# Capturing age-related changes in functional contrast sensitivity with decreasing light levels in monocular and binocular vision

Hanna Gillespie-Gallery, Evgenia Konstantakopoulou, Jonathan A. Harlow, John L. Barbur

Applied Vision Research Centre, The Henry Wellcome Laboratories for Vision Sciences, School of Health Sciences, City University London, London, EC1V 0HB

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**Purpose**

It is challenging to separate the effects of normal aging of the retina and visual pathways independently from optical factors, decreased retinal illuminance and early stage disease. This study determined limits to describe the effect of light level on normal, age-related changes in monocular and binocular functional contrast sensitivity.

**Methods**

95 participants aged 20 to 85 were recruited. Contrast thresholds for correct orientation discrimination of the gap in a Landolt C optotype were measured using a 4 four-alternative, forced-choice (4AFC) procedure at screen luminances from 34 to 0.12 cd/$m^2$, at the fovea and parafovea (0° and ±4°). Pupil size was measured continuously. The Health of the Retina index ($HR_{index}$) was computed to capture the loss of contrast sensitivity with decreasing light level. Participants were excluded if they exhibited performance outside the normal limits of interocular differences or $HR_{index}$ values, or signs of ocular disease.

**Results**

Parafoveal contrast thresholds showed a steeper decline and higher correlation with age at the parafovea than the fovea. 83% of participants with clinical signs of ocular disease had $HR_{index}$ values outside the normal limits. Binocular summation of contrast signals declined with age, independent of interocular differences.

**Conclusion**

The $HR_{index}$ worsens more rapidly with age at the parafovea, consistent with histological findings of rod loss and its link to age-related degenerative disease of the retina. The $HR_{index}$, and interocular differences could be used to screen for and separate the earliest stages of sub-clinical disease from changes caused by normal aging.

**Introduction**

As light levels decrease, visual performance worsens making everyday tasks difficult, such as reading and face discrimination,[1-3] especially for older people and those with retinal diseases.[4,5] It has been suggested that more information about the state of the retina is evident from mesopic rather than photopic visual function.[5] This study assessed the monocular contrast sensitivity in a functionally relevant task to quantify normal aging of the foveal and parafoveal retina between photopic and mesopic light levels as well as binocular summation, while accounting for age-related confounding variables.

When assessing the difficulties older people face at low light levels due to retinal changes, there are a number of confounding factors to account for. Pupil miosis[6,7] and increased scattering and absorption of light by the lens[8-11] reduce the contrast of the image on the retina and retinal illuminance; simulating these changes in younger participants does not, however, produce the same reduction in contrast sensitivity,[12,13] suggesting that neural, age-related changes to the retina and visual pathways[14-17] result in a reduction in performance on psychophysical measures and reveal retinal disease,[18] such as age related macular degeneration (AMD).[19,20]

Contrast sensitivity declines with age[21,22] and is more sensitive to the effects of normal aging or disease than high contrast visual acuity.[23-29] Mesopic contrast sensitivity declines in the 50s, ten years before photopic contrast sensitivity.[4] This could be attributed to the age-related reduction in the number of rods at the parafovea,[14,15] which is more severe in cases of AMD.[30] In accordance with these histopathological findings, parafoveal deficits in rod adaptation have been found at the parafovea in age-related maculopathy,[31-34] but not normal aging.[35,36]

The investigation of age-related changes in binocular summation of contrast thresholds can provide useful information on the status of visual pathways. Based on signal detection theory, binocular viewing provides two independent estimates of the stimulus, provided the noise in the two eyes is uncorrelated.[37] Binocular vision should therefore improve detectability by a factor of $\sqrt{2} \backsimeq 1.4$; however, summation often shows different values, suggesting the involvement of neural summation comprised of mechanisms that only respond to binocular inputs.[38] Binocular summation for contrast can be significantly reduced in older people, and some experience inhibition (performance in binocular viewing which is worse than monocular viewing).[39,40] The decline in binocular summation with age has often been attributed to large inter-ocular differences in sensitivity or image contrast [41-43] however this association has not always been found.[40] Binocular summation may decrease with eccentricity or light level, but results in the literature are mixed.[41,44-48]

This study determined whether there is greater parafoveal than foveal loss in visual function with age, by calculating the Health of the Retina index ($HR_{index}$) to quantify changes over mesopic and photopic light levels. Additionally, it was explored whether interocular differences can account for changes in binocular summation with age.

## Methods

### Participants

Participants were recruited by advertising the study within City University London. Tests were approved by the City University Research and Ethics Committee and the study adhered to the principles of the Declaration of Helsinki. Informed consent was obtained for all participants. The participants underwent an ophthalmic assessment which included measurement of visual acuity, refraction, binocular vision assessment, pupil reactions, slit lamp assessment of the anterior eye and indirect ophthalmascopy of the macula, optic nerve head and peripheral retina using a 90 D lens.

### Contrast Sensitivity Assessment

The contrast vision of each participant was assessed using a 'Functional Contrast Sensitivity' (FCS) test.[49] Stimuli were presented on a high resolution NEC Multisync Diamondtron CRT monitor (model FR2141 SB, 19.5 in), using a 30 bit color graphics card (ELSA, Model Gloria, SL, Germany) with 1280x1024 pixels, at a frame rate of 120 Hz. The monitor was calibrated automatically with a LMT 1009 luminance meter and bespoke software (LUMCAL, City Occupational Ltd, UK).

Participants viewed the display from 2m. The task was to discriminate the direction of the gap in a Landolt ring optotype, which occurred in one of four diagonal directions. Between presentations, a fixation cross and four oblique guides were displayed to help maintain central fixation and accommodation. The spectral composition of the background had predominantly long-wavelength (LW) and middle-wavelength (MW) content (CIE x=0.43, y= 0.485) to minimise chromatic aberrations and variation in short wavelength (SW) absorption of light by the macular pigment and the crystalline lens.[50] The stimulus was presented for 80ms at the specified contrast with 2σ Gaussian-weighted, rising and falling profiles (σ = 53ms). Stimuli were presented in one of three randomly interleaved locations, at +4°, 0° or -4° from fixation, along the horizontal meridian. A staircase procedure with 10 reversals, was employed, to vary the Weber Contrast of the stimulus using a two-down, one-up procedure reducing the chance response probability to 1/16.[51] Interleaved staircases employed increments which decreased according to an exponential function. Starting contrast increments were 5% and ending contrast increments were 1% for the highest light level and 10% and 2%, respectively, for the lowest light level.

Size scaling of the stimulus was employed to account for the reduction in spatial resolution with increasing eccentricity. A gap size was 4 min arc at 0° (diameter 20 min arc) and 6 min arc at ±4° (diameter 30 min arc), corresponding to spatial frequencies of 7.5 and 5 c/deg, important in tasks on visual displays[49] and are affected by aging, whereas lower spatial frequencies are mostly unaffected by aging.[22] The fixed gap size was significantly larger than the acuity limit at high light levels to ensure it would not be below the acuity limit at low light levels, resulting in mid to high spatial frequencies being used to discriminate the location of the gap.

Participants were tested at background luminances, 34.00, 7.60, 3.20, 1.60 and 0.12 cd/m$^2$. Spectrally calibrated neutral density filters were employed for background luminances below 3 cd/m$^2$.

Participants viewed the screen binocularly, followed by the right eye alone and then the left eye alone at each light level.[52] The eye not being tested was covered with an opaque, infrared transmitting filter which allowed the iris illumination needed for pupil measurements. The participants were tested at the brightest screen luminance first, followed by the next, lower screen luminance meaning that less time was required for adaptation between luminance levels than using a randomised procedure. A minimum of five minutes adaptation time was provided for the lowest luminance from the second lowest luminance and two minutes for other luminances.

**Estimates of Lens Optical Density**

The SW absorption of the crystalline lens was measured with the Macular Assessment Profile (MAP) test, for which a full description has been provided previously.[53] The MAP test estimates lens optical density (OD) for SW light with respect to the mean density of young observers. The test was performed monocularly for each eye at a viewing distance of 0.7m. The OD was measured to ensure firstly that no participants had higher values than found in previous samples and secondly that there were no significant differences in OD between the two eyes.

**Pupil Measurements**

Pupil diameter was measured during the FCS test using the P_SCAN 100 system[54,55] which employs infrared video imaging techniques with pulsed infrared illumination to measure the centre co-ordinates of the pupil and to compute its size. Pupil measurements were taken monocularly while the participant performed the test and were averaged to produce a mean pupil size for each luminance; separate estimates were made for binocular and monocular viewing.

**Estimating Retinal Illuminance**

Retinal Illuminance (*E*) was measured in trolands (td) as $E = L \times P$, where L is the screen luminance (L) in cd/m$^2$ and P is the pupil area in mm$^2$.

**Calculating $HR_{index}$ for Contrast Sensitivity**

The group data provided an average measure of the change in threshold contrast sensitivity with retinal illuminance for five light levels. The $HR_{index}$ reflects the fractional difference between the area under the participant's threshold curve and the corresponding median curve for the group (Appendix 1). For each participant, a $HR_{index}$ at three retinal locations, one foveal and two parafoveal, was calculated for each eye. The same method was applied to the binocular measurements. For the group data, results at ±4° were combined because the area did not differ between -4° and +4° ($t(53)=1.28$, $p=0.21$).

**Identifying participants with significantly elevated contrast thresholds**

Participants with detectable clinical signs of disease were excluded from the calculation of the $HR_{index}$. Participants were also excluded if they exhibited differences outside the 95% limits in lens optical density or contrast sensitivity at corresponding loci between their eyes, as early stage retinal diseases tend to affect the eyes asymmetrically and/or start at the parafovea.[30,56] To identify participants with substantial interocular differences in contrast thresholds ($IO_{difference}$) the following parameter was calculated:

$$IO_{difference} = |A_{LE} - A_{RE}|$$

Where $A_{LE}$ is the area under the curve for one eccentricity for the left eye, and $A_{RE}$ is the area under the curve for the corresponding eccentricity in the right eye. If a participant was excluded at one retinal location, all results were excluded.

**Calculating binocular summation ratio (BSR) and interocular percentage increase (IPI)**

BSRs were calculated as the ratio of the best eye's contrast threshold to the binocular contrast threshold.

$$BSR = \frac{Best\ eye\ threshold}{Binocular\ threshold}$$

IPI) was calculated to investigate its influence on binocular summation. It was calculated as the absolute difference of the thresholds between the eyes as a ratio of the best eye threshold, where $T_{LE}$ is the average left eye threshold and $T_{RE}$ is the corresponding right eye threshold.

$$IPI = \frac{|T_{LE} - T_{RE}|}{Best\ eye\ threshold}$$

**Statistical Analysis**

The JMP statistical software was used to fit the non-linear function that describes the variation in the participant's threshold with retinal illuminance (SAS Institute Inc., Cary, North Carolina). MATLAB (the MathsWorks, Inc.) was used to estimate the probability density functions for the measured $HR_{index}$ values and to compute the 95% limits. For statistical analysis, each participant contributed one data point only for each condition, obtained by averaging results across eyes and eccentricities.

## Results

### Identification of outliers

A total of 95 participants were recruited (age range 20 to 85 years). Twelve participants (12.6%) were excluded due to a presence or history of ocular disease or injury (table 1). The lens optical density values were within the range reported previously.[53] A total of thirteen participants had significant interocular differences limits and were excluded; four participants (4.2%) showed asymmetrical optical density of the crystalline lens, and nine (9.5%) participants had differences in the area under the threshold curve outside the 95%.

**Table 1.** Description of participants excluded following the clinical exam

| Condition | Frequency (%) |
|---|---|
| Early signs of AMD (drusen, RPE changes) | 6 (50%) |
| Diabetes | 2 (17%) |
| Corneal opacities | 1 (8.3%) |
| Iris trauma | 1 (8.3%) |
| Retinal holes | 1 (8.3%) |
| Retinitis Pigmentosa | 1 (8.3%) |

Sixteen participants (16.8%) were excluded because the area under the curve for calculation of the $HR_{index}$ fell outside the 95% limits at the fovea or parafovea. The $HR_{index}$ was calculated for each remaining participant separately for each parafoveal and foveal location. Figure 1 shows the age distribution of all participants (n=54 normals, mean age ± SD = 43.9 ± 14.7 years). The ratio of males to females was 16:11.

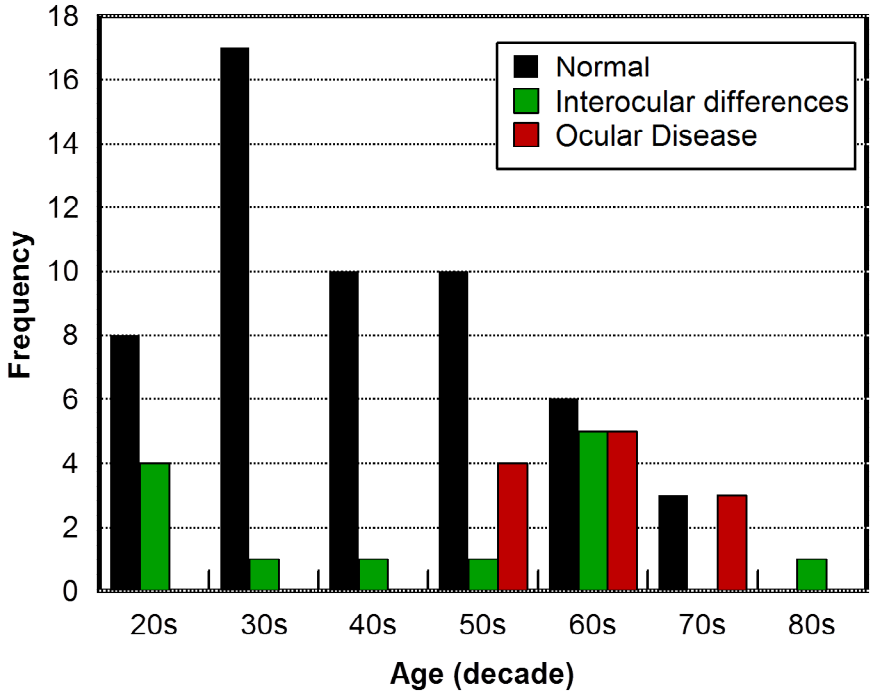


Figure 1. Age distribution of included participants and those excluded due to ocular disease or interocular differences outside the 95% limits. Those with either interocular lens or contrast threshold differences outside the normal limit are combined into the "Interocular differences" category

**$HR_{index}$ for monocular functional contrast thresholds**

Figure 2 shows the contrast thresholds as a function of retinal illuminance for foveal and parafoveal targets for the included participants. The asymptote of the foveal data reveals improved contrast thresholds at the fovea at high light levels; parameter p1 suggest that as the light level decreases performance declines more gradually at the parafovea (226.1) than the fovea (241.7). The age dependence of contrast thresholds on adaptation luminance is more apparent at the parafovea (figure 2D) than the fovea (figure 2A). Figures 2C and 2F show results for excluded participants, who may only show high thresholds at a particular retinal illuminance or retinal location, while other results can be within the normal range.

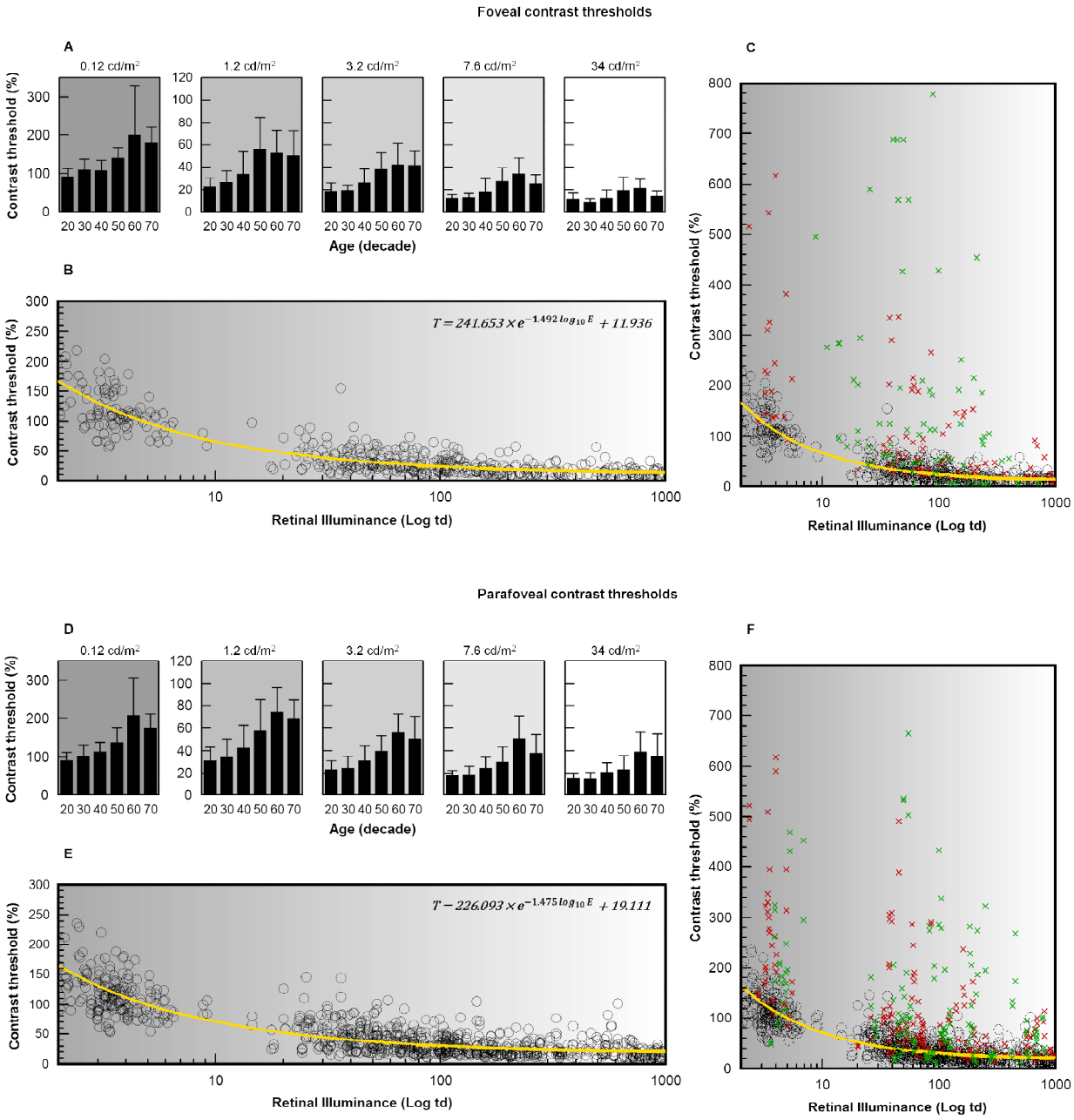


Figure 2. Contrast thresholds for participants at the range of light levels. For the foveal data each participant contributes two points for each screen luminance, one from each eye. For the parafoveal data, each participant contributes four points for each luminance level, from ±4° in each eye. A to C show foveal data. A contrast thresholds for the five background luminances employed. Note that each bar represents one decade, i.e. 20 indicates results from ages 20 to 29 years of age and error bars show one SD. B contrast thresholds for normal participants and curve fitted to the data in the form, $T=p1xe^{p2\log E}+p3$. C data as in B with data from participants with ocular disease (red) or outlying interocular differences (green). D to F show the corresponding graphs for parafoveal data.

Figure 3 shows the $HR_{index}$ as a function of age at the fovea and parafovea ($r^2$=0.19, p<0.001 and $r^2$=0.34, p<0.001, respectively), where no differences were found in the variance of older and younger participants at the fovea or parafovea (Levene's statistic=0.591, p=0.446 and Levene's statistic=1.908, p=0.173, respectively). Although the gradient of decline of the $HR_{index}$ was steeper at the parafovea, this did not reach significance (repeated measures ANCOVA, F(1,52)=2.554, p=0.116).

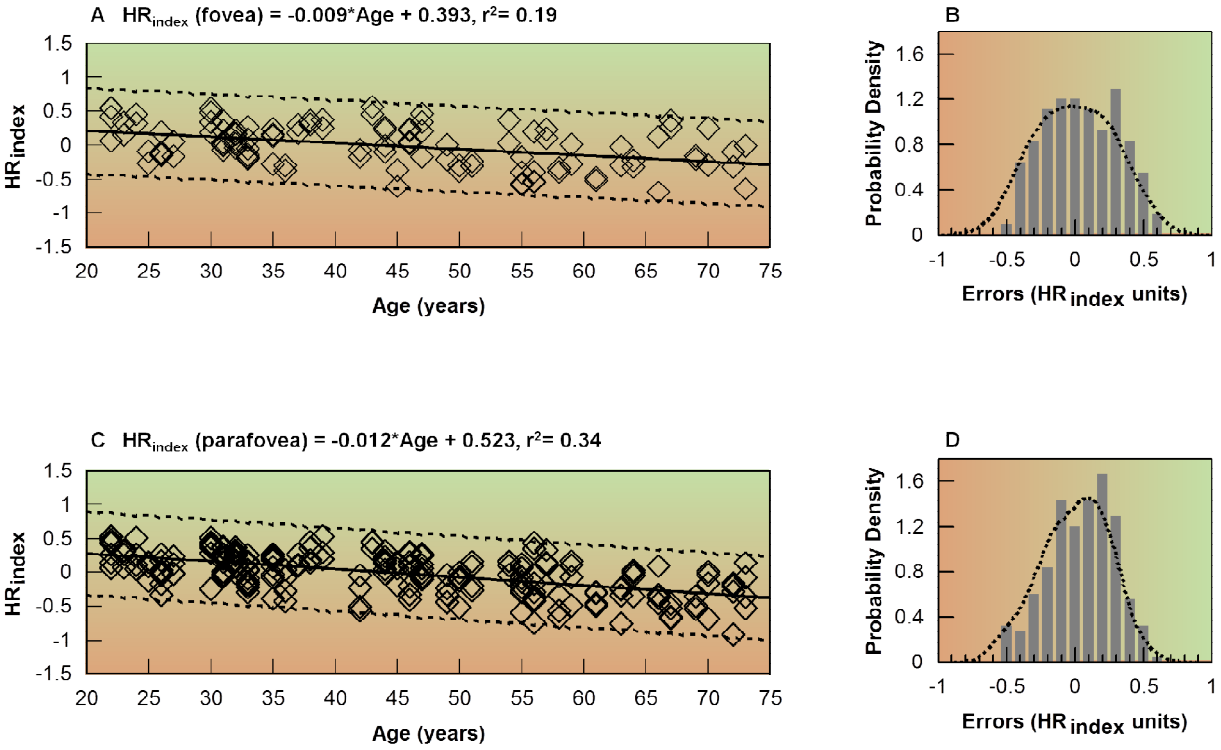


Figure 3. HR index as a function of age. Panels A and C show the $HR_{index}$ for the fovea and parafoveal respectively. Dashed lines show the 95% limits. Panels B and D show the probability density distributions of the errors of values from the regression line. For the foveal data each participant contributes two points, one from each eye. For the parafoveal data, each participant contributes four points, from ±4° in each eye.

Figure 4 shows the $HR_{index}$ for participants with ocular disease and interocular differences outside the 95% limits. 10 out of 12 of those with ocular disease and 11 out of 13 of those with significant interocular differences had $HR_{index}$ values outside the normal limits for at least one eccentricity.

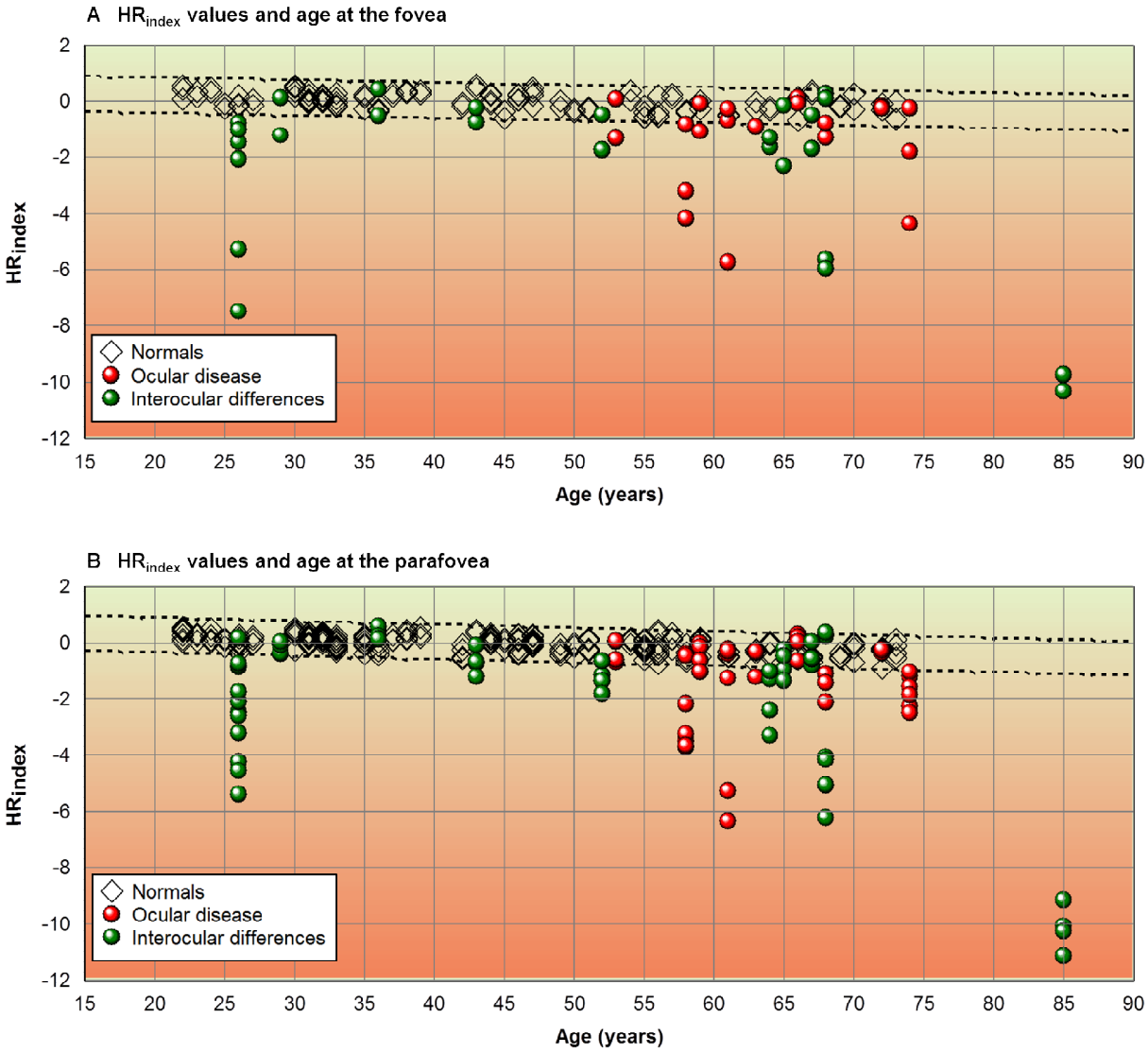


Figure 4. HRindex for normal participants, those with ocular disease and with interocular differences outside the 95% limits. For the foveal data, (A), each participant contributes two points, one from each eye. For the parafoveal data, (B), each participant contributes four points, from ±4° in each eye. In total, each participant has six points over the two graphs.

Normal participants show a steady increase in contrast thresholds with decreasing retinal illuminance (Figure 5). A participant with macular drusen exhibits $HR_{index}$ values outside of the normal limits, with particularly elevated thresholds at low light levels in the parafovea.

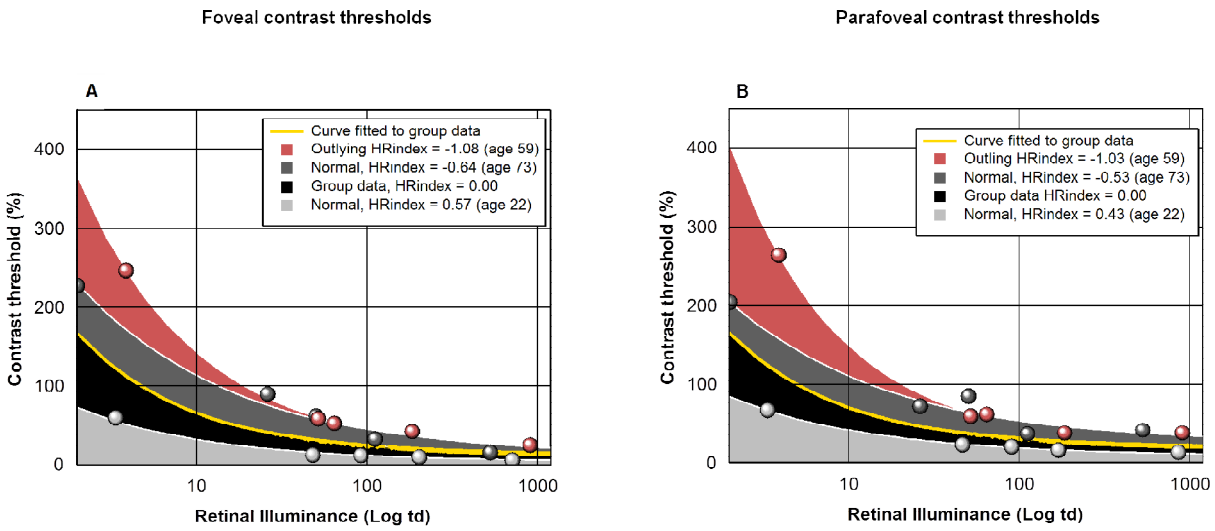


Figure 5. Examples of contrast thresholds and the corresponding $HR_{index}$ values for normal and excluded participants. Panels A and B show the contrast thresholds for two normal observers at the fovea and parafovea, respectively and for a 59 year old with drusen. The younger participant has a smaller area under the curve than the group data, resulting in a positive $HR_{index}$. However the older participant has a greater area under the curve than the group data resulting in a negative $HR_{index}$, yet still within the 95% limits in figure 3. The participant with drusen also has a negative $HR_{index}$ but is outside the 95% limits at both eccentricities.

Figure 6 shows how contrast thresholds change at the fovea and parafovea for three retinal illuminance levels as a function of age. Points were derived from curves fitted to each individual's data. A repeated measures ANCOVA with two factors, eccentricity (fovea and parafovea) and light level (900, 25, 5 td) with age as a covariate was performed. Thresholds were best at the fovea ($F(1,53)=13.570$, $p<0.001$), at higher light levels ($F(1,53)=1253.731$, $p<0.001$) and in younger participants ($F(1,52)=36.203$, $p<0.001$). More interestingly contrast thresholds increased more rapidly with age at the parafovea than the fovea ($F(1,52)=4.718$, $p<0.05$) and at lower light levels ($F(1,52)=11.250$, $p<0.01$). Correlations with age were stronger at the parafovea than fovea.

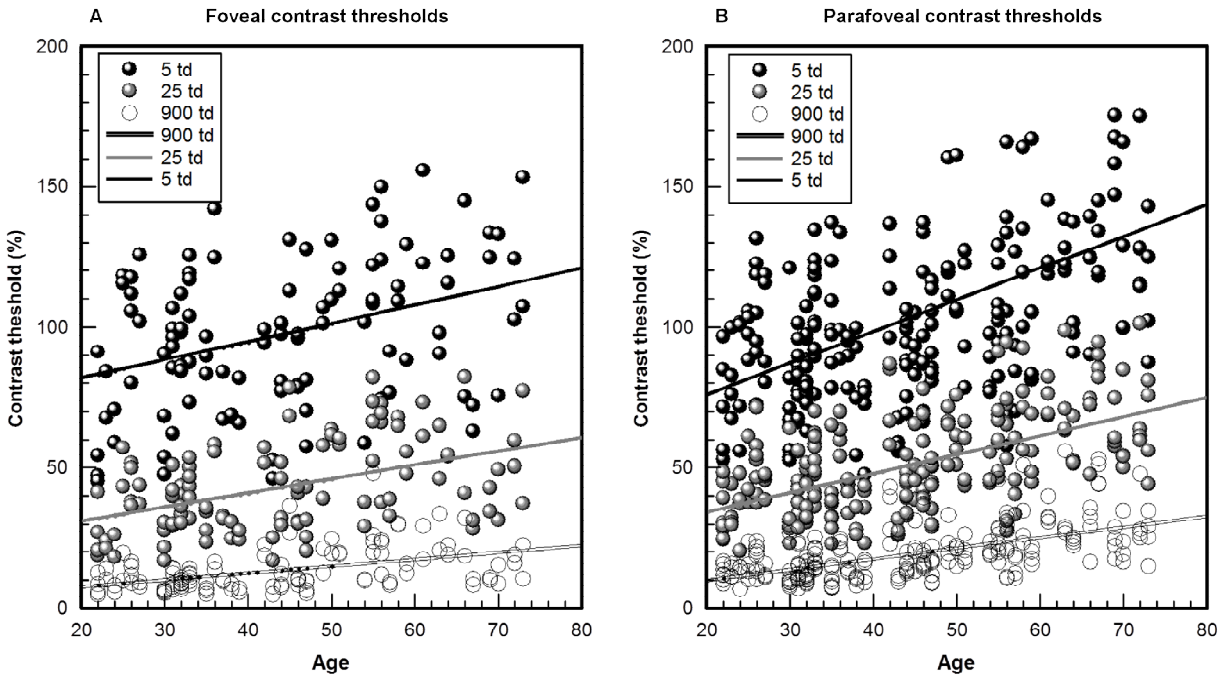


Figure 6. Foveal and parafoveal contrast thresholds at 900. 25 and 5 td. A foveal contrast thresholds, at 5 td, $y = 0.6495x + 68.906$ $R^2 = 0.129$; at 25 td, $y = 0.4946x + 21.299$, $R^2 = 0.2044$; at 900 td, $y = 0.242x + 2.9257$, $R^2 = 0.2046$. B parafoveal contrast thresholds, at 5 td, $y = 1.1275x + 53.396$, $R^2 = 0.3422$; at 25 td, $y = 0.6783x + 20.686$, $R^2 = 0.3275$; at 900 td, $y = 0.3827x + 2.3396$, $R^2 = 0.3485$.

**Binocular summation**

52 of the 54 participants had binocular vision. BSRs were calculated at 1 td increments between 2-900 td and then averaged to produce one BSR value using the curve fitted to each participant's thresholds to account for differing retinal illuminance both between participants and in monocular and binocular conditions. The BSRs for contrast sensitivity are variable (mean 1.52, range 0.75-2.75[57]) and all but one participant fell within this range. A repeated measures ANCOVA with eccentricity and age revealed that they both had a significant effect on binocular summation (table 2), suggesting that BSRs are higher at the parafovea (M=1.43, SD=0.28) than the fovea (M=1.33, SD=0.31) ($p<0.05$) and that BSRs decreases with age ($p<0.01$). The interaction between age and eccentricity was not significant. BSRs were significantly correlated with age at the fovea ($r^2=0.12$, $p<0.05$) and the parafovea ($r^2=0.11$, $p<0.05$) (Figure 7A). Eight, participants showed binocular inhibition (BSR <1) seven of whom were over the mean age of 43.9.

Increasing interocular differences can reduce binocular summation and cause inhibition. An independent measures ANCOVA with eccentricity and IPI (table 2) revealed a main effect of IPI on binocular summation, but no effect of eccentricity or an interaction between these factors. Low values of IPI result in high levels of binocular summation and vice versa ($r^2=0.10$, $p<0.01$, figure 7B). IPI has no relationship with age at the fovea ($r^2=0.05$, $p=0.23$) or parafovea ($r^2=0.004$, $p=0.66$) (Figure 7C).

Table 2. Description of ANCOVAs describing the effects of age, foveal location and normalised interocular thresholds difference on binocular summation. Degrees of freedom are F(1,57) for the effects of age ANCOVA and F(1,100) for the effects of interocular percentage increase.

| ANCOVA | F | p value |
|---|---|---|
| **Age (IV) and Eccentricity** | | |
| *Age (covariate)* | 9.03 | p<0.01** |
| *Eccentricity (fovea and parafovea)* | 5.79 | p<0.05* |
| *Age x Eccentricity* | 0.25 | p=0.62 |
| **IPI and Eccentricity** | | |
| *IPI (covariate)* | 12.31 | p<0.01** |
| *Eccentricity (fovea and parafovea)* | 0.02 | p=0.89 |
| *IPI x Eccentricity* | 1.88 | p=0.17 |

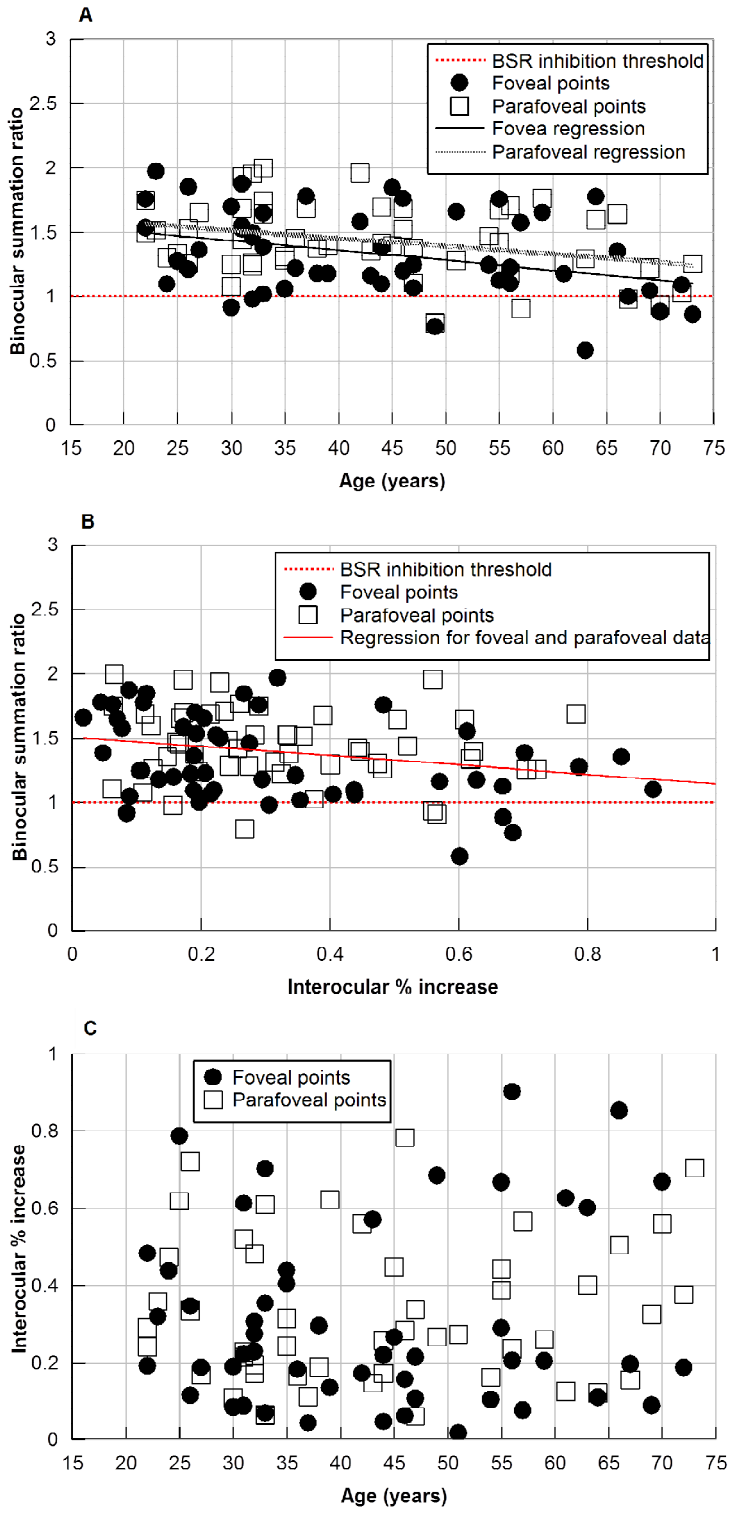


Figure 7. BSR values below 1 (the BSR inhibition threshold) indicate binocular inhibition. A Binocular summation ratio for normal, binocular participants (n=52). Binocular summation was calculated as the best monocular contrast threshold divided by the binocular contrast threshold at retinal illuminances between 900td and 2td. The solid line shows the linear fit to the foveal data (-0.0077*Age + 1.667, $r^2$=0.12, p<0.05) and the dashed line the fit to parafoveal data (-0.0063*Age +1.705, $r^2$=0.11, p<0.05). B a linear fit to both foveal and parafoveal points as the ANCOVA revealed no effects of eccentricity (-0.363*Interocular percentage increase + 1.5082, $r^2$ = 0.10, p<0.01). C IPI has no relationship with age at the fovea ($r^2$=0.05, p=0.23) or parafovea ($r^2$=0.004, p=0.66).

## Discussion

### The $HR_{index}$ at the fovea and parafovea

The findings in this study show that contrast vision declines with age, consistent with large population studies of aging and contrast vision.[27,58] The current approach, however, isolates the decline in contrast vision to retinal factors, independently of decreased retinal illuminance and increased optical density of the lens. The $HR_{index}$ method provides a single number to simply represent contrast performance over a range of light levels.

A linear decline in contrast sensitivity was found from 20 to 74 years of age (Figures 3 and 6), by measuring an observer's contrast threshold and at their retinal illuminance. Studies that did not account for retinal illuminance suggest that declines in visual performance with age over the lifespan are best fit with bilinear and/or exponential functions,[27,59] or only show a decline in performance from 50 years,[59] highlighting the need to measure retinal illuminance for a wide range of light levels.

Parafoveal performance showed a significantly steeper decline with age than foveal performance (Figure 6). Earlier studies have not found greater functional declines at the parafovea compared to the fovea in normal aging,[35,36] but have in early AMD.[31-34] The parafovea exhibits a significant loss of rod photoreceptors with healthy aging, particularly in patients diagnosed with AMD.[30] Since older eyes have 13.5% larger rods, resulting in similar rod coverage[14] and increased parafoveal spatial summation,[60,61] age-related functional loss at the macula may manifest as a loss of contrast or other spatial perception rather than absolute sensitivity. No difference in the rate of parafoveal and foveal decline was found using the $HR_{index}$ which summarises performance at photopic and mesopic light levels, suggesting that to quantify the effects of aging research should focus on performance at lower light levels. Therefore our results suggest that age-related rod loss at the parafovea affects contrast vision in normal aging and not just in macular disease.

The $HR_{index}$ limits identified 83% of participants who had signs of ocular disease; Hahn et al.[59] identified only 67% of those with early AMD in a parafoveal letter recognition task. The range of light levels used in this study may have allowed the identification of more participants with ocular disease and although the participants in this study had a range of conditions. A larger sample and longitudinal study would, however, be required to determine reliably the sensitivity and specificity of the $HR_{index}$.

Interocular differences can have functional consequences such as increasing the number of driving accidents.[62] In this study 85% of those with large interocular differences also had $HR_{index}$ values outside the normal limits and interocular differences were larger in those with ocular disease ($p<0.01$). Differences in contrast sensitivity between the eyes could be due to differences in optical aberrations, accommodation and scattered light, however the use of Landolt ring

gap sizes of four and six arc min and the restriction of light to MW and LW are likely to minimise these effects. Selective structural changes in the retina or an imbalance in the cortical area dedicated to each eye may contribute more to the measured differences in contrast sensitivity between the eyes, suggesting that any deficits in $HR_{index}$ might be related to photoreceptor/retinal or higher processing deficits.

The decline in contrast sensitivity with age shows a greater decrease than previously calculated for color vision;[63] at the parafovea the gradient is more than double that computed for chromatic $HR_{index.}$ The assessment of more retinal locations, the extension into the lower mesopic range and the use of interocular differences as an additional filter may have made this assessment more sensitive.

**Binocular summation of contrast signals**

BSRs were calculated, for the first time accounting for retinal illuminance difference between participants and monocular and binocular conditions.[64] BSR decreased with age in accordance with previous finings.[39,40] In addition, eight out of fifty two participants showed binocular inhibition, a greater proportion than previously reported,[39,65] despite the fact that our methods maximised BSR which is highest for stimuli at threshold.[43,46] These findings could be because BSR was averaged from 900-2td, whereas previous studies are conducted under photopic conditions and BSR is reduced at lower retinal illuminances (paired t-test, $t(51)=2.509$, $p<0.05$; at 900td, M=1.34, SD=0.37; at 2td, M=1.15, SD=0.37). These results suggest that when measuring visual function over a large range of light levels, a greater proportion of people may experience difficulties binocular vision than previously reported.

The decrease in BSR in normal aging has often be attributed to increases in interocular differences with age.[27,41,43] However, as the thresholds of the eyes increase, the interocular difference should also increase proportionately in accordance with Weber's Law. If one defines the interocular difference as the interocular percentage increase (IPI) in contrast thresholds, as described above, IPI has no relationship with age at the fovea ($r^2=0.05$, $p=0.23$) or parafovea ($r^2=0.004$, $p=0.66$) (figure 7C). Therefore, any decrease in BSR with age must be explained by neural factors either at the retina or the cortex. In support of a central, neural aetiology, BSR declines at the same rate with age for both foveal and parafoveal locations. Possible explanations included poorer photoreceptor activity, increases in cortical noise or delayed signal timing with age.[16,66,67]

BSR was higher at the parafovea compared to the fovea, contrary to previous findings.[41,44] In this study a slightly larger target size was used at the parafovea compared to the fovea, which improves summation.[44] Most studies of binocular summation use the same target size across the visual field; this results in a corresponding reduction in sensitivity as the receptive fields of retinal ganglion cells increase, acting as an additional extraneous factor. The

stimuli in this study were size scaled to control for differences in sensitivity, possibly revealing a real increase in binocular summation when sensitivity changes are corrected for. The size scaling was appropriate, as the area under the curves for foveal and parafoveal data were similar.

**Conclusion**

Independently of retinal illuminance, older people have difficulty with contrast vision due to neural changes in the retina and reduced binocular summation. The parafovea is more susceptible to aging than the fovea and advanced testing of its function may prove useful in detecting retinal disease. Methods employed in this study have identified individuals with losses of spatial vision despite minimizing the effects of pupil miosis, light scatter and the use of MW and LW light. The contrast-based $HR_{index}$ confirms previous findings on chromatic sensitivity and extends its applicability. BSR revealed a number of older individuals showing binocular inhibition, raising questions about the quality of binocular vision in older people in the absence of clinically recognizable deficits or disease.

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## Appendix 1

Change in the contrast discrimination thresholds as a function of retinal illuminance were fitted with the equation:

$$T = p1 \times e^{p2\, log_{10} E} + p3$$

Where *T* is the measure of contrast threshold, *E* is the retinal illuminance, p3 is the asymptotic threshold, and *p1* and *p2* are constants. The best-fit parameters *p1, p2* and were computed for the group of participants the fitted curves are shown in figures 2B and 2E.

The equation was then integrated to compute the area under the curve for thresholds at each of the three retinal locations in each eye producing six values for each participant.

$$A = \int_{2}^{900} (T = p1 \times e^{p2\, log_{10} E} + p3) d\, log_{10} E = \left[\frac{p1}{p2} \times e^{p2\, log_{10} E} + p3\, log_{10} E + C\right]_{2}^{900}$$

The fitted curve for the group was used as a reference against which every participant was compared at each retinal location. Then the equations above were used separately to compute participant-specific dependence on retinal illuminance and the corresponding $HR_{index}$. To improve stability of the nonlinear fitting algorithm, a sixth point was added to the dataset to correspond to 80% of the best threshold (predicted, best threshold at high retinal illuminance at 3000 td, corresponding to approximately 150 cd/m$^2$).

The $HR_{index}$ was defined as the difference between the area under the participant's threshold curve ($A_p$) and the corresponding area computed for the normal group ($A_{group}$)

$$HR_{index} = 1 - \frac{A_p}{A_{group}}$$

A positive $HR_{index}$ indicates performance better than the average normal participant. Correspondingly, a negative value indicates contrast discrimination that falls below that expected for the average normal participant.