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ORIGINAL ARTICLE

Effects of Light Scatter and Blur on Low-Contrast Vision and Disk Halo Size

María Cinta Puell* and Catalina Palomo-Álvarez*

ABSTRACT

Purpose. To investigate the individual effects of forward light scatter (FLS) and refractive blur on low-contrast vision and the size of the disk halo produced in response to an external glare source.

Methods. Monocular disk halo radius, high- and low-contrast distance visual acuity (HCVA, LCVA), and contrast sensitivity (CS) were determined in 25 eyes of 25 healthy subjects under normal, FLS, and blur conditions. FLS was induced using the filter Black ProMist 2 to simulate an early cataract. Blur was induced using a +1.00 diopter lens to simulate an uncorrected refractive error.

Results. Similar significant mean increases in halo radius were observed for the FLS (0.32 ± 0.10 log arc min; $P<.0001$) and refractive blur (0.40 ± 0.18 log arc min; $P<.0001$). Under induced blur, 3 lines of HCVA (0.32 ± 0.15 logMAR; $P<.0001$) and 4 lines of LCVA (0.39 ± 0.16 logMAR; $P<.0001$) were lost. FLS had a minimal (but significant) effect on HCVA, but worsened mean LCVA by more than 1 line (0.13 ± 0.10 logMAR; $P<.0001$). Similar significant mean CS reductions of 0.17 ± 0.12 ($P<.0001$) and 0.14 ± 0.12 log units ($P<.0001$) were produced in response to FLS and refractive blur, respectively (approximately 1 triplet).

Conclusions. Forward light scatter and refractive blur contributed to an increased size of the disk halo produced by a glare source in similar proportion. Although defocus blur has a substantial effect on LCVA, a loss of more than 1 line of LCVA after best refractive correction would be indicative of FLS.

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Key Words: forward light scatter, disk halo, straylight, refractive blur, visual acuity, contrast sensitivity, early cataract

Uncorrected refractive error and cataract are the leading causes of visual impairment affecting 43 and 33% of the world population, respectively.[1–4] In high-income countries, uncorrected refractive error (either undiagnosed or inadequately corrected) was described as the most frequent cause of moderate to severe vision impairment in 2010.[5] Uncorrected refractive error has been associated with a reduced quality of life and visual function. This association has been demonstrated in a variety of populations.[6–9] The Singapore Malay Eye Study demonstrated that uncorrected myopia was independently associated with three items of the VF-11 scale requiring distance vision, even when participants wore their glasses: reading street signs, recognizing friends, and watching television. This link was not detected for uncorrected hyperopia.[7] In a Latino population, it was observed that subjects with myopia had significantly more distance vision difficulty regardless of correction than subjects without refractive error.[9] More recently, the Salisbury Eye Evaluation study revealed that compared with individuals with normal vision, subjects with uncorrected refractive error showed slower walking speeds, slower near task performance, more frequent driving cessation, and worse self-reported visual difficulty.[8]

It is known that many individuals with uncorrected refractive error[10] or untreated cataracts continue to drive[11] even if their vision does not meet the standards for driving.[10,11] Driving is likely to be particularly challenging for those with visual impairment given the associated reduction in contrast sensitivity and enhanced problems with glare that are critical for performing tasks as diverse as reading road signs or detecting pedestrians or other road hazards. The presence of cataract could aggravate such limitations because of increased scattering of light. Many reports have indicated that some persons with cataract who have good visual acuity report glare and other visual problems.[12] In these individuals, visual problems are mainly the outcome of increased forward light scatter, which causes a veiling luminance that reduces retinal image contrast and provokes disability glare, yet has minimal effects on visual acuity.[12–14]

The impact of refractive blur on standard clinical measures of vision such as visual acuity is well known,[15,16] and several studies have addressed the effects of simulated dense cataract[13,17–19] on visual function. However, few investigations have examined the

*PhD
Applied Vision Research Group, Faculty of Optics and Optometry, Universidad Complutense de Madrid, Madrid, Spain (both authors).

effects of early cataract and uncorrected refractive error under low contrast and glare conditions. A greater understanding of the effects of refractive blur and forward light scatter on visual performance is essential because vision impairment may be worse under low contrast, low luminance, or glare conditions. These conditions can affect quality of life, mobility such as walking in dim light or driving at night, in fog, or heavy rain, and can increase falls, with older adults being disproportionally affected. This type of knowledge may provide additional information for the clinician to help decide when a patient needs to have their cataracts removed.

In western countries, indications for cataract surgery are changing with more patients being operated on at younger ages and with better visual acuities.[20–23] Data collected by the Swedish National Cataract Register have shown that the median visual acuity of the eye planned for surgery increased from 0.1 in 1992 to 0.4 decimal (0.4 logMAR) in 2009.[20] Despite this, a recent systematic review and meta-analysis revealed an existing lack of scientific evidence to guide the clinician in deciding when to offer cataract surgery to an individual patient.[21] Several studies have shown that, besides visual acuity, contrast sensitivity,[24,25] contrast acuity,[26] disability glare,[25] and straylight[24,27,28] should be considered in patient selection for cataract surgery. Recently, it was reported that high-contrast visual acuity, straylight, and disk halo radius discriminated well between normal and cataractous eyes, and that among these factors disk halo radius showed the better diagnostic capacity.[29]

In this study, we determined the extent to which forward light scatter (early cataract simulation) and blur (uncorrected refractive error simulation) could affect low-contrast vision and the size of a disk halo induced by an external glare source. These effects were modeled through simulations in young eyes with optimal visual acuity to minimize the confounding effects of age.

METHODS

Subjects

The study was conducted at the Faculty of Optics and Optometry, Universidad Complutense de Madrid, Spain. The subjects enrolled were 25 healthy young students of mean age 21.8 ± 3.0 years (range 20–30) with a mean spherical equivalent of -0.33 ± 1.05D. Measurements were made in one eye only and the eye with the best visual acuity was selected. In each eye, we determined visual acuity and subjective refraction and conducted a slit-lamp and ophthalmoscope examination. Inclusion criteria were a best-corrected distance visual acuity of at least 20/20, a refractive error no greater than ± 3.00D sphere or ± 1.50D cylinder, and a normal ophthalmologic examination result. Subjects were excluded if they had a systemic or eye disease or had undergone refractive surgery.

The study protocol adhered to the guidelines of the Declaration of Helsinki and was approved by our institution's review board. Subjects were informed about the study protocol before giving their written consent to participate.

Inducing Forward Light Scatter and Refractive Blur-Inducing Forward Light Scatter and Refractive Blur

Test measurements were performed with the subjects wearing their best distance correction (if needed) under different conditions: (1) baseline or normal, (2) forward light scatter, and (3) refractive blur. Forward light scatter was induced by placing a light scattering filter in front of the eye during the tests, as described elsewhere.[30] The filter used was Black ProMist 2 (Tiffen, Hauppauge, NY) reported to best simulate forward light scatter in early cataract.[30] Induced forward light scatter was confirmed by measuring straylight using a C-Quant straylight meter (Oculus Optikgeräte, Wetzlar, Germany) as previously described,[31] with the scatter filter inserted in the instrument. Straylight increased with induced forward light scatter in all eyes [mean increase of 0.51 ± 0.14 log (s); $P < .0001$].

Monocular refractive blur was induced with a spherical +1.00 diopter (D) lens to simulate an uncorrected refractive error defined as at least a 2-line improvement in visual acuity after correction.[9] A 2-line improvement in visual acuity has been recently defined in a meta-analysis of indications for cataract surgery as the benefit offered by cataract surgery.[21] The lowest refractive power needed for a mean change of 2 lines in high-contrast visual acuity is +1.00D.[16] Moreover, the legal requirement for a driver's license in Europe is 0.3 logMAR. We therefore selected a +1.00D lens to simulate a visual acuity level close to this basic requirement.

Forward light scatter and blur induced conditions consisted of each participant's baseline refractive correction plus either the light scattering filter or defocusing lens. The order of testing under each condition was randomized.

Disk Halo Size

Disk halo size was measured in a dark room using the Vision Monitor (MonCv3; Metrovision, France). This clinical psychophysical test has been described in detail elsewhere.[32] The right glare source was used to test right eyes and the left source to test left eyes. For the present purposes, the test was performed using a letter luminance level of 5 cd/m^2. Optotypes on the monitor screen are arranged in three radial lines of letters emerging from the periphery toward the glare source. Each line contains 10 letters forming 10 rings at intervals of 33 arc min at a distance of 2.5 m. Each letter corresponds to a visual acuity of 20/60 (0.48 logMAR). After 5 minutes of dark adaptation, the subject was encouraged to read the optotypes from the periphery toward the glare source until a letter could not be identified. Letters not identified in each line were recorded, and the test result was calculated as the average distance from the glare source for the 3 lines. This distance was taken as the disk halo radius and expressed as its angle in log arc min.

Visual Function

Best-corrected distance visual acuity was measured monocularly using high-contrast (96%) and low-contrast (10%) logMAR letter charts under photopic (85 cd/m^2) luminance conditions at a distance of 4 m. Subjects were encouraged to guess letters, even if they were unsure, though testing was stopped when four mistakes in a row were made. Scoring was letter by letter. Thus, each letter read correctly on each line was given a score of 0.02 log units. In these charts, a loss of one line of letters corresponds to a logMAR increase in visual acuity of 0.1.

Contrast sensitivity at low spatial frequency (close to 1 c/deg) was determined at 1 m using the Pelli-Robson letter chart (Clement Clarke International, UK). Contrast in each successive triplet of

TABLE 1.

Mean values of halo radius (log min arc), high-contrast visual acuity (HCVA) and low-contrast visual acuity (LCVA) (log MAR), and contrast sensitivity (CS) (log units) determined in normal, forward light scatter (FLS), or refractive blur test conditions; mean ± SD (max, min)

	Normal	FLS	Blur
Halo radius	1.98 ± 0.12 (1.82, 2.19)	2.31 ± 0.07 (2.16, 2.46)	2.38 ± 0.18 (1.99, 2.58)
HCVA	−0.06 ± 0.05 (−0.14, 0.04)	0.01 ± 0.07 (−0.10, 0.14)	0.26 ± 0.15 (0.00, 0.54)
LCVA	0.03 ± 0.06 (−0.10, 0.12)	0.16 ± 0.10 (0.00, 0.36)	0.42 ± 0.16 (0.06, 0.64)
CS	1.96 ± 0.03 (1.95, 2.10)	1.79 ± 0.13 (1.65, 1.95)	1.82 ± 0.12 (1.65, 1.95)

letters decreases by a factor of 0.15 log units. The value noted was the log contrast sensitivity of the last triplet in which at least two letters were seen correctly.

Disk halo size, visual acuity, and contrast sensitivity were determined with best spectacle correction. Tests were performed using a trial frame with the spherocylindrical correction lens (if needed) and the forward light scatter filter or defocus lens.

Statistical Analysis

Statistical tests were performed using the software package SPSS for Windows, version 15.00 (SPSS Inc., Chicago, IL). The normal distribution of data was confirmed by the Shapiro-Wilk test. A series of one-way repeated measures ANOVA was conducted examining the effect of one within-subject factor (normal, FSL, or blur test condition) on disk halo radius, high-contrast visual acuity, low-contrast visual acuity, and contrast sensitivity. We used the Greenhouse-Geisser adjustment method to correct for departures from sphericity when necessary and the Bonferroni procedure for post hoc testing.

According to a priori power calculations, for a critical P value of 0.05, the minimum sample size was 23 subjects. This would be sufficient to detect statistical significance for an anticipated mean halo radius difference of 0.1 log arc min and mean low-contrast visual acuity difference of 0.06 logMAR (three letters of visual acuity) between testing conditions. This calculation was based on assumptions of an overall variability of 0.06 log units and power of 0.90.

RESULTS

Table 1 provides the mean straylight, halo radius, high-contrast visual acuity and low-contrast visual acuity (logMAR), and contrast sensitivity (log units) values recorded under the three test conditions: normal, forward light scatter, and refractive blur. Significant effects of the test condition (normal, forward light scatter, or refractive blur) were produced on halo size (F = 86.65; P < .0001), high-contrast visual acuity (F = 93.48; P < .0001), low-contrast visual acuity (F = 114.56; P < .0001), and contrast sensitivity (F = 31.73; P < .001).

Fig. 1 shows the box plots of halo radius (log arc min) recorded under normal, forward light scatter, or refractive blur testing conditions. Mean increases from baseline were produced in halo radius in conditions of induced forward light scatter (0.32 ± 0.10 log arc min;

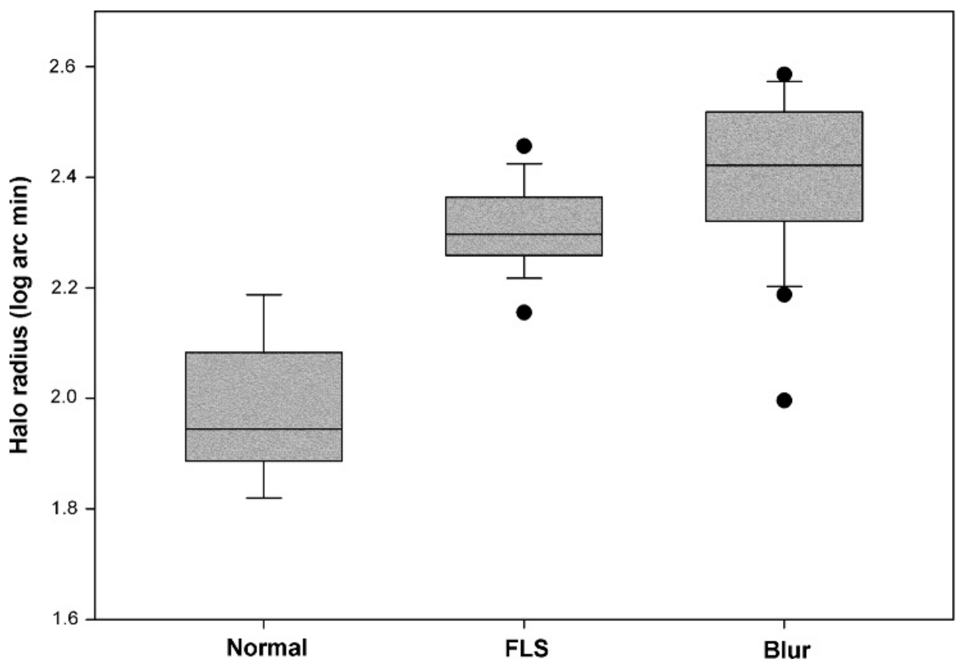

FIGURE 1.

Box plots of halo radius (log arc min) recorded under normal, forward light scatter (FLS), or refractive blur testing conditions. The boxes represent the interquartile range (Q25–Q75) around the median (horizontal line) and minimum and maximum values.

$P < .0001$) and refractive blur (0.40 ± 0.18 log arc min; $P < .0001$). However, mean halo radius did not vary significantly (dif 0.07 ± 0.19, p = NS) when measured with the scatter filter or defocus lens.

Compared with baseline values, forward light scatter led to a mean worsening of high-contrast visual acuity by 3 letters or 0.07 ± 0.05 logMAR ($P < .0001$) whereas mean low-contrast visual acuity was worse by 1 line and 1 letter, or 0.13 ± 0.10 logMAR ($P < .0001$). Using the defocus lens, mean high-contrast visual acuity was 0.32 ± 0.15 logMAR ($P < .0001$) worse and low-contrast visual acuity was 0.39 ± 0.16 logMAR ($P < .0001$) worse (Fig. 2). The mean changes produced in high-contrast visual acuity and low-contrast visual acuity were significantly greater in response to blur than forward light scatter. Mean differences in these changes between conditions of blur and forward light scatter were 0.25 ± 0.14 logMAR ($P < .0001$) for high-contrast visual acuity and 0.27 ± 0.14 logMAR ($P < .0001$) for low-contrast visual acuity.

Compared to baseline values, mean contrast sensitivity reductions of 0.17 ± 0.12 ($P < .0001$) and 0.14 ± 0.12 log units ($P < .0001$) were produced in response to forward light scatter and refractive blur, respectively (approximately 1 triplet). These reductions were not significantly different between them.

DISCUSSION

The findings of this study indicate that the forward light scatter typical of early cataract and low levels of refractive blur have detrimental effects on vision and on the size of the disk halo induced by a glare source. It was observed here that blur and forward light scatter similarly worsened halo size and contrast sensitivity, and that blur worsened high-contrast visual acuity and low-contrast visual acuity to a greater extent than forward light scatter. In turn, forward light scatter only had a minimal effect on best-corrected high-contrast visual acuity but worsened best-corrected low-contrast visual acuity by more than 1 line.

The light scatter induced in the participants of our study was approximately the same as that experienced by early cataract patients.[30] However, the forward light scatter induced by the filter used here is likely to be more homogeneous than that produced by the crystalline lens with its refractive index irregularities or high-order aberrations. The refractive blur induced in the study subjects of +1.00D to simulate uncorrected refractive error[9] gave rise to a visual acuity that was ≥2 lines worse in most of the eyes examined (80%, 20 eyes).

Previously, we reported a coefficient of repeatability for halo radius measurements of 44 arc min[32] corresponding to ±0.19 log arc min (this value was derived from transforming the raw data[32] in log arc min and then the coefficient of repeatability was calculated). This means that a change in halo size of more than 0.19 log arc min between visits can be considered clinically significant. Moreover, in a previous study, we found that disk halo radius values were 0.3 log arc min higher in the cataract group than in the control group. The mean disk halo radius (2.40 log arc min) in these patients with age-related cataract is similar to the mean values found here for both simulations,[29] and all these values are also close to the reported disk halo radius cutoff (2.30 log arc min) showing a high sensitivity to diagnose cataract.[29] The mean changes in halo radius produced in the present conditions of induced forward light scatter and refractive blur were 0.32 and 0.40 log arc min (approximately 3 rings, clinically significant), respectively. These similar responses are in line with previous observations of significant correlation between disk halo radius and straylight or mesopic low-contrast visual acuity in normal eyes with best correction.[33] Hence, the linear contributions of forward light scatter (straylight) and wavefront aberrations (blur) to halo size seem to be of similar proportions. Consistently, wavefront

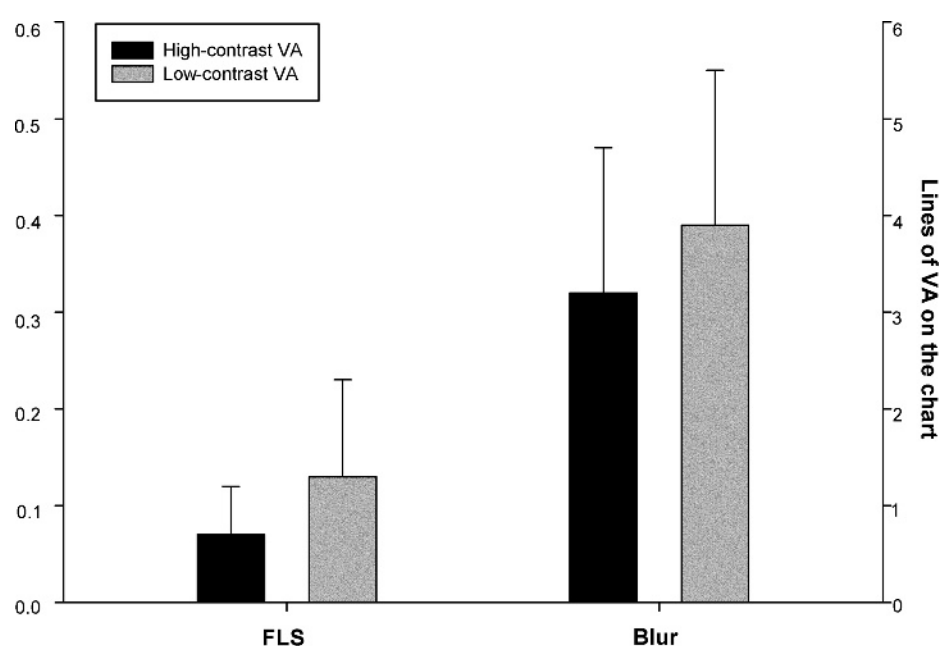

FIGURE 2.

Mean changes (worsening) produced in high-contrast visual acuity (HCVA) and low-contrast visual acuity (LCVA) in conditions of forward light scatter (FLS) and blur compared with normal conditions (baseline). Mean and standard deviation visual acuity differences are plotted as logarithms of the minimum angle of resolution (logMAR units) on the left Y-axis and as numbers of lines on the chart on the right Y-axis.

aberrations are known to affect mesopic low-contrast visual acuity.[34] Moreover, the mean disk halo radius obtained here can be deduced from the linear regression equation reported previously[33] (halo radius against photopic visual acuity) using the mean high-contrast visual acuity and low-contrast visual acuity values obtained under both simulation conditions.

Our forward light scatter filter induced little change in high-contrast visual acuity, as observed in other studies,[13,17,35] and an average high-contrast visual acuity of 20/20 was recorded for this simulated effect of early cataract. Straylight is thought to be fairly independent of high-contrast visual acuity.[14,36] Effectively, it has been established that visual acuity is determined by the central peak of the point-spread function of the light distribution of the retinal image, which is mainly degraded by wavefront aberrations,[37] whereas forward light scatter affects point-spread function skirts more.[14] Greater reductions in visual acuity with diffusive blur have been reported for medium- and low-contrast acuity charts than for high-contrast charts.[15] The worsened distance monocular low-contrast visual acuity induced here by forward light scatter of approximately 1 line is in agreement with the findings of a study simulating forward light scatter after endothelial keratoplasty.[35] More dramatic changes in binocular low-contrast visual acuity measured at 1 m have been reported for the use of Vistech light-scattering goggles simulating the effects of a dense cataract.[13] In age-related cataract patients, the contrast-dependent effect of cataract on contrast acuity was found to be significant, supporting the clinical relevance of recording visual acuity at low-contrast levels in these patients.[26]

In our study, refractive blur gave rise to worsened high-contrast visual acuity and low-contrast visual acuity by 3 and 4 lines, respectively. These changes are in line with those described for a dioptric blur of 1.0D in one study[16] but smaller than the changes detected in another study using projections of slide-type charts from photographs of the original chart.[15] The change in visual acuity induced by up to 3.0D of refractive blur was basically linear in both studies. Low-contrast acuity targets have been described as more greatly affected by small amounts of blur than high-contrast targets.[15,16] Bearing in mind that the driving standard is usually around 0.3 logMAR, this high-contrast visual acuity was achieved under conditions of induced forward light scatter in all subjects, yet in 11 subjects (44%), high-contrast visual acuity was lower than this value when tested under conditions of blur induced by a +1.00D lens. A greater reduction in visual acuity is observed in response to refractive defocus than to diffusive blur.[15] It seems that a relatively small amount of uncorrected refractive error will significantly reduce visual acuity and even further compromise an individual's ability to perform low-contrast tasks. Indeed, our simulation of uncorrected refractive error produced changes in visual acuity that were 4.5- and 3-fold those produced by forward light scatter. However, it should be noted that based on our findings, in conditions of best spectacle correction, a low-contrast visual acuity worsened by more than 1 line would be indicative of the presence of forward light scatter.

The slight mean decrease (1 triplet of letters) in contrast sensitivity detected in the present study was similar in conditions of early cataract (forward light scatter) and uncorrected refractive error (blur) simulation. It is known that low spatial frequency contrast sensitivity is relatively unaffected by small amounts of refractive blur.[38] In contrast, in studies using frosted lenses[18] or Vistech goggles[13,17] to simulate dense cataract, substantial effects were detected on Pelli-Robson contrast sensitivity (4 and 6 triplets of letters).

There is scarce scientific data to help the clinician decide which patients are most likely to benefit from cataract surgery. Timing of cataract surgery is complex and, as highlighted in a recent meta-analysis, the outcome of cataract surgery is unrelated to preoperative visual acuity.[21] According to 5-year trends in three large cataract surgery databases for three different countries, late surgery on an eye with poor visual acuity means an increased risk of complications, whereas early surgery on an eye with excellent preoperative visual acuity could mean an increased risk of poorer visual acuity.[22] The results of the present study in which amounts of refractive blur or forward light scatter observed in older individuals with early or mild cataract were simulated may help identify candidates for cataract extraction. Thus, apart from visual acuity, both low-contrast visual acuity and disk halo measurements may provide clinically relevant information for the clinician.

In conclusion, forward light scatter and refractive blur should be considered when reduced visual function is reported under conditions of low contrast and glare. The contribution of forward light scatter and blur to disk halo radius measured using the Vision Monitor MonCv3 seems to be of similar proportion for both parameters. Although defocus blur has a substantial effect on low-contrast visual acuity, a loss of more than 1 line of low-contrast visual acuity after best refractive correction would be indicative of increased forward light scatter. In a clinical context, we propose a 0.3 log arc min increase in disk halo radius, a 0.15 log unit decrease in contrast sensitivity, and a loss of more than 1 line of low-contrast visual acuity, all measured with the best spectacle correction, should be considered as indications for cataract surgery. To help prevent impaired vision, the refractive and cataract status of especially older persons should be regularly checked and updated or treated accordingly.

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María Cinta Puell
Faculty of Optics and Optometry
Universidad Complutense de Madrid
Av. Arcos de Jalón 118
Madrid 28037, Spain
e-mail: puellma@ucm.es