil diameter and visual acuity. This pattern of
results held when thresholds were considered by retinal
eccentricity: glaucoma patients required a significantly higher
letter-recognition contrast threshold at the fovea (by 235.7%,
\( F_{(1,23)} = 7.71, P = 0.011 \)) and at 3° (by 227.8%, \( F_{(1,23)} = 18.42, P <
0.001 \)) and at 6° (by 243.9%, \( F_{(1,23)} = 29.94, P < 0.001 \)). Note that
this pattern of results held even after controlling for the
age difference (approximately 7 years) between the glaucoma
patients and age-similar normal controls (\( F_{(1,22)} = 23.02, P <
0.001 \)). Here, we conducted a separate MANCOVA on the data
set containing only glaucoma patients and age-similar normal
controls using age, visual acuity, and pupil diameter as
covariates.
 Threshold Thickness and Letter-Recognition Contrast in the macular RGC shaded area region in Fig. 1C); there was a significant decrease of results remained similar for the center and inner circles (the suggesting age-related changes in retinal structure. The pattern olds for older adults at the fovea (by 66.3%, \(F(1,25) = 19.40, P < 0.001\)) averaged across all testing locations. This pattern of results held for the center and inner circles as well (the shaded area in Fig. 1C); there was a significant decrease for glaucoma patients compared to age-similar normal controls (by 20.1%, \(F(1,25) = 19.12, P < 0.001\)).

### The Effects of Aging: Higher Contrast Requirement for Letter Recognition and Thinner Macular RGC Layer Thickness in Older Adults

In this section, we report the effects of aging on contrast requirement for letter recognition and macular RGC layer thickness in the macular region of healthy eyes. Thus, we compared both functional and structural data between normally sighted older adults and normally sighted young adults.

As shown in Figure 2A, there was a significantly higher letter-recognition contrast threshold for normal older adults compared to normal young adults (by 65.2%, \(F(1,25) = 53.56, P < 0.001\)) averaged across all testing locations, indicating age-related decline in contrast sensitivity. This pattern of results held even when contrast thresholds were considered by retinal eccentricity: There were significantly higher contrast thresholds for older adults at the fovea (by 66.3%, \(F(1,25) = 22.66, P < 0.001\)), at 5° (by 63.7%, \(F(1,25) = 25.29, P < 0.001\)), and at 6° (by 66.5%, \(F(1,25) = 34.66, P < 0.001\)).

As shown in Figure 2B, we also observed a significant decrease in the macular RGC+ layer thickness for older adults compared to young adults (by 8.0%, \(F(1,25) = 9.81, P = 0.004\)), suggesting age-related changes in retinal structure. The pattern of results remained similar for the center and inner circles (the shaded area region in Fig. 1C); there was a significant decrease in the macular RGC+ layer thickness for older adults compared to young adults (by 6.4%, \(F(1,25) = 4.88, P = 0.037\)).

### Relationship Between the Macular RGC+ Layer Thickness and Letter-Recognition Contrast Threshold

Using multiple regression analysis, we aimed to determine the role of macular RGC+ layer thickness in the letter-recognition contrast threshold. Thus, in this model, macular RGC+ layer thickness, visual acuity, and pupil diameter were entered as predictors whereas the letter-recognition contrast threshold was the dependent variable. We found that the macular RGC+ layer thickness was the only significant factor (a coefficient value of \(-0.02, P = 0.016\)) contributing to the letter-recognition contrast threshold. Neither visual acuity (\(P = 0.951\)) nor pupil diameter (\(P = 0.904\)) were statistically significant. Furthermore, this multiple regression analysis revealed that approximately 48% \((F(3,46) = 11.25, r^2 = 0.48, P < 0.001\)) of the variance in letter-recognition contrast threshold was accounted for by this model.

Using a partial correlation analysis, we quantified the correlation between the letter-recognition contrast threshold and macular RGC+ layer thickness after controlling for pupil diameter and visual acuity (Fig. 3A). In the partial correlation plot, \(c(i,a,b)\) represents the residuals from the regression of the variable on the \(a\) and \(b\) variables. Each data point represents the mean macular RGC+ layer thickness after controlling out the effects of PD and VA. (A) Correlation between letter-recognition contrast threshold and macular RGC+ layer thickness after regressing out the effects of pupil diameter (PD) and visual acuity (VA). (B) Correlation between Pelli-Robson contrast sensitivity (CS) and macular RGC+ layer thickness after regressing out the effects of PD and VA. (C) Correlation between visual acuity (logMAR) versus macular RGC+ layer thickness after regressing out the effects of PD and CS.

Figure 3B plots the mean macular RGC+ layer thickness for each of the three subject groups. There was a decrease in RGC+ layer thickness for glaucoma patients compared to age-similar normal controls (by 17.4%, \(F(1,25) = 34.66, P < 0.001\)) averaged across all testing locations. This pattern of results required for multiple regression analysis, we aimed to determine the role of macular RGC+ layer thickness in the letter-recognition contrast threshold. Thus, in this model, macular RGC+ layer thickness, visual acuity, and pupil diameter were entered as predictors whereas the letter-recognition contrast threshold was the dependent variable. We found that the macular RGC+ layer thickness was the only significant factor (a coefficient value of \(-0.02, P = 0.016\)) contributing to the letter-recognition contrast threshold. Neither visual acuity (\(P = 0.951\)) nor pupil diameter (\(P = 0.904\)) were statistically significant. Furthermore, this multiple regression analysis revealed that approximately 48% \((F(3,46) = 11.25, r^2 = 0.48, P < 0.001\)) of the variance in letter-recognition contrast threshold was accounted for by this model.

Using a partial correlation analysis, we quantified the correlation between the letter-recognition contrast threshold and macular RGC+ layer thickness after controlling for pupil diameter and visual acuity (Fig. 3A). In the partial correlation plot, \(c(i,a,b)\) represents the residuals from the regression of the variable on the \(a\) and \(b\) variables. Each data point represents the mean macular RGC+ layer thickness after controlling out the effects of PD and VA. (A) Correlation between letter-recognition contrast threshold and macular RGC+ layer thickness after regressing out the effects of pupil diameter (PD) and visual acuity (VA). (B) Correlation between Pelli-Robson contrast sensitivity (CS) and macular RGC+ layer thickness after regressing out the effects of PD and VA. (C) Correlation between visual acuity (logMAR) versus macular RGC+ layer thickness after regressing out the effects of PD and CS.
recognition.27 Both behavioral 19–23 and anatomical/imaging 10,11,13,14 studies show that even in young adults (i.e., visual field test) to measure peripheral vision.4 Recently, the age-related decrease in retinal (or retinal nerve fiber layer [RNFL]) thickness has been reported in previous studies.61,62 For example, Alamouti and Funk61 measured the retinal and RNFL thicknesses in 100 healthy eyes using OCT scans (the age of their participants ranged from 6 to 79 years). They found that both the retinal thickness and the nerve fiber layer thickness were significantly correlated with age: The retinal thickness decreased by 0.53 μm per year and the RNFL thickness decreased by 0.44 μm per year. However, what makes our current study different from these previous studies is that our thickness measurements were made in the macular region whereas others were around the optic nerve head.

The age-related decrease in the retinal layer thickness has been attributed to age-related losses of RGCs.63–65 The thinning of macular RGC+ layer thickness is likely to reflect age-related losses or shrinkage of RGCs and axons as suggested in histological studies.66,67 For example, according to a study by Curcio and Drucker,66 the density of RGCs subserving the central 1° of vision was reduced by 25% in healthy older adults compared to younger adults; Gao and Hollyfield68 also reported a considerable age-dependent reduction of the ganglion cell layer neurons in the human retina. Taken together, aging appears to produce approximately 15% to 25% loss of RGCs near the fovea.68 Furthermore, according to a
other hand, previous neurophysiological studies of nonhuman eyes.73–75 As can be seen in the Table, some glaucoma patients exhibited mild cataracts (NSC 1± or 2±). Unfortunately, lack of lens status information for our normally sighted participants precluded using cataracts as a covariate in our statistical analyses, we still found that the same pattern of results held. Besides, cataracts or dry eye cannot explain the observed differences in retinal layer thickness among our subject groups and the covarying nature of the macular RGC+ layer thickness and letter-recognition contrast threshold (r = −0.65, P < 0.001). Taken together, we believe that neither cataracts nor dry eye could reduce contrast sensitivity.80,81 However, using medical records, we confirmed that only two of our glaucoma patients had dry eye. When these patients’ data were excluded from the statistical analyses, we still found that the same pattern of results held. Besides, cataracts or dry eye cannot explain the observed differences in retinal layer thickness among our subject groups and the covarying nature of the macular RGC+ layer thickness and letter-recognition contrast threshold (r = −0.65, P < 0.001). Taken together, we believe that neither cataracts nor dry eye could explain our functional data and the significant structure–function relationship observed in the current study. This, however, is not to dismiss the potential role of optical characteristics or higher-level cortical mechanisms associated with either glaucoma or normal aging for contrast requirements for pattern recognition in general (see Refs. 59, 68, and 82 for reviews).

Finally, for a better characterization of the age-related structure–function relationship, a wider range of age groups, including individuals aged 70 or older, should be considered in a future study.

To summarize, the results reported in the current study demonstrate that the glaucomatous eye and the aged eye are associated with decreased macular RGC+ layer thicknesses. This decreased macular RGC+ layer thickness appears to be responsible for a higher contrast requirement for pattern recognition in the central visual field. Our findings further

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**Figure 5.** Effect of cataracts on functional data. (A) Mean letter-recognition contrast threshold for glaucoma patients with cataracts, whereas the orange bar on the right represents the mean threshold of those without cataracts. *Gray open circles* represent an individual subject’s data point. The *dashed lines* indicate the IQR, and the *dotted lines* indicate median values. Error bars: ±1 SEM. n.s., no significant difference. (B) Between-eye (within-subject) correlation between macular RGC+ layer thickness and letter-recognition contrast threshold was computed using the within-subject correlation measure.52,76 Only the 10 glaucoma patients who had letter-recognition contrast threshold data from both eyes were included in this analysis. Each dot represents measurements from a single eye. *Circles* represent a data point from the right eye whereas *squares* are from the left eye. Measurements between two eyes of a patient are connected by a gray dashed line.
suggest that a progressive reduction of the RGC layer thickness due to either glaucoma or normal aging may undermine central pattern vision.

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References


