Glaucoma

Impairments of Contrast Discrimination and Contrast Adaptation in Glaucoma

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Purpose. Contrast detection is commonly measured clinically; however, discrimination between contrasts is also important for natural vision. Furthermore, optimal performance requires the visual system to adapt to ambient contrast conditions. Recent studies of primate neurophysiology demonstrate significant retinal involvement in contrast adaptation. This study was conducted to investigate whether glaucoma alters contrast adaptation. Both detection and discrimination task performance were examined.

Methods. Psychophysical contrast detection and discrimination thresholds were measured in central vision, for a vertically oriented D6 centered on 3 cyc/deg. Thresholds were measured with and without adaptation to low (15%)- and high (70%)-contrast, vertically oriented, 3-cyc/deg sinusoidal gratings. Fifteen people with glaucoma, and 15 age-similar control subjects participated. Full-contrast discrimination (dipper) functions were measured for a subset (three patients with glaucoma and three control subjects).

Results. On average, the glaucoma group showed elevated detection and discrimination thresholds relative to control subjects (detection: $t(28) = 2.42$; $P = 0.02$; discrimination: $F_{1,28} = 6.157$, $P = 0.02$). For the subset of additionally tested participants, normalized contrast discrimination functions were similarly shaped for all observers. Glaucoma group thresholds were less influenced by contrast adaptation than were control subjects, for discrimination ($F_{1,28} = 10.89$, $P < 0.01$) but not detection ($F_{1,28} = 2.28$; $P = 0.11$). Differences between groups were greatest for low-contrast stimuli (significant interaction between contrast and group: $P < 0.01$).

Conclusions. Glaucoma alters the effect of contrast adaptation on discrimination performance, particularly at low contrast. The study of suprathreshold aspects of vision may reveal new insights into the pathophysiology of glaucoma and possibly relate better to real-world visual performance than detection measures. (*Invest Ophthalmol Vis Sci.* 2010;51:920–927) DOI: 10.1167/iovs.08-3332

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Contrast detection thresholds are regularly measured in glaucoma, most commonly using perimetric strategies. However, more natural visual tasks often involve the discrimination between objects of different contrasts to assist in the defining of object features including boundaries. Natural image contrast processing also requires the visual system to adapt to the ambient conditions to enable maximum performance.

Several recent studies have begun to explore the presence and nature of suprathreshold contrast processing abnormalities in glaucoma.[1–3] These studies all use variants of the suprathreshold pedestal contrast discrimination paradigms described by Pokorny and Smith.[4] The tasks involve the presentation of a four-square array where one of the squares differs in luminance from the others. The observer's task is to determine which is the odd square. The stimuli can be manipulated to bias stimulus processing to either magnocellular or parvocellular systems depending on the presence or absence of an adapting luminance pedestal four-square array. Hence the tasks incorporate aspects of both contrast discrimination and adaptation.

Adaptation is a key feature of visual processing and is designed to maximize sensory performance across the very wide range of natural viewing conditions.[5] Contrast adaptation refers to the process by which the visual system alters the operating characteristics of contrast-sensitive mechanisms according to the ambient contrast conditions.[5] It has been proposed that contrast adaptation repositions the contrast response function around the adapting level (alters the contrast gain), which should theoretically result in an increase in sensitivity to change in contrast around the adapting level, in addition to an increase in contrast detection threshold.[5–8] There is clear psychophysical evidence of an increase in contrast detection threshold in the presence of adaptation to a stimulus of similar orientation and spatial and temporal frequency (for example, see Refs. 6, 9). However, although electrophysiological evidence supports the concept that contrast adaptation should result in an improvement of contrast discrimination,[10,11] human psychophysical results are equivocal. (For example, see Refs. 5, 8 for support, but also Ref. 12.) These results do not imply an absence of effect of contrast adaptation on discrimination thresholds, but rather that the nature of the effect on contrast discrimination is quite dependent on the specific experimental conditions such as the features of the adapting and test stimuli, as well as whether one eye or both is used to view the stimuli.[13]

There is convergent evidence from functional magnetic resonance imaging[14] and visual neurophysiology[10] that demonstrates that contrast adaptation involves cortical neurons and is a process of active regulation rather than merely fatigue.[11,15] However, there is also recent evidence of contrast adaptation at the level of the lateral geniculate nucleus (Ref. 16; however, see Ref. 17). Retinal ganglion cells also demonstrate adaptation to contrast as well as luminance,[18,19] with recent neurophysiological studies demonstrating a significant retinal ganglion cell contribution to contrast adaptation for the magnocellular pathways in particular.[16] As glaucoma is primarily a disease of

TABLE 1. Experimental Conditions

Condition	Adapting Stimulus	Reference Interval	Test Interval
Contrast Detection			
No adaptation	None	Mean luminance	3 cyc/deg D6
Low-contrast adaptation	15% contrast, 3 cyc/deg grating	Mean luminance	3 cyc/deg D6
High-contrast adaptation	70% contrast, 3 cyc/deg grating	Mean luminance	3 cyc/deg D6
Contrast Discrimination			
No adaptation: low contrast	None	15% contrast, 3 cyc/deg D6	(15 + Δ)% contrast, 3 cyc/deg D6
No adaptation: high contrast	None	70% contrast, 3 cyc/deg D6	(70 + Δ)% contrast, 3 cyc/deg D6
Adaptation: low contrast	15% contrast, 3 cyc/deg grating	15% contrast, 3 cyc/deg D6	(15 + Δ)% contrast, 3 cyc/deg D6
Adaptation: high contrast	70% contrast, 3 cyc/deg grating	70% contrast, 3 cyc/deg D6	(70 + Δ)% contrast, 3 cyc/deg D6

Δ, a contrast increment that was the measured parameter for the discrimination tasks. The reference and test intervals were randomized in order within the two-interval, forced-choice methodology.

retinal ganglion cells, we predicted that it would reduce the ability to adapt to suprathreshold contrasts. Our experiments were designed to test the following specific predictions:

- The effect of contrast adaptation on contrast *detection* thresholds is less in individuals with glaucoma than in approximately age-matched control subjects.
- The effect of contrast adaptation on contrast *discrimination* thresholds is less in individuals with glaucoma than in approximately age-matched control subjects.

METHODS

Participants

Fifteen volunteers with primary open-angle glaucoma (age range, 54–83 years) and 15 approximately aged-matched control subjects (age range, 55–82 years) participated in the study. The mean age of the glaucoma group was higher than that of control subjects; however, it was not significantly different (glaucoma: mean age, 73 years, SD, 9; control subjects: mean age, 68 years, SD, 7; $t(28) = -1.80$, $P = 0.08$). Subjects with glaucoma were recruited either from the tertiary care glaucoma clinic of one of the authors (MJW) or from the Glaucoma Clinic of the Melbourne Optometry Clinic (Victorian College of Optometry). Control subjects were recruited from the Melbourne Optometry Clinic.

To be eligible to participate, people with glaucoma had to have a clinical diagnosis of primary open-angle glaucoma with a repeatable glaucomatous visual field loss. Visual fields were documented with a perimeter (Medmont Pty. Ltd., Camberwell, VIC, Australia), with the average defect (AD) ranging from 0.73 to −4.22 dB (mean, −1.83 dB; SD 1.61 dB) and the pattern defect (PD) ranging from 1.09 to 13.1 dB (mean, 8.01 dB; SD 3.68 dB). The AD and PD global indices for the Medmont perimeter are similar in concept to the mean deviation and pattern standard deviation of the Humphrey Field Analyzer (Carl Zeiss Meditec, Dublin, CA); however, they are not numerically interchangeable. A comparison of the global indices between these two machines has recently been published.[20]

In addition to the those already mentioned, inclusion criteria were a visual acuity of 6/7.5 or better in the selected eye, no more than 5 D of sphere or 2 D of cylindrical distance refractive error, and no systemic conditions or medications known to affect visual performance. Control subjects had to have normal findings in a comprehensive eye examination and no history of intraocular pressure above 20 mm Hg, when measured with applanation tonometry. As our psychophysical testing was performed monocularly, if both eyes met the glaucoma inclusion criteria, then the test eye was chosen at random. The choice of eye for individuals in the control group was matched to that of the glaucoma group.

All participants provided written informed consent before participation in the study, in accordance with a protocol approved by our institutional human research ethics committee and with the tenets of the Declaration of Helsinki.

Equipment for Psychophysical Testing

Stimuli were generated using custom software (written in MatLab 7.0.4; The MathWorks, Natick, MA). Stimuli were generated (ViSaGe System; Cambridge Research Systems, Kent, UK) and presented on a γ-corrected 21-in. monitor (frame rate, 100 Hz; resolution, 1024 horizontally by 768 vertically; Trinitron G520; Sony, Tokyo, Japan). The mean luminance of the monitor was 54 cd/m^2. The monitor was γ-corrected on a weekly basis (OptiCal photometer; Cambridge Research Systems), which confirmed that the monitor mean luminance was stable throughout the duration of the study. Participants wore refractive correction appropriate for the viewing distance of 1 m which was maintained using a chin and forehead rest. Testing was performed monocularly with a translucent occluder, to maintain equivalent ambient luminance in the occluded and nonoccluded eyes. There is some evidence that glaucoma affects light adaptation. Translucent patching avoids alterations to contrast thresholds over time that result from luminance adaptation when opaque patching is used.[21,22] Participants attended two test visits, each of approximately 1.5-hours' duration which included task training and rest breaks as required. As adaptation experiments are lengthy, we limited testing to a single eccentricity: the fovea. This choice was based on previous psychophysical results consistent with alterations of short-wavelength stimulus adaptation[23] and contrast gain[1] for foveal viewing in glaucoma, and our previous observations of glaucomatous deficits measured with the Pokorny and Smith stimulus in the fovea.[3] Furthermore, attentional differences between participants are likely to be minimized for foveal viewing compared with more eccentric testing, which may be important, as contrast adaptation can be altered by attentional processes.[24]

Contrast Detection and Discrimination

We measured contrast detection and discrimination thresholds before and after adaptation to grating stimuli of the same orientation and spatial frequency as the test stimulus. Contrast discrimination performance for such stimuli has been extensively studied previously in both young adults and healthy older individuals[25–28] and the methods can be readily extended to the incorporate contrast adaptation.[5–8,12,13] As adaptation experiments are very time consuming for participants, we were limited to testing a single spatiotemporal frequency profile, and so we chose a stimulus combination that is likely to be detectable by a significant number of neurons in both the M and P pathways (3 cyc/deg, 1 Hz, achromatic) as a starting place for exploring adaptation effects in glaucoma. Both low- and high-contrast adaptation conditions were used. A summary of the test parameters is presented in Table 1. Full details are provided in the following text.

The test stimulus for both contrast detection and discrimination was a D6 (sixth spatial derivative of a Gaussian horizontally, multiplied by a vertical Gaussian). The D6 stimulus was defined as follows:

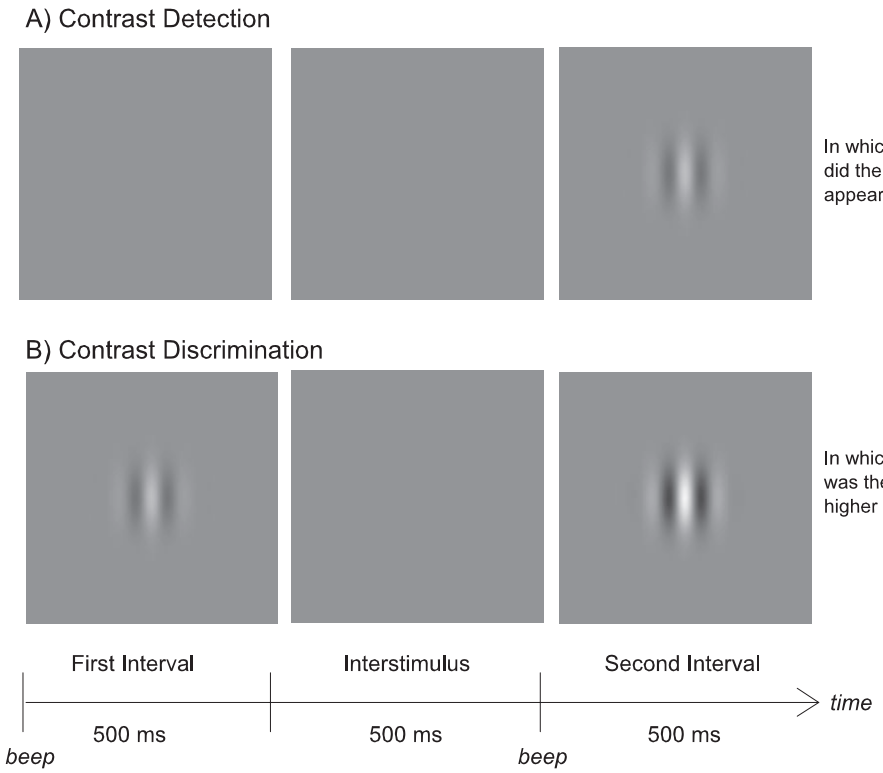

FIGURE 1. Methodology for contrast detection (**A**, *top*) and discrimination (**B**, *bottom*) tasks.

$$D6(x, y) = L_m\left\{1 + \frac{C}{15}\left[15 - 90\left(\frac{x}{\sigma}\right)^2 + 60\left(\frac{x}{\sigma}\right)^4 - 8\left(\frac{x}{\sigma}\right)^6\right] \times \exp\left(-\frac{x^2}{\sigma_x^2} - \frac{y^2}{\sigma_y^2}\right)\right\} \quad (1)$$

where C is the pattern contrast and L_m the mean luminance. The space constant σ determines the peak spatial frequency, which is $1.73/(\pi\sigma)$, with the D6 pattern having a bandwidth of one octave at half amplitude. The vertical space constant σ_x was set at 0.74°. Other details of D6 stimuli are described elsewhere.[29] For this study, the spatial frequency of the D6 was 3 cyc/deg and was chosen to be comparable with previous literature exploring contrast adaptation in normal observers.[5,7,8]

Detection and discrimination thresholds were both measured using a two-interval, forced-choice procedure (Figure 1). The two intervals were 500 ms in duration and were separated by an interstimulus interval of 500 ms. Each interval was preceded by an auditory tone. For the detection task, one interval (chosen at random from trial to trial) contained the D6 stimulus ($C > 0$ in equation 1), whereas the other interval showed a blank screen at mean luminance ($C = 0$ in equation 1). Participants were required to identify the interval that contained the D6 and responded by means of a button press (CB6 response box; Cambridge Research Systems).

In the discrimination task, a D6 stimulus was shown in both intervals ($C > 0$ in equation 1). The reference interval (chosen at random from trial to trial) presented the reference contrast (C_r), whereas the other interval showed the reference contrast plus a contrast increment ($C_r + \Delta C$). Participants were instructed to choose the interval with the highest contrast stimulus and similarly responded by a button press.

Detection and discrimination thresholds were determined using a three-down, one-up staircase procedure. Every time three sequential correct responses were made, the contrast of the test stimulus was reduced by 25%. It was incremented 25% with every incorrect response. Each experimental run involved two interleaved staircases, which terminated after six reversals each. The result of an individual staircase was determined as the mean of the last four reversals, and the two staircase results were averaged to give the final contrast detection or discrimination threshold estimate for each observer. No formal checks of response accuracy were incorporated in the procedure; however, the experimenter watched the observers throughout the testing, and all were given substantial training before participating in the experiments. Contrast discrimination thresholds were obtained for reference contrasts of 15% and 70% and were measured in separate runs.

Dipper Functions

Contrast discrimination performance has been well studied in people with normal vision (for example, Refs. 25–27). A typical contrast discrimination experiment requires observers to differentiate between two stimuli differing in contrast only slightly, with the contrast discrimination threshold being measured as the smallest difference in stimulus contrast that affords such differentiation. Provided that the reference and test stimuli have similar spatiotemporal characteristics, contrast discrimination curves (thresholds plotted against reference contrast) are characteristically "dipper" shaped. The terminology "dipper" refers to the fact that, at low reference, contrast stimulus visibility is facilitated, resulting in contrast discrimination thresholds being less than contrast detection thresholds. Contrast discrimination thresholds increase as the reference contrast increases, approximating Weber's law behavior, although with an exponent typically closer to 0.7 than the 1.0 implied by Weber's law.[27] Contrast discrimination functions can be predicted from contrast detection thresholds in normal observers[30] and have been shown to be similar in younger and older adults with normal vision once performance is normalized to the individual observer's contrast detection threshold.[28] To determine whether elevations in contrast discrimination thresholds in glaucoma are largely explicable by elevations in contrast detection thresholds, we more intensively tested a subset of participants. Six participants (three control subjects [aged 63, 73, and 83 years] and three with glaucoma [aged 55, 79, and 80 years]) completed further testing to measure contrast discrimination functions. These observers were invited to attend an

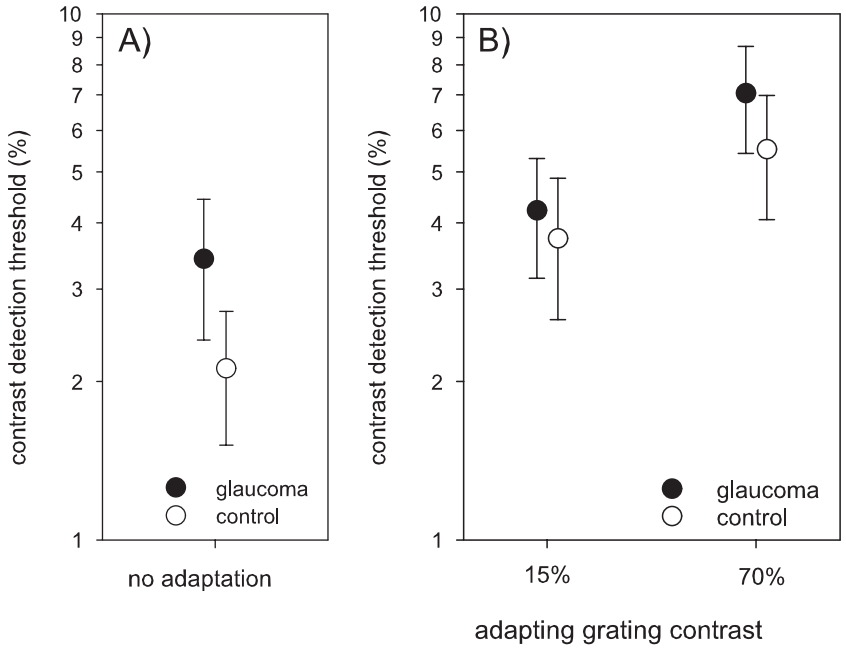

FIGURE 2. Comparison of performance between the glaucoma and control groups for the contrast detection task. Group mean contrast detection thresholds (**A**) in the absence of and (**B**) after adaptation. All data are shown as the mean ± 95% CI of the mean. Data have been shifted slightly horizontally for clarity.

additional test session of 1 hour and were chosen to be approximately representative of the age and performance range of the groups. Contrast discrimination thresholds were measured for a further eight reference contrasts which were set multiples (0.5, 1, 2, 3, 4, 5, 7, and 10) of the particular individual's contrast threshold.

Contrast Adaptation

The adapting stimulus comprised vertical cosine gratings of 3 cyc/deg that covered a square 16° of visual angle. Two adapting conditions were used: a low-contrast (15%) and a high-contrast (70%) grating in cosine phase relative to the grating center, and both were slowly contrast reversed at a mean rate of 1 Hz. The counterphase flicker was drawn at random for each trial with equal probability within the range of 0.5 to 1.5 Hz, to prevent the subject from making eye movements synchronized to the flicker. These temporal frequencies cover a range that is very similar to the dominant temporal frequency contained in the 500-ms square-wave temporal envelope of the test stimulus.

At the beginning of each experimental run, the participants viewed the adapting stimulus for 3 minutes. After the initial adaptation period, the contrast detection and discrimination tasks proceeded identically to those without adaptation, with two exceptions: a top-up adaptation period of 5 seconds was provided between each pair of stimulus presentations in the two-interval, forced-choice procedure; and a blank screen of mean luminance was presented for 1 second after the adapting grating to avoid sequential masking effects. The interstimulus interval between the two presentations remained at 500 ms, during which the monitor displayed the mean luminance. The staircase thresholding procedure was exactly the same as for the nonadapting condition.

After adaptation, both contrast detection and discrimination thresholds were measured. Contrast discrimination thresholds were measured for reference contrasts of 15% and 70% for the adapting gratings of 15% and 70% contrast, respectively.

Statistical Analysis

All thresholds were log base 10 transformed before analysis (SPSS, ver. 16.0; SPSS Inc., Chicago, IL). Groups were compared by repeated-measures ANOVA or *t*-tests as appropriate. If data violated the sphericity assumption of repeated measures, the Greenhouse-Geisser correction was used.

RESULTS

Contrast Detection before and after Adaptation

The mean performances of the glaucoma and control groups for the contrast detection tasks are shown in Figure 2. In Figure 2A the contrast detection thresholds are compared in the absence of adaptation, and contrast detection thresholds after adaptation are shown in Figure 2B. In the absence of adaptation, the glaucoma mean threshold was elevated relative to control subjects ($t(28) = 2.42$, $P = 0.02$), consistent with the well-known deficit of contrast detection that is expected in glaucoma. Adaptation resulted in an elevation of contrast thresholds for both groups (comparison of Fig. 2B to 2A).

We hypothesized that the effect of adaptation should be less in the glaucoma cohort. A repeated-measures ANOVA (between subjects factor of group; within subjects factor of adaptation contrast [0%, 15%, and 70%]) showed that when both the adapted and unadapted data were included, the trend for elevated contrast detection thresholds in the glaucoma group was no longer statistically significant ($F_{1,28} = 3.24$, $P = 0.08$). In the case of reduced adaptation in the glaucoma group, we should expect the data of the glaucoma group to be more similar to that of control subjects after adaptation; however a significant interaction between adapting contrast and group should be expected (a greater difference between groups for an adapting grating of 0%, than for 15% or 70%). The analysis did not reveal a significant interaction ($F_{1,28} = 2.28$, $P = 0.11$), hence our prediction of altered adaptation effects due to glaucoma on contrast detection tasks was not supported by the data.

A possible confound is that the adapting grating would have been relatively less suprathreshold for some individuals than others, because the glaucoma group demonstrated reduced contrast thresholds in the absence of adaptation. Hence, the relative adapting strength of the grating will have varied between groups. To explore this issue, we calculated an adaptation ratio for each subject, determined as the contrast threshold after adaptation divided by the contrast threshold before adaptation. Hence, an adaptation ratio of 1 indicates no change in contrast thresholds after adaptation. Group mean adaptation ratios are shown in Figure 3A. There were no significant dif-

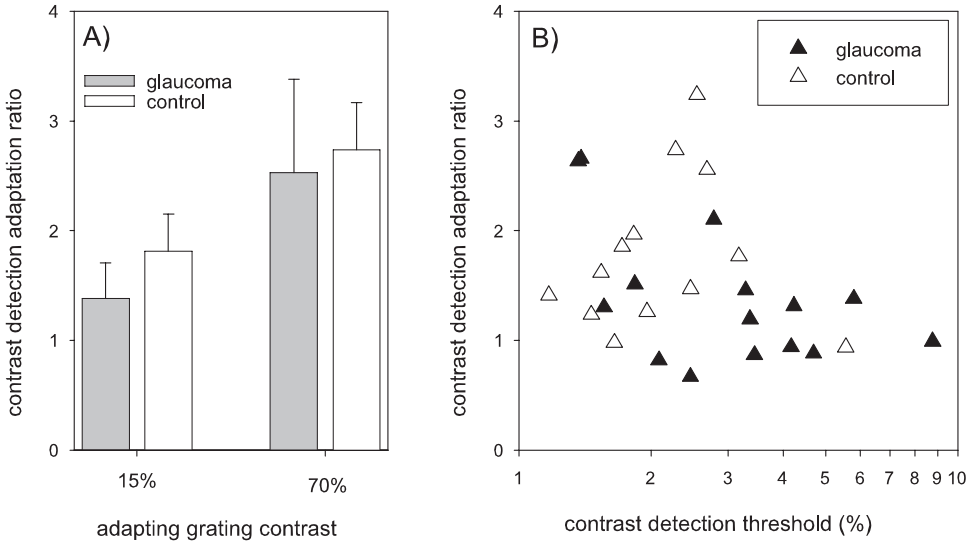

FIGURE 3. **(A)** The mean adaptation ratio (±95% CI of the mean) for the glaucoma and control groups. The adaptation ratio was determined as the ratio of adapted to unadapted thresholds for each participant. A ratio of 1 indicates that thresholds were unchanged after adaptation, whereas a ratio higher than 1 indicates that adaptation resulted in an elevation of threshold. (**B**) Relationship between adaptation ratio and contrast detection threshold for each participant.

ferences between groups for this parameter ($F_{1,28} = 0.90$, $P = 0.35$), indicating that the magnitude of contrast threshold shift due to adaptation did not significantly differ between groups. In Figure 3B, individual participant contrast detection thresholds are related to adaptation ratios for the 15% contrast condition. There was no statistically significant relationship between these measures in either group (Pearson product moment correlation: control group, $r = -0.12$, $P = 0.66$; glaucoma group, $r = -0.43$, $P = 0.12$).

Contrast Discrimination before and after Adaptation

Figure 4 shows group mean performance (±95% confidence interval [CI] of the mean) for the contrast discrimination tasks. A repeated-measures ANOVA (between-subjects factor: group; within-subjects factors: contrast [15%, 70%] and adaptation status [absent, present]) showed a significant main effect of group ($F_{1,28} = 6.157$, $P = 0.02$) demonstrating a statistically significant elevation of contrast discrimination thresholds in the glaucoma group. Figure 4 shows that the greatest elevation of discrimination thresholds occurs for the 15% contrast condition in the absence of adaptation. Consistent with the figure, the three-way interaction of contrast by adaptation status by group was significant ($F_{1,28} = 6.638$, $P = 0.02$). However, the main purpose of the experiment was to test the prediction that glaucoma alters the impact of contrast adaptation on contrast discrimination performance. The interaction between adaptation status and group was significant ($F_{1,28} = 10.895$, $P = 0.003$), hence the data support our prediction.

In normal observers, when contrast discrimination thresholds are measured across the range of possible reference contrasts (0%–100%), performance can be described by a dipper function.[26,27] The data in Figure 4A suggest a difference in the slope of the rising phase of the contrast discrimination function in people with glaucoma compared with control subjects. It is not possible to determine whether this is the case from the data in Figure 4, because the differences in contrast detection thresholds between individuals within the groups may result in

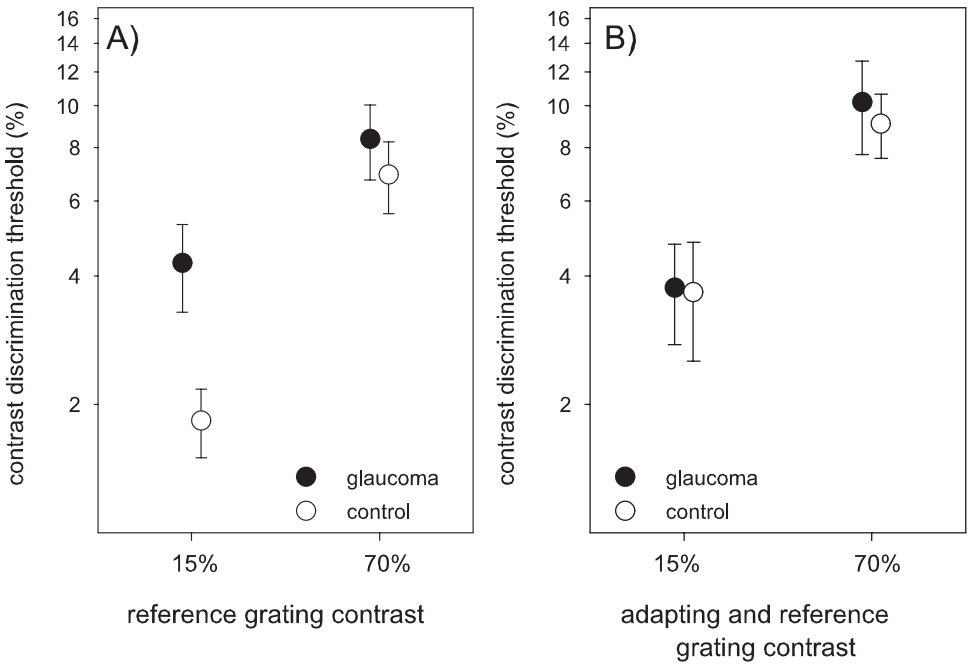

FIGURE 4. Contrast discrimination performance for the glaucoma and control groups (mean, ±95% CI of the mean), in the absence of (**A**) and after (**B**) adaptation. Data have been shifted slightly horizontally for clarity.

the 15% stimulus not being on the rising arm of the dipper function in all individuals. To explore for possible differences in the shape of the dipper function between people with glaucoma and those without, we measured more complete functions on a subset of three control subjects and three people with glaucoma. Data are shown in Figure 5. Reference contrasts were determined as a set multiple of the individual observer's own contrast detection threshold. The raw data were fit with the function

$$C_r = \{[1 + C_r^n(1 + nw)]^{1/n} - C_r\}T_0 \quad (2)$$

where C_t is the contrast discrimination threshold, C_r is the reference contrast, n is the transducer exponent, w is the intrinsic Weber fraction, and T_0 is an estimate of the detection threshold. The derivation of this equation appears elsewhere,[31] and it has been used to fit contrast discrimination data of a form similar to that presented here.[28] As is shown in Figure 5, the function shapes were similar in people with and without glaucoma when parameters were normalized relative to the individual's contrast detection thresholds (superimposed data from all participants shown in Fig. 5A). This is despite the raw contrast discrimination thresholds of these individuals differing between the participants with glaucoma and the control (Fig. 5B for the 15% reference contrast condition).

We also calculated adaptation ratios in the same manner as for the contrast detection task. In Figure 6A, the mean adaptation ratios (+95% CI for the mean) for the contrast discrimination tasks are compared between the complete participant groups ($n = 30$). Consistent with the raw data analysis, a repeated-measures ANOVA demonstrated that the adaptation ratios were significantly different between groups ($F_{1,28} = 6.17$, $P = 0.02$), and there was a significant interaction between contrast and group ($F_{1,28} = 4.34$, $P = 0.04$). For the low-contrast condition (15%), the glaucoma mean adaptation ratio was close to unity, implying no mean effect of adaptation on performance. Both groups showed an elevation in contrast discrimination threshold in the presence of the 70% adapting grating. There was no trend for a relationship between saliency of the adapting grating and contrast discrimination adaptation ratio (Pearson-product moment correlations: control subjects: $r = 0.09$, $P = 0.76$; glaucoma: $r = -0.03$, $P = 0.90$, see Fig. 6B). Visual field summary indices were also not significantly correlated with the contrast discrimination adaptation ratio (Spearman rank order correlations: pattern defect index, $r = 0.18$, $P = 0.52$; age defect index, $r = 0.41$, $P = 0.13$).

Discussion

This project was designed to test whether glaucoma changes contrast adaptation for threshold (detection) and/or suprathreshold (discrimination) tasks. In the absence of adaptation, both contrast detection and discrimination thresholds were elevated foveally in our glaucoma cohort when compared with a group of age-similar control subjects. Differences in contrast adaptation were present in the glaucoma cohort; however, only for the suprathreshold (discrimination) task. In particular, for the discrimination of low-contrast gratings, adaptation to a grating of similar contrast, spatial, and temporal frequency had minimal effect on thresholds for our glaucoma group, but markedly elevated thresholds in the control subjects (Fig. 6A). On the contrary, for the detection task, adaptation similarly affected performance in the control and glaucoma groups (Fig. 3A).

Although the data in Figure 6B suggest that the differences in adaptation strength between groups for the discrimination task cannot be simply explained by relative differences in the salience of the adapting grating, we cannot rule out this explanation completely. This question could be assessed, by presenting to all participants individually adjusted adapting gratings at a fixed multiple of the individual's contrast threshold and then measuring full contrast discrimination functions. Such an experiment was not possible within the scope of the present study and would require many additional hours of observation per participant.

Theoretically, adaptation should improve contrast discrimination. Single-cell neurophysiology is consistent with this idea; however, psychophysical results are equivocal (see Refs. 5, 8 for support, but also Ref. 12). Our results do not support an improvement in contrast discrimination performance for the specific conditions of monocular testing with translucent occlusion in elderly observers. Perhaps the closest methodology to ours was used by Abbonizio et al.[13] who demonstrated on average improvement in contrast discrimination performance when testing binocularly, but not monocularly, in observers with normal vision. Abbonizio et al. speculated that this result may arise due to differences in retinal illuminance due to opaque occlusion; hence, we used translucent occlusion in our experiments. Nevertheless, our control group showed a significant impairment relative to unadapted thresholds (adaptation ratios greater than 1, see Fig. 6A). Abbonizio et al. do not state the age range of their participants; however, it is likely that our observers were significantly older on average. There is evidence that healthy ageing alters other suprathreshold contrast tasks such as the impact of surround contrast on perceived contrast[32]; hence, it is possible that differences in contrast processing due to healthy ageing are also important when comparing our results to those of previous contrast adaptation studies. Further experiments are needed to disentangle these possibilities.

It is interesting to consider the neural underpinning of altered contrast adaptation due to glaucoma. Some aspects of contrast adaptation arise retinally,[19] and glaucoma should be primarily predicted to alter these processes. The main retinal input to contrast adaptation is for the magnocellular pathway. Consequently, early retinal ganglion cell damage due to glaucoma may alter aspects of suprathreshold contrast processing that are more detectable when testing the magno- than the parvocellular pathways. Indeed, a recent study found differences in foveal contrast gain for magno processing in glaucoma.[1] Our stimuli were not designed to be specific for either magno- or parvocellular processing. However, as the magnocellular pathways show rapid contrast gain and saturate at high contrast, our finding of greatest alterations to adaptation for low-contrast stimuli is not inconsistent with damage to magnocellular contrast processing.

The LGN is also implicated in contrast adaptation processes, and the LGN is clearly altered in experimental animal models of glaucoma.[33] Aberrant feeding forward of information from the retina, via the LGN to the cortex will also potentially alter cortical aspects of contrast adaptation. Further work is needed to elucidate these mechanisms; for example, ascertaining the level of spatial frequency or orientation tuning of the adaptation anomalies may provide clues to the relative likelihood of a cortical origin, as might a dichoptic experimental paradigm. The question could also be addressed via neurophysiological measures of contrast responses in experimental animal models of glaucoma.

The results of this study suggest that the active regulation of contrast processing (gain/adaptation) is altered in glaucoma, particularly in low-contrast conditions, and hence that measures other than contrast detection may be useful for both the detection of early functional damage and for the assessment of real-world significance of glaucomatous visual impairment. Fur-

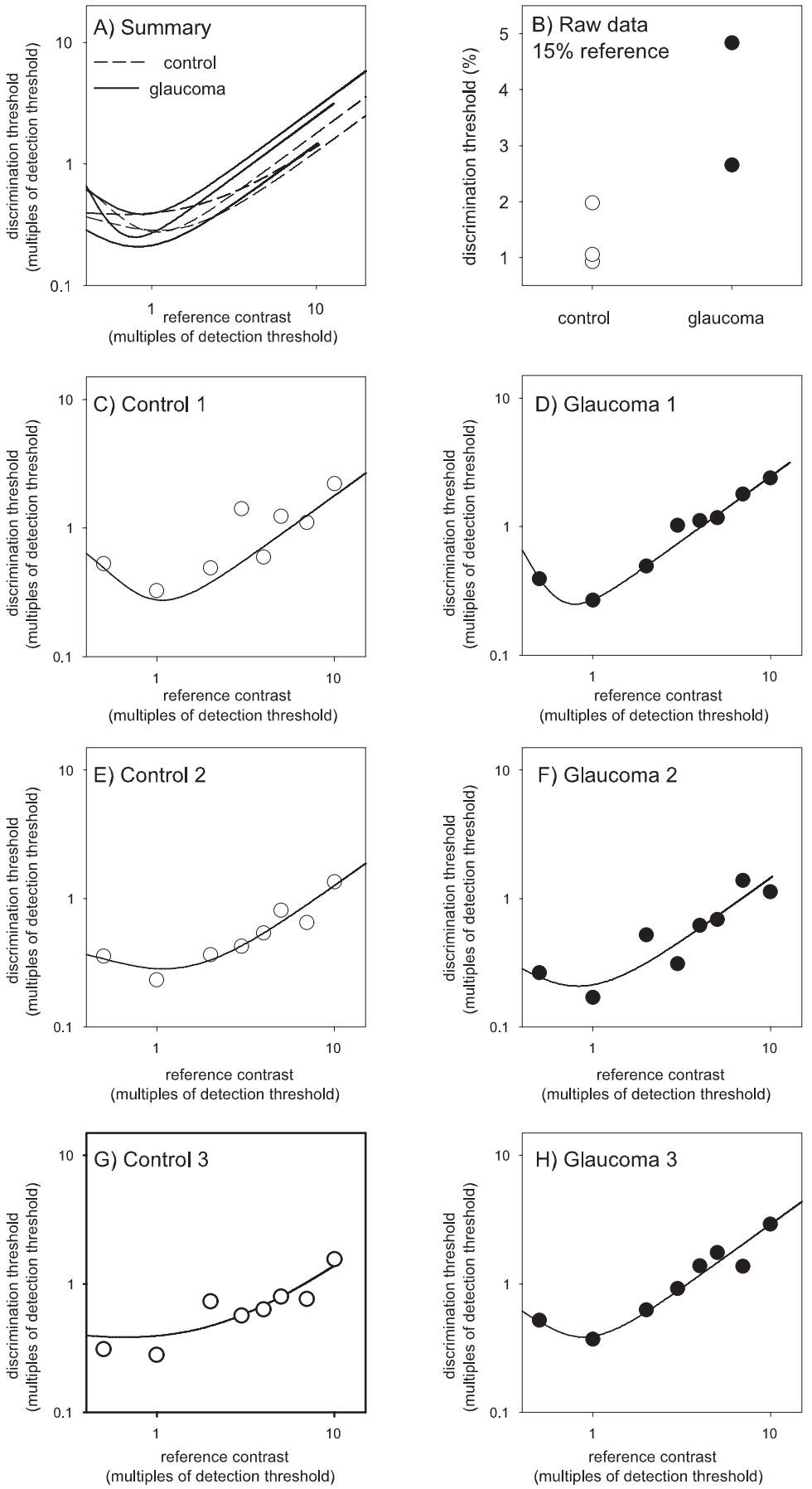

FIGURE 5. Normalized contrast discrimination thresholds for three participants without glaucoma (**C**, **E**, **G**) and three with glaucoma (**D**, **F**, **H**). Discrimination thresholds measured in multiples of contrast detection threshold are plotted against the reference pedestal contrast (also measured in contrast threshold units). *Solid lines*: best fitting version of equation to the data. (**A**) A superimposed summary of the fit curves for all participants. (**B**) The raw contrast discrimination thresholds measured for the included participants for a reference contrast of 15% (the data contribute to the group mean data shown in Fig. 4A).

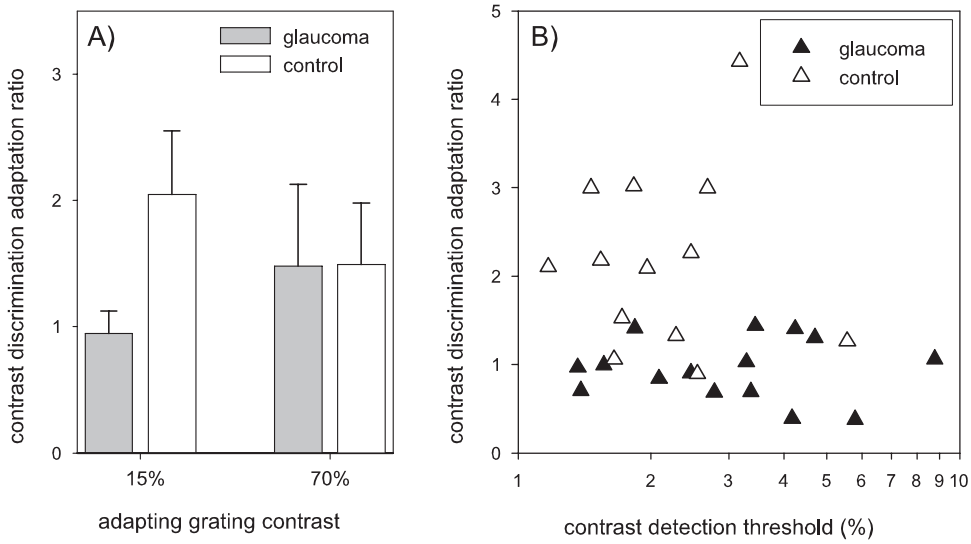

FIGURE 6. Comparison of the contrast discrimination adaptation ratio between groups. All aspects of the figure are the same as in Figure 3.

ther work is needed to determine how robust such findings are when applied to midperipheral vision (as is typically assessed for glaucoma). The robustness of these measures to fluctuations in attention and variations in retinal illuminance between participants also should be studied. Nevertheless, given that natural visual environments necessitate correct interpretation of differences in object contrast that are made once adapted to ambient conditions, deficits in these processes in glaucoma may relate better to the quality of subjectively reported vision than currently clinically measured contrast detection thresholds.

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