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Understanding disability glare: light scatter and retinal illuminance as predictors of sensitivity to contrast

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The presence of a bright light in the visual field has two main effects on the retinal image: reduced contrast and increased retinal illuminance due to scattered light; the latter can, under some conditions, lead to an improvement in retinal sensitivity. The combined effect remains poorly understood, particularly at low light levels.

A psychophysical flicker-cancellation test was used to measure the amount and angular distribution of scattered light in the eye for 40 observers. Contrast thresholds were measured using a functional contrast sensitivity test. Pupil-plane glare-source illuminances (i.e. 0, 1.35, 19.21 lm/m^2), eccentricities (5°, 10°, 15°), and background luminances (1, 2.6, 26 cd/m^2) were investigated.

Visual performance was better than predicted, based on loss of retinal image contrast caused by scattered light, particularly in the mesopic range. Prediction accuracy improved significantly when the expected increase in retinal sensitivity in the presence of scattered light was also incorporated in the model.

Scattering; (290.0290) Vision, color, and visual optics; (330.0330) Stray light; (290.2648) Vision - contrast sensitivity; (330.1800) Psychophysics; (330.5510) Visual adaptation; (330.7320)

Introduction

In the presence of a bright source of light, it is common for an observer to experience problems with spatial vision [1, 2]; for example, glare from oncoming car headlights can pose a particular challenge to the night-time driver. The term used to describe the visual impairment that occurs in the presence of bright light sources is 'disability glare' [3]. The detrimental effects of glare can be attributed primarily to scattered light within the eye [4-7]. The 'veil' of scattered light reduces the contrast, and thereby the quality, of the retinal image. Although it is possible to estimate the amount of scattered light on the retina in the presence of glare [8], predictions of visual performance under such conditions often overestimate the detrimental effects at low light levels.

It is well established that the retina responds differently according to the level of ambient lighting [9, 10]. An increase in retinal illuminance produces a much larger improvement in sensitivity to contrast in the mesopic range than a similar increase in the photopic range [9, 11-13]. Although the effects of glare on contrast sensitivity in the photopic range have been studied previously [14, 15], it has been recognised that the findings do not generalise to mesopic viewing conditions.

Some studies using high intensity glare have found little evidence of improvement in contrast sensitivity due to increasing adaptation luminance [16]. Interestingly though, others have found the effects of disability glare to be less severe than would be predicted based on scattered light and, in some cases, the presence of glare caused an improvement in visual performance [17-19]. Although there have been several qualitative explanations for the phenomenon, involving, for example, increased luminance of the surround field [18], a threshold to the disability glare effect [17], or the adaptation state of the retina [19], a quantitative model that accounts for changes in retinal sensitivity to contrast in the presence of glare sources remains to be produced.

In order to establish how sensitivity to contrast is affected by glare-induced light scatter, contrast thresholds were measured at different eccentricities, under different background luminance levels at a number of glare-source intensities. In addition, the light scatter function of the eye (i.e., the amount as well as the angular distribution of light scattered within the eye) was measured for each observer, enabling predictions of retinal image contrast in the presence of glare that are tailored individually.

Methods

Participants

24 female and 29 male participants took part in the study. All participants undertook an ocular examination, which involved ophthalmoscopy and refraction; in addition, general health, ocular health, medication and family ocular health were recorded. Visual acuity was corrected using participants' own glasses or contact lenses. Exclusion criteria were based on the presence of ocular disease, damage, surgery or intraocular lenses in either eye; 10 participants were excluded on this basis. Three participants who experienced extreme difficulty performing either task were also excluded. Older participants with early-stage cataract — grade 1, nuclear cataract or less — were not excluded from the analysis, as this was deemed to constitute normal ageing. No exclusions were made based on outlying results. No exclusions were made based on visual acuity, as the target size was well above threshold. Of the 53 participants who took part, 13 were excluded as a result of the criteria employed and the results from the remaining 40 observers (17 female and 23 male), were used in the final analysis. The age of the final sample ranged from 21 to 68, with a mean age of 42 years. There were 26 participants below the age of 50 years and 14 above.

This study was approved by the Senate Research and Ethics Committee at City University London, and adhered to the principles of the Declaration of Helsinki. All participants provided written consent to take part in the study.

Functional Contrast Sensitivity (FCS) Contrast thresholds were measured under binocular viewing conditions using the FCS test, which has been described previously[20].

Apparatus. The FCS test was implemented on the P_SCAN pupillometer, which employs a 50 cm NEC CRT monitor for the generation of visual stimuli. In addition, the P_SCAN system enables simultaneous, binocular measurement of pupil size and the point of regard every 20 ms [21]. Chin and forehead rests were used to position the observer's head. The observer viewed the centre of the display from a distance of 1.6 m through a large, infrared reflecting mirror oriented at 45° with respect to the viewing direction. A black wooden hood was positioned over the head-rest and camera equipment to block light reaching the subject's eyes from other than the forward direction.

Glare was introduced using two (Perkin Elmer, four primary) LED units driven by a TTi Precision DC PSU (model TSX3510). The LED units were stacked vertically and surrounded by black felt to reduce the angle of illumination and to create the impression of a single glare-source location positioned horizontally, 10° to the right of fixation (Fig. 1).

Stimuli. An observer's view of the stimuli is shown in Fig. 1. A Landolt C target of positive luminance contrast was employed. The chromaticity co-ordinates of both the target and background were set to x = 0.305, y = 0.323 (CIE 1931). The target was presented either at the centre of the display or ± 5° from fixation, along the horizontal meridian. Consequently, the eccentricity of the target with respect to the glare-source was 5°, 10° or 15°. The observer fixated at the centre of the screen, regardless of target location. Diagonal guides placed well outside the stimulus area were used to aid accommodation and to guide fixation. The guides were presented for 150 ms followed by a delay of 800 ms, during which the screen was uniform, before the presentation of the stimulus, lasting 160 ms. Contrast thresholds were measured using a one-up, two-down staircase procedure with variable step sizes; the contrast of the target with respect to the screen background was adjusted automatically according to the participant's response. Each run consisted of three, randomly-interleaved staircases: one for each target location. One run yielded three contrast thresholds, as well as the average pupil diameter during the test. In total, the subjects completed 360 runs.

The luminance conditions followed a three by three design. Three background luminance levels were used to cover the high mesopic and the low photopic range: 1, 2.6 and 26 cd/m^2 (as shown in Fig. 1(A, B and C, respectively). Three glare levels were used: No Glare — glare-source switched off — (Fig. 1(A)), Low Glare — 1.35 lm/m^2 — (1(B)), and High Glare — 19.21 lm/m^2 — (1(C)). The runs for the nine lighting combinations were randomised.

A supra-threshold target gap size of 4′ was chosen at the fovea to ensure that small fluctuations of accommodation and differences in higher order ocular aberrations that can cause large inter-observer differences when assessing the limit of spatial resolution would not confound significantly the results of this study. Peripheral targets were scaled in size to maintain similar contrast visibility across the three target locations. The scaling factor was determined using threshold measurements for four young participants at a display luminance of 26 cd/m^2. A target gap size of 8' was selected for the peripheral locations.

Procedure. Participants were given a minimum of three minutes to dark-adapt while the test was explained, demonstrated and practiced. Each participant completed one experimental run for each of the nine luminance conditions. As each run consisted of three staircases — one for each eccentricity — completion of the test yielded 27 contrast thresholds and typically nine estimates of pupil diameter. On a small number of occasions (~5%) the automatic measurement of pupil size failed because of noisy pupil images. The luminance conditions were set at the beginning of each run, and participants were instructed to avoid looking directly at the glare-source.

The task used a four-alternative forced choice procedure. Target orientation was varied in a random order and the participants' task was to indicate, in their own time, the orientation of the Landolt C using a response keypad. The test was carried out binocularly. The typical duration of the test (9 runs) was 1 hour 40 mins.

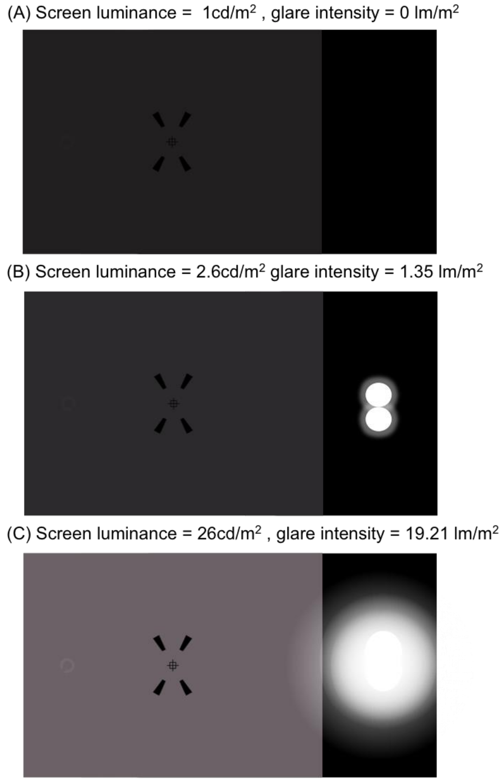

Fig. 1. Observers' view of the experimental setup. The functional contrast sensitivity test was carried out on a CRT monitor. The glare source was positioned to the right of the monitor, 10° from fixation. The Landolt C target was presented at three locations, which corresponded to angular eccentricities of 15°, 10° and 5° with respect to the glare source. The three locations were interleaved randomly and the observer's task was to report the orientation of the gap. The gap size was set at 4′ for foveal targets and 8′ for peripheral targets.
The screen luminance was at (A) 1 cd/m^2, (B) 2.6 cd/m^2 or (C) 26 cd/m^2. The task was performed under (A) no glare, (B) low intensity glare: 1.35 lm/m^2 or (C) high intensity glare: 19.21 lm/m^2. Pupil size was measured continuously and the mean value during the test was used to calculate retinal illuminance.

Flicker-nulling technique

The scatter function of the eye was measured using a flicker nulling technique, which employs a series of extended annuli to estimate both the amount and the angular dependence of scattered light [22]. Although extended annuli are employed, the flicker-nulling principle is the same as that employed in the Compensation Comparison technique used by van den Berg and colleagues [23, 24].

Apparatus. The light scatter measurement program was also implemented on the P_SCAN system [25] using the same CRT monitor which was calibrated for internal scatter for each scatter-source eccentricity. The observer viewed the centre of the display from 0.7 m. A chin and forehead rest was used for head position and fixation was maintained on the centre of the display. A hood was positioned over the head-rest to minimise the amount of external light reaching the observer.

Stimuli. The scatter stimulus consisted of three concentric circles: a central dark target disc, an isolation annulus and an outer scatter source. The background and isolation annulus luminance was set at 5 cd/m^2 and 25 cd/m^2, with chromaticity coordinates of x = 0.169, y = 0.085 and x = 0.450, y = 0.450, respectively. An annular scatter source of specified eccentricity was generated on the display together with a central, black disc, subtending 0.8°, which formed the test target; both the target and the scatter source had chromaticity coordinates of x = 0.290, y = 0.317. The light scatter stimulus consisted of a burst of sinusoidal flicker at a frequency of 8.6 Hz, with a mean luminance of 50 cd/m^2 and 100% modulation. The light that is scattered over the central black disc portion of the retinal image also varies sinusoidally in phase with the scatter source. Meanwhile, the luminance of the screen over the central test target was modulated sinusoidally in counter-phase. The observer was able to control the mean screen luminance over the central dark disc, which could be adjusted up or down as needed to cancel out the flicker caused by scattered light. A presentation consisted of a ~350 ms burst of flicker; its short duration ensuring that the change in pupil size was negligible during the stimulus. Although the time-averaged light flux on the retina remains unchanged during the modulation of the scatter source, the pupil constricts to the onset of high frequency flicker with a somewhat longer latency [26]. The mean screen luminance of the test target varied between presentations depending on the observer's response, whereas the mean luminance of the light scatter annulus remained unchanged.

The test used light scatter annuli at five different eccentricities and the size of each was selected to ensure equal pupil-plane illuminance across conditions. Once the flicker-null point was determined, the next annulus was selected in random order. One run consisted of five repetitions for each of the five annuli. Scatter parameters were computed based on mean estimates for each of the five annuli.

Procedure. Participants were given a minimum of three minutes to dark-adapt. Each participant completed two full runs and the mean scatter parameters were used in the final analyses. Only one participant was unable to complete both runs, and the value for the single run was used in the analysis. Participants were asked to fixate on the central disc during each presentation and to indicate verbally the presence or absence of flicker. The test was carried out binocularly.

The experimenter adjusted the mean screen luminance of the test target after each presentation by means of two response buttons. Adjustments were made to increase or decrease the mean luminance of the centre dark disk so as to minimise the perceived flicker over the disc. Since the dioptrics of the eye inevitably also scatter some of the light from the test target that originates from the screen, the equivalent veiling luminance may be slightly overestimated. However, the error is expected to be small since a large percentage of the light scattered would normally remain within the area of the test target. The typical duration of a single test was 12 mins.

Scatter-based predictions of functional contrast thresholds

Equation 1 is used to estimate the equivalent 'veiling luminance' attributed to scattered light on the retina, and is derived from the classic Stiles-Holladay equation, based on the work of Holladay[27, 28], Stiles[29] and later Stiles and Crawford[30].

$$L_s = kE\theta^{-n} \tag{1}$$

Where:

L_s is the luminance of an external source that is expected to generate the same retinal illuminance as that resulting from light scattered by the glare-source (cd/m^2). This is known as the equivalent veiling luminance.

k is the straylight parameter. This value is proportional to the amount of light scattered within the eye. A large k value indicates a greater amount of light scatter.

E is the illuminance at the plane of the pupil, produced by the glare-source (lm/m^2).

θ is the angular eccentricity of the glare-source in relation to the target (degrees).

n is the light scatter index. This value is inversely proportional to the angular distribution of scattered light within the eye. A large n indicates a narrow angle of scattered light.

k and n are constants for a given eye. These parameters can therefore be used to estimate the amount of light scattered by a glare-source of known eccentricity and pupil-plane illuminance.

In the absence of glare, measured Weber contrast of the Landolt C target, C_{m0}, is calculated using:

$$C_{m0} = \frac{L_t - L_b}{L_b} \tag{2}$$

Where L_t is the luminance of the target and L_b is the luminance of the background.

In the presence of glare, light scatter, L_s, is added to the retina at locations that correspond to both the target and background. This reduces the 'real' retinal image contrast, C_r, like so:

$$C_r = \frac{(L_t + L_s) - (L_b + L_s)}{L_b + L_s} = \frac{L_t - L_b}{L_b + L_s} \tag{3}$$

On the assumption that, at threshold, an observer requires the same retinal image contrast to resolve the gap in the presence of glare, C_{mg}, as in the absence of glare, C_{m0}, then it follows that:

$$C_{m0} = C_r = \frac{L_t - L_b}{L_b + L_s} \tag{4}$$

And hence:

$$L_t = C_{m0}(L_b + L_s) + L_b \tag{5}$$

Once the stimulus luminance needed to achieve a retinal image contrast of C_{m0} in the presence of glare is known, it is possible to calculate the corresponding stimulus contrast as measured on the display. As in Equation 2, the predicted measured stimulus contrast becomes:

$$C_{mg} = \frac{C_{m0}(L_b + L_s) + L_b - L_b}{L_b} = C_{m0}\left(\frac{L_s}{L_b} + 1\right) \tag{6}$$

The correction for scatter is applied to each observer based on his / her own measured values of k, n and FCS thresholds.

Combined predictions of functional contrast thresholds

In an attempt to improve upon existing scatter-based predictions, the formula was altered to incorporate a model that predicts contrast thresholds as a function of adaptation luminance. The model developed also takes into account the Stiles-

Crawford (S-C) effect [31], whereby a photon travelling along the axis of a photoreceptor [32] is absorbed more readily than when approaching obliquely. Although the S-C effect does not alter the retinal image contrast, differences in pupil size, and thereby the magnitude of the S-C effect, can cause changes in 'effective' retinal illuminance. The relationship between pupil size and the magnitude of the S-C effect has been described previously by Applegate et al [33]. Luminous efficiency, based on pupil radius, r, is given by:

$$f(r) = 10^{0.05r^2} \tag{7}$$

In order to establish how retinal sensitivity to contrast depends on effective retinal illuminance, contrast thresholds were measured over a range of four log units in a separate study using the similar stimulus parameters. Constant retinal illuminance can be achieved using an artificial pupil, or when viewing the display with the natural pupil [9], by adjusting the luminance of the screen to account for changes in pupil size.

Figure 5 shows the results from both techniques i.e. using a 3.9 mm artificial pupil, with apodization applied post-hoc, and using free-viewing conditions and real-time apodization applied to keep effective retinal illuminance constant and independent of pupil size. The two data sets are in good agreement, which confirms that the closed loop technique designed to maintain constant, retinal illuminance with an apodized pupil is equivalent to what can be achieved using a fixed size, artificial pupil. A function was fitted to the combined apodized data. The contrast thresholds are best described using an equation of the form:

$$C_e = b_1 \times exp(-b_2 \times \log(E_e)) + b_3 \tag{8}$$

Where:

C_e is the expected contrast threshold.

E_e is the 'effective' retinal illuminance (Trolands) at the point of interest on the retina.

b_1, b_2 and b_3 are constants. The model was applied to measured data, both at the fovea and at 5° in the periphery, yielding different constants for the two retinal locations. The foveal constants were b_1= 79.66, b_2= 1.97 and b_3= 18.37; peripheral constants were b_1= 70.39, b_2= 1.81 and b_3= 14.17. As a note, using constants obtained without S-C apodization in Eq. 8 did not change the overall pattern of results.

Similar equations were obtained for two other observers, but it was not practically possible to measure contrast thresholds over the full range of retinal illuminance levels for every subject investigated in the study. Although, retinal sensitivity to contrast will undoubtedly exhibit some inter-subject variability, the region of interest, which involves the rapid increase in contrast thresholds in the mesopic range, is likely to remain largely unchanged. Nevertheless, this assumption may limit somewhat the accuracy of the predicted thresholds.

In Eq. 6 a 'baseline' contrast threshold, C_{m0}, is used in the scatter-based prediction of FCS thresholds for each observer; in order to account for changes in retinal sensitivity a new baseline contrast, C_{m0}', needs to be calculated. Using Eq. 8, the threshold expected in the presence of glare, C_{eg}, and that in the absence of glare, C_{e0}, can be determined; the ratio between the two represents the change in retinal sensitivity to contrast and is used to calculate the new baseline:

$$C_{m0}' = C_{m0} \frac{C_{eg}}{C_{e0}} \tag{9}$$

The new baseline, C_{m0}', replaces the measured contrast in the absence of glare, C_{m0}, in Eq. 6 to yield new predictions that take into account the loss of contrast caused by scattered light and the corresponding change in retinal sensitivity:

$$C_{mg}' = C_{m0}' \left(\frac{L_s}{L_b} + 1 \right) \tag{10}$$

Results

Equivalent veiling luminance and scatter parameters

The light scatter test yielded values for the scatter parameter, k, and the scatter index, n, which are shown in Table 1. These constants were utilised in Equation 1 in order to calculate the equivalent veiling luminance, L_s, of the glare-source. Higher L_s values indicate a greater amount of scattered light within the eye. Mean L_s values for glare-sources of different eccentricities are plotted in Fig. 2. It is clear from the scatter plot that observers over the age of fifty years are more likely to have a greater amount of scattered light within the eye.

Large k values indicate a greater amount of scattered light within the eye. As expected, those aged fifty years or older had significantly larger k values (mean = 57.14) than younger participants (mean = 33.46), $t(38) = 3.90$, $p < .01$. In agreement with previous literature, this finding indicates that scatter within the eye increases over the age of fifty years[34-36].

Small n values indicate a large angular distribution of light scatter within the eye. There was no significant difference in n values between old (mean = 2.11) and young (mean = 1.98) observers. The mean values are comparable to the often-used value [37] of 2.

Table 1: Mean k and n values for old and young observers

$Ls = kE\theta^{-n}$	Mean		Standard Deviation	
	< 50 yrs	> 50 yrs	< 50 yrs	> 50 yrs
Age (years)	33.5	57.1	8.4	5.1
k, scatter parameter	12.7	24.0	6.2	12.2
n, scatter index	1.98	2.11	0.26	0.35

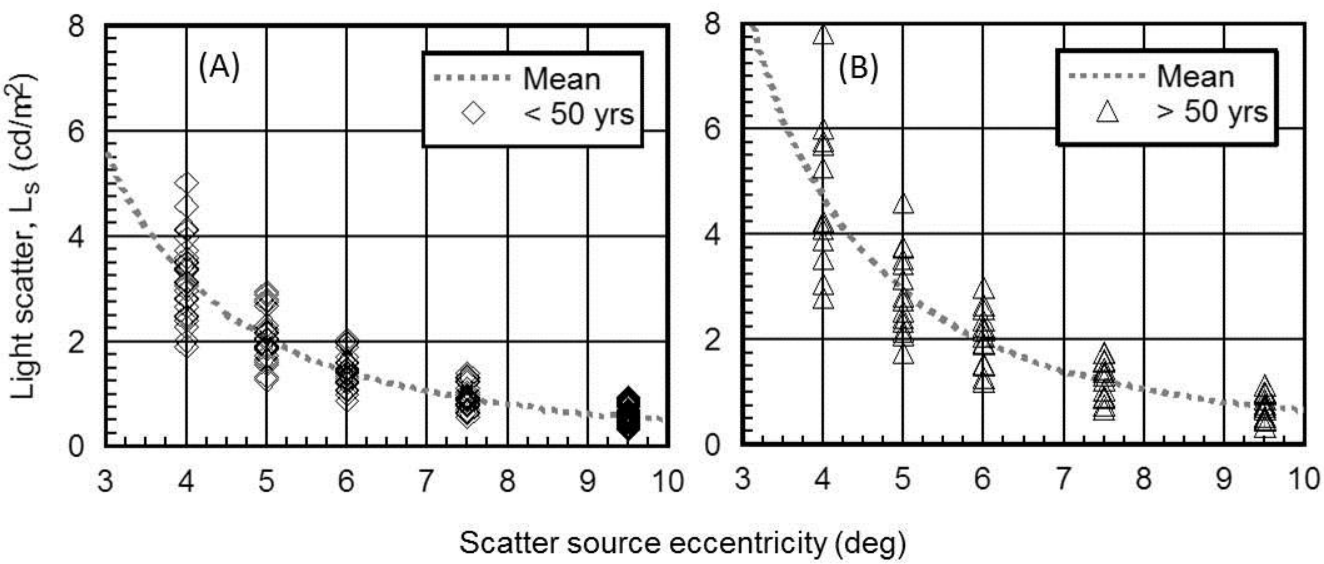

Fig. 2. Light scatter as a function of effective eccentricity of the scatter-source is given by $L_s = kE\theta^{-n}$. Each data point represents the mean fitted light scatter measurement (from two runs) at the given eccentricity for one of forty observers. The test was carried out on a visual display, using an annular source of scatter and a disc-like central target. The scatter test employs five glare source eccentricities and the measured data are used to compute the parameters k and n, which relate to the amount and angular distribution of scattered light in the eye respectively. (A) (<50 yrs): $L_s = 10.37 \times E \times \theta^{-1.94}$; (B) (> 50 yrs): $L_s = 19.12 \times E \times \theta^{-2.11}$, where $E = 4.6$ lm/m^2.

Disability glare – absolute functional contrast thresholds

Contrast thresholds were obtained at three eccentricities, for three different backgrounds, in the absence of glare and in the presence of two levels of glare. The three variables, each with three levels, therefore equate to 27 conditions. Mean contrast thresholds for each condition are shown in Fig. 3 on a logarithmic scale.

In order to rule out confounding variables such as eye dominance or gaze aversion, the contrast thresholds for targets on the left and right of fixation in the absence of glare were compared. The results showed no significant differences between left and right contrast thresholds at any of the background luminance levels tested. As spatial scaling across eccentricity is luminance dependent [38-40], contrast thresholds for foveal targets in the absence of glare were significantly higher than for peripheral targets.

As observers who were over the age of fifty years were found to have elevated levels of scattered light within the eye, a corresponding increase in contrast thresholds was expected. A 2×3×3×3 mixed ANOVA revealed a statistically significant main effect of age group on thresholds, $F(1,38) = 33.67$, $p < .001$, with those aged fifty years or over requiring higher target contrast than younger observers.

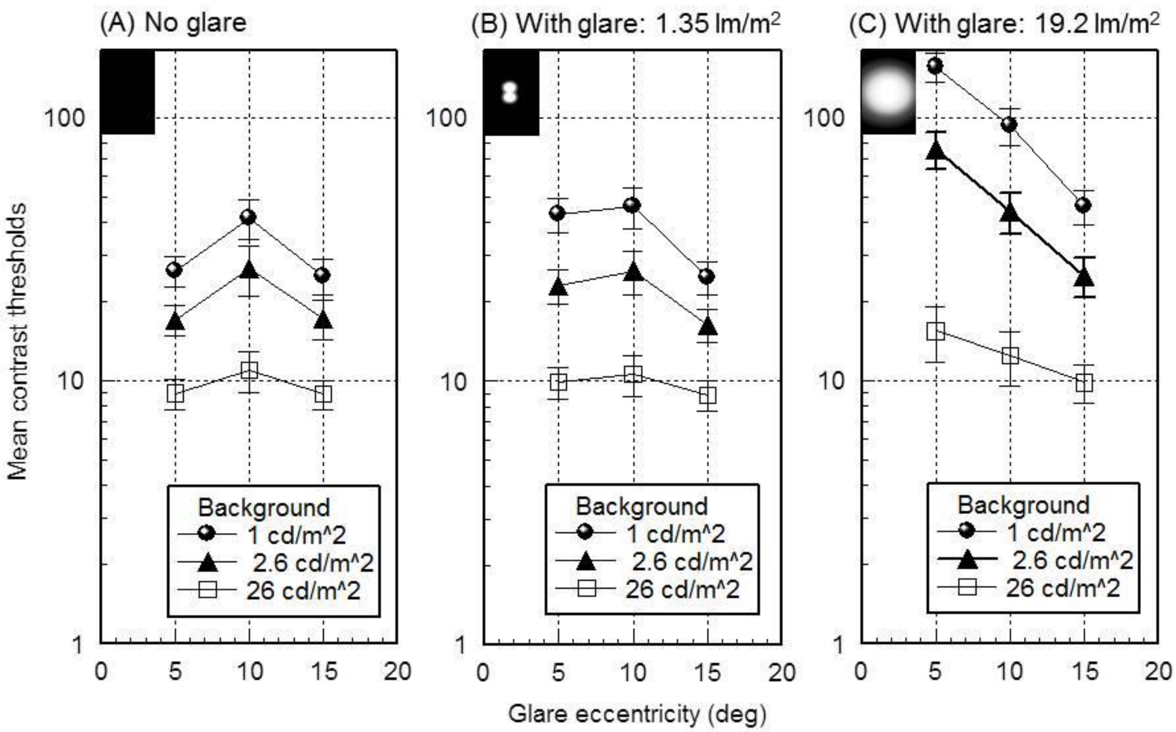

Fig. 3. Mean FCS thresholds for 40 observers. The intensity of the glare source was set to produce a pupil plane illuminance of 0 (A), 1.35 (B) and 19.2 lm/m^2 (C). In the absence of glare (A), contrast thresholds at the foveal target location were higher than in the periphery at all screen luminance levels. In the presence of a low intensity glare source (B), thresholds increased at the 5° target location only. In the presence of high intensity glare (C), thresholds for all eccentricities increased at 1cd/m^2 and 2.6cd/m^2 screen luminance. At 26cd/m^2 screen luminance, thresholds increased for the 5° target location only. The error bars represent ± 2 standard errors of the mean.

Disability glare –predictions of functional contrast thresholds

Whereas the pattern of results has thus far been in line with expectations, the question remains as to whether it is possible to predict reliably changes in visual performance due to the presence of glare, using scatter-based formulae. Scatter-based predictions of contrast thresholds were obtained using Equation 4 and are plotted against measured thresholds in Fig. 4 on a logarithmic scale. In the presence of low intensity glare, 1.35 lm/m^2, the scatter-based predictions appear to be reasonably accurate. Although the data become more dispersed as thresholds increase, showing that larger errors are associated with larger thresholds, the deviation from the X = Y line is not biased. However, in the presence of high intensity glare, 19.21 lm/m^2, at the lowest background luminance level, 1 cd/m^2, there is a clear bias in the deviation of data points from the X = Y line. This finding indicates that at low background luminance the predictions over-estimate contrast thresholds. This can also be seen, albeit to a lesser extent, at the 2.6 cd/m^2 background luminance level.

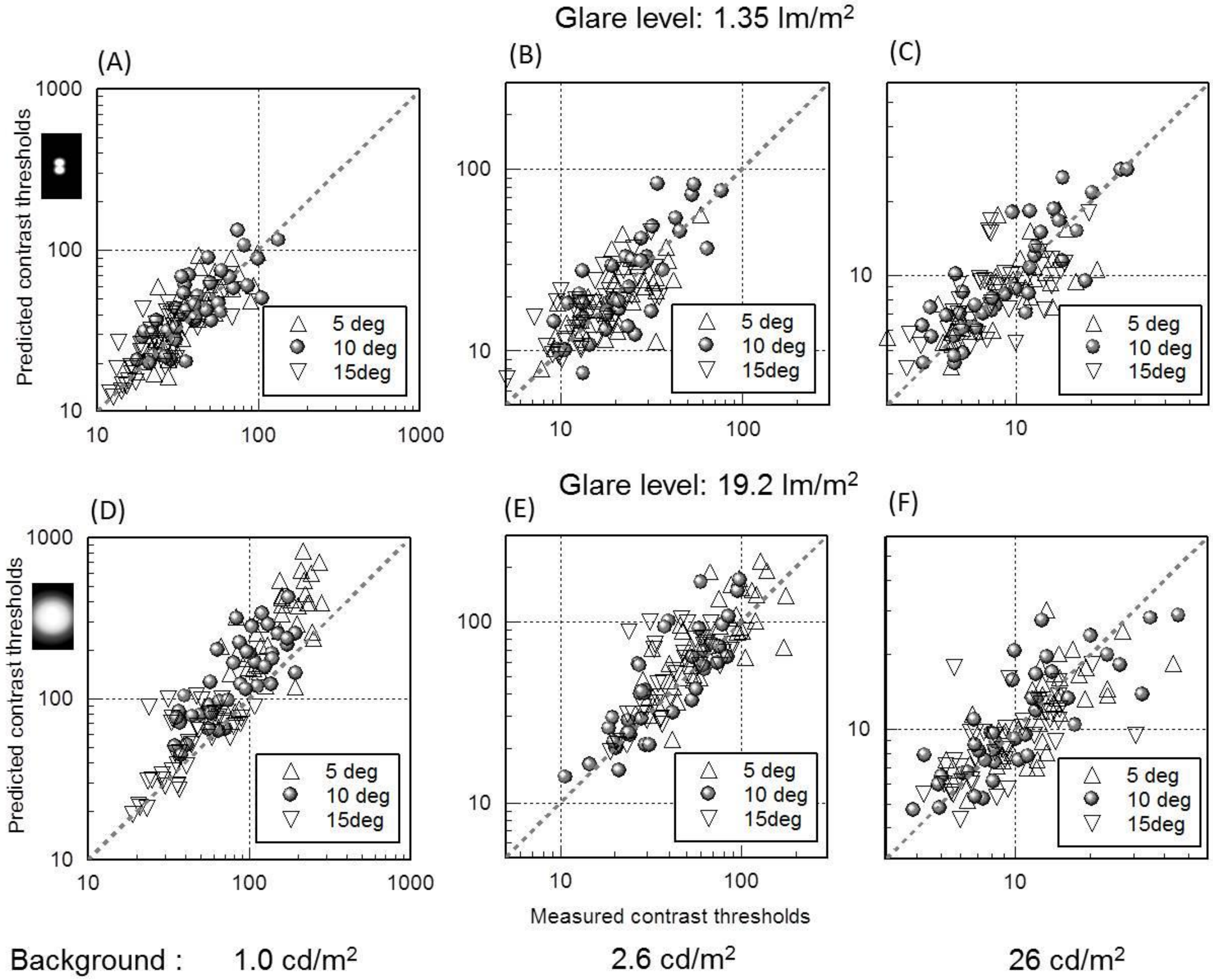

Fig. 4. Relationship between measured thresholds and model predictions based solely on scattered light. Each data point represents the threshold for one participant in one of the 18 conditions, i.e. each participant is represented three times in each subplot. The x = y line illustrates 100% accuracy of predictions; data points that fall above this line indicate an over-estimation of the contrast threshold in the presence of glare, i.e. better performance than expected. The largest over-estimation of thresholds was in the presence of high intensity glare at 1 cd/m² screen luminance.

In an attempt to improve upon the accuracy of the scatter-based predictions (Eq. 1 and 4) retinal sensitivity was incorporated using Equation 5. The function that was used to find the multiplication factor in Equation 5 is shown in Fig. 5 on a logarithmic scale. Luminance was multiplied by the measured pupil area in order to provide an estimation of the adaptation state of the retina in terms of retinal illuminance. Due to pupil constriction, the retinal illuminance in the presence of glare was sometimes lower than in the absence of glare. Predictions and analyses were carried out on all measured data for which pupil diameter measurements were available.

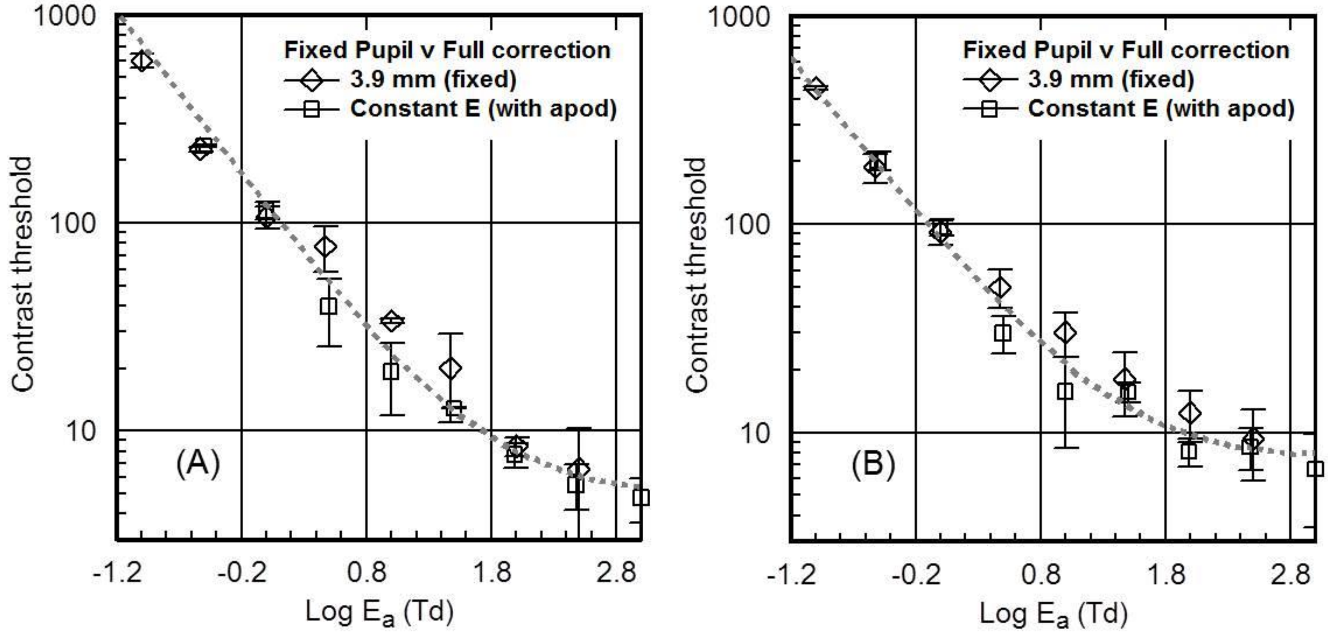

Fig. 5. Functional contrast sensitivity thresholds as a function of effective retinal illuminance measured for a Landolt ring stimulus, and plotted on a log scale at (A) the fovea and (B): ±5 deg in the periphery. Each graph compares thresholds measured using an unrestricted pupil size or a fixed pupil diameter of 3.9 mm. The natural pupil method employed a dynamic feedback technique to control the luminance of the screen so as to maintain the required level of retinal illuminance; both measures incorporate the Applegate apodization. The dotted line represents the function, $CT = b_1 \times Exp(-b_2 \times \log(E)) + b_3$, which was fitted to the combined data sets. Fovea: $b_1 = 94.71$, $b_2 = -1.82$, $b_3 = 5.03$; ±5 deg: $b_1 = 78.04$, $b_2 = -1.72$, $b_3 = 7.5$.

All of the following analyses were conducted on a logarithmic scale as this yielded data that were more normally-distributed. To determine whether there was an effect of age group upon prediction accuracy, a 2×2×3×3 mixed ANOVA was carried out using the absolute discrepancies for each prediction. There was a significant main effect of age on prediction-accuracy for both predictions, with scatter-based predictions exhibiting a larger effect, $F(1,34) = 13.35$, $p < .001$, than combined predictions, $F(1,29) = 5.27$, $p < .05$. Whereas it was hoped that the accuracy of the new predictions would not be age-dependent, this result is not particularly surprising. Firstly, it has already been established that older participants tend to have higher contrast thresholds, which increases the scope for error; a lapse in concentration during the CAA test in the absence of glare would therefore lead to a larger error in the estimated contrast threshold in the presence of glare for an older observer. Secondly, the contrast threshold curve is more representative of young participants and it is entirely possible that the shape of the curve exhibits some inter-subject variability and a significantly different rate of change in older subjects at lower retinal illuminances. This, again, would lead to larger errors in the estimation of thresholds in the presence of glare.

The accuracy of both predictions was assessed in terms of the size of the absolute discrepancies. Upon inspection of the errors, differences in accuracy between the two predictions in the presence of low intensity glare (1.35 lm/m^2) appeared to be small. A 2×3×3 repeated measures ANOVA (with prediction type, background luminance and eccentricity as factors) confirmed that there was no significant main effect of prediction type on the size of absolute discrepancies in the presence of low intensity glare. Similarly, in the presence of high intensity glare, 19.21 lm/m^2, and at photopic background luminance, 26 cd/m^2, a 2×3 ANOVA (with prediction type and eccentricity as factors) confirmed that there was no significant main effect of prediction-type. However, in the presence of high intensity glare and at the background luminance level of 2.6 cd/m^2, there was a greater variation in the size of errors between the two predictions; a 2×3 ANOVA revealed a significant main effect of prediction type, $F(1,38) = 7.49$, $p < .01$. Differences in errors between conditions are even more pronounced at the lowest, 1 cd/m^2, background luminance, confirmed by a larger significant main effect $F(1,37) = 9.25$, $p < .005$. The relationship between measured and new predicted thresholds is shown in Fig. 6 on a logarithmic scale.

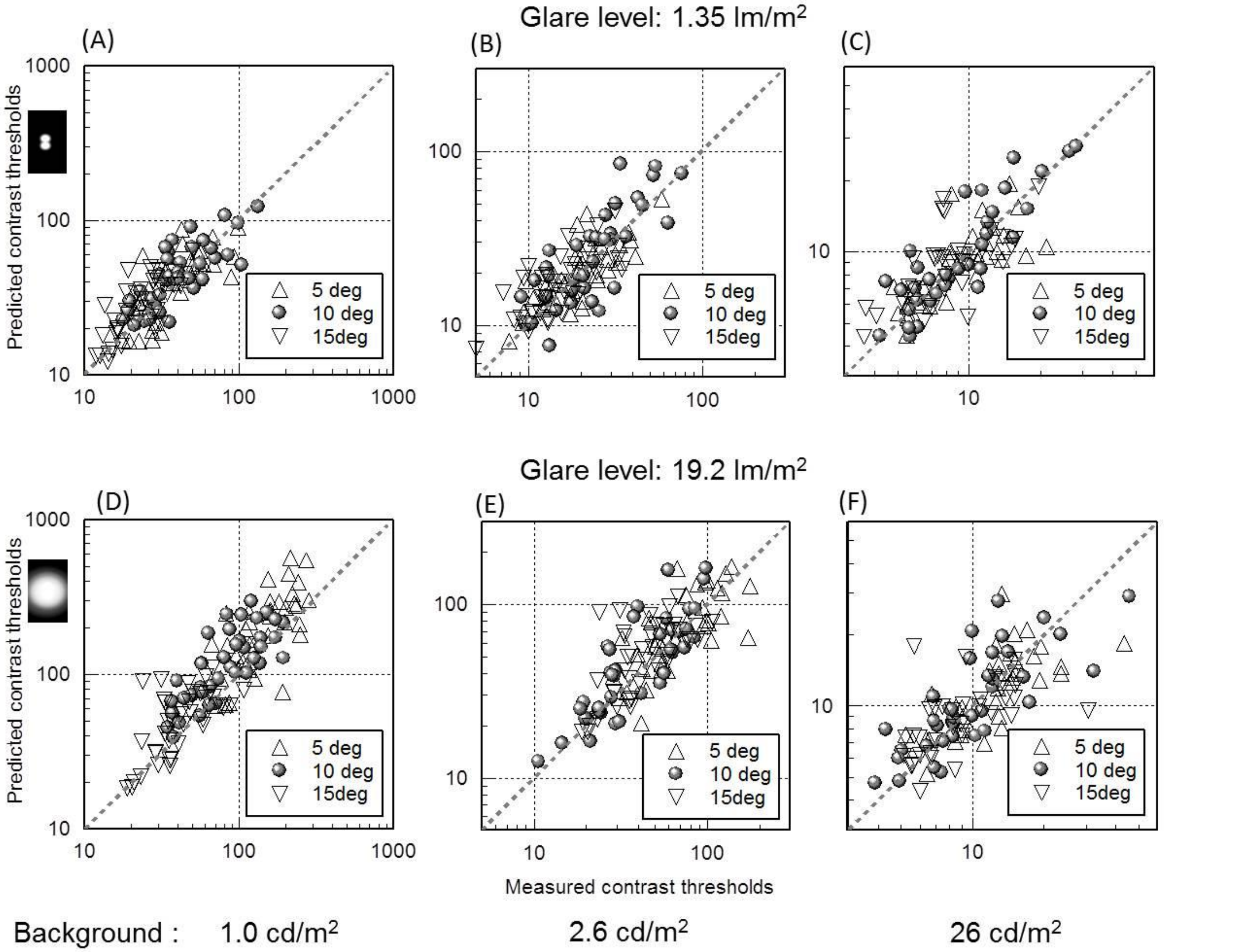

Fig. 6. Relationship between measured thresholds and model predictions based on changes in retinal sensitivity combined with changes in scattered light. As in figure 4, the x = y line illustrates the expected 100% prediction accuracy.

A comparison at the lowest background luminance and highest glare level is shown in Fig. 7 on a linear scale to show the difference in raw thresholds between the two predictions

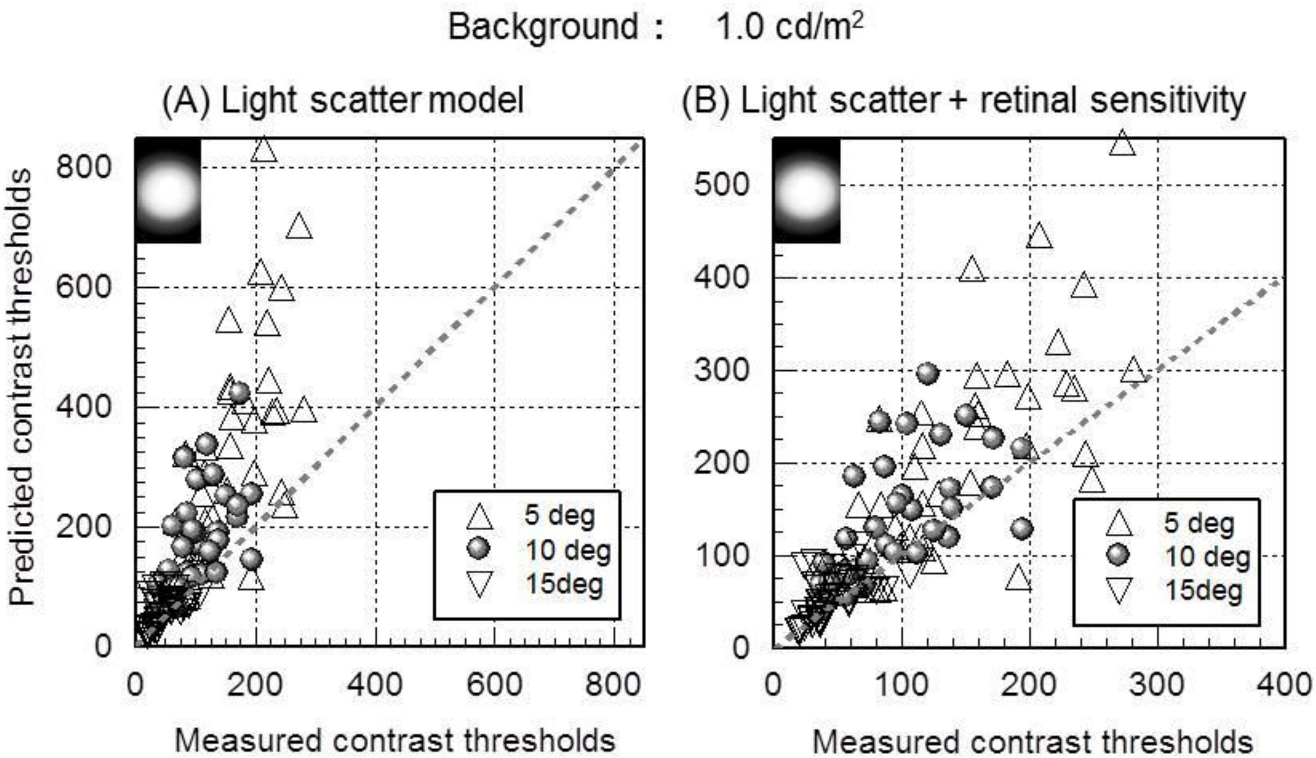

Fig. 7. Data from both (A) Fig. 4.D and (B) Fig. 6.D are replotted on a linear scale to illustrate more clearly why it is necessary to also consider how the presence of a glare source at low background luminance affects retinal sensitivity to contrast, in addition to the direct changes in the physical contrast of the retinal image through scattered light.

Discussion

The current investigation addresses the question of whether visual performance can be predicted with reasonable accuracy based on measured forward light scatter within the eye. Previous work has demonstrated good predictions of visual performance based solely on scattered light under photopic lighting conditions [14, 15, 41]. In the mesopic range, however, when most people report experiencing problems with glare [42], the scatter-based prediction becomes less reliable [17-19]. Although it is well known that retinal sensitivity increases with luminance [9, 10, 12, 13], there has of yet been no systematic attempt to model its effect on visual performance under glare conditions.

Two predictions — one based solely on forward light scatter and one that was further combined with a model of retinal sensitivity — were used to estimate contrast sensitivity thresholds in the presence of glare. Upon assessment of each of the predictions, the largest discrepancies were found to be associated with those based solely on scattered light, with prediction accuracy at its poorest when the background luminance was low. In the mesopic range, the superiority of the combined predictions in terms of accuracy indicates that the addition of light from the glare source is advantageous, despite the fact that the additional light does not contribute to the illumination of the stimulus itself. The improvement in prediction accuracy, afforded by the incorporation of retinal sensitivity, lends support to the hypothesis that the concurrent increase in retinal sensitivity is at least partially capable of offsetting the disadvantage of reduced physical contrast in the presence of glare.

Despite the improvement in prediction when using the combined model, there remains a significant over estimation of thresholds in some conditions. Prediction accuracy may be further improved by calculating mean luminance across the entire visual field or by applying a weighting function according to cortical representation of the retinal image. Any refinement to such a measure that increases prediction accuracy is not only useful for the glare community, but may also elucidate mechanisms that determine the adaptation state of the retina.

The overestimation of contrast thresholds in the presence of glare was shown to be larger for observers aged fifty years and over. Given the well-established decline in visual function with age, both as a result of changes in the optics of the eye [34-36, 43-45] and neural changes [46-49], it seems unlikely that the discrepancy in the older group's performance would be due to additional protective factors. A more likely explanation would be that the contrast threshold curve, upon which the estimations of retinal sensitivity are based, is not entirely representative for older observers. There are also a number of other individual differences — initial thresholds, iris pigmentation [50] and susceptibility to discomfort glare [51], to name just a few — that could impact upon visual performance in the presence of glare. Furthermore, it would be of great interest to investigate the extent to which the relationship is affected by pathological conditions that are associated with increased scatter, such as cataracts [18, 52], corneal dystrophy [37], keratoconus [53] and retinitis pigmentosa [54], as well as the potential effects of contact lens wear [55, 56] and refractive surgery [57-59]. Expanding the sample upon which the contrast threshold curve is based has the potential to improve the accuracy of the predictions, possibly by tailoring the formulae to specific age groups.

Although there may be several ways to improve upon the new combined predictions, the evidence presented here shows that retinal sensitivity to contrast is a critical factor in predicting visual performance. This finding is particularly relevant to research dealing with high intensity glare under low ambient luminance conditions, such as street lighting and car headlights. Future research investigating visual function in the presence of glare would benefit from taking into account concurrent changes in retinal sensitivity, particularly in the mesopic range.

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