Optical Instrument for the Study of Time Recovery from Total Disability Glare Vision

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Disability glare is defined as the loss of contrast sensitivity of the retinal image due to intraocular straylight originated from the presence of an intense and broad bright light in the field of vision. This loss of vision can range between loss of vision at high spatial frequencies or total temporal blindness. If the extreme case occurs, the recovery time is crucial in night driving conditions or those professional activities in which the maximum visual acuity is required at any moment. The recovery time depends mainly on the intensity and glare angle of the light source, ocular straylight and the photoreceptor response at the retina. The recovery time can be also affected by ocular pathologies, aging or physiological factors that increase ocular straylight. The aim of this work was on the one hand, to develop a new optical instrument based on psychophysical methodology, and on the other hand to investigate the recovery time from total disability glare (photo-bleaching) as a function of the contrast of the visual target the glare angle of the source in healthy volunteers. Result showed significant exponential correlation between recovery time and contrast of the visual target and linear correlation between contrast sensitivity and the glare angle. Those finding allowed to obtain an empirical expression to compute the recovery time required to restore the contrast sensitivity baseline vision after photo bleaching. Finally, a statistical dependence of the recovery time with age was found for shorts glare angles that disappears as the glare angle increases.

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1. INTRODUCTION

Transmission of light through clear ocular media is crucial for normal vision [1]. Imperfections of ocular media such as tear film [2] disorder, vitreous turbidity, cataracts, corneal opacifications [3] or post-operative complications of implanted of intraocular lenses [4] can lead to light scattering that generates glare vision. This phenomenon known as ocular straylight, causes retinal haze and compromises both retinal contrast sensitivity and visual acuity [5-7]. Ocular straylight gives rise to a veil of glare or veiling glare that is uniformly superimposed on the retinal visual field. Besides the intrinsic straylight sources from refractive ocular structures, retinal fundus reflectance contributes to ocular straylight [8] and depends on the light source, eye pigmentation and age [9-11].

In 1911, Cobb [12] introduced the concept of equivalent veiling luminance (L_{eq}) to define retinal straylight. While ocular straylight does not exceed the threshold at which the retinal contrast is negligible, the equivalent veiling luminance depends on the relative position of the glare source (glare angle, α) with the visual field and the eye itself [13]. In this sense, ocular straylight parameter (S) can be calculated as the multiplication of the squared glare angle of the light source and the relationship between equivalent veiling luminance and the illuminance of the light source (E_{bl}) [14] given by:

$$S = \alpha^2 * (L_{eq}/L_{bl})$$

Ocular straylight can be measured by psychophysical approaches such as the equivalent luminance method [15] or optical (objectives) techniques based on double-pass technology [16]. According to the *International Commission on Illumination* (CIE), straylight and disability glare sensitivity are equivalent concepts [17-19] in the sense that out-of-focus light due to straylight generates the veiling luminance [20], then disability glare corresponds to the equivalent luminance caused by ocular straylight when a glare source is intercepting the visual field at a certain angular distance [18].

Glare vision can be classified into five main categories: disability glare [5], discomfort [21], photostress [22], dazzling [23] and disphotopsia [24].

Total disability glare or photostress occurs when the light entering the eye is intense enough to cause immediate bleaching of the retinal photoreceptors (photo-bleaching) that temporally overrides the visual function without retinal damage [25].
Photostress recovery time was proposed in 1962 by Chilaris [26] as a diagnostic and prognostic test to assess the macular function after retinal photo-bleaching. Since then, recovery time in photostress conditions has been proposed to assess the visual function in glaucoma, chorioretinopathy [27], macular degeneration or diabetic retinopathy patients [28]. In that sense, the Macular Degeneration Detector (MDD-2) [29], Eger macular stressometer (EMS) [30], Scotometer [31] or Brightness Acuity Test [32] devices have been previously developed and reported for the macular photostress recovery time. While those effective systems were focused on finding differences between pathological and control retinas affecting the macular function, our work proposes an optical psychophysical study involving optical properties of the glare source and the contrast of the observed test in healthy subjects.
The aim of this work was to develop a compact optical instrument to investigate the relationship between the recovery time, the glare angle of the light source and the contrast of the visual stimulus in healthy subjects.

2. METHODS

2.1 Participants

This research was reviewed by an independent ethical review board and conforms to the principles and applicable guidelines for the protection of human subjects in biomedical research (Ethical Committee of Research of the Health Sciences Institute of Aragon, Spain) approved with reference: C.P.-C.I.PI20/377. Measurements procedure and data collection were carried-out according to the Thetenets of the Declaration of Helsinki.
All participants were informed about the nature and of the study and signed an informed consent document. The measurements were carried out in 108 eyes of 54 participants (mean age 24.5 ± 6.4 years old). Exclusion criteria consisted of those subjects presenting any ocular pathology including photophobia. The measurements were carried-out at Visual Optics Research Laboratory of the University of Zaragoza (Spain) by an experienced clinical optometrist.

2.2 Total Disability glare vision instrument

Total disability glare instrument incorporates a bright glare source composed of a high power 535 nm LED source. coupled to a holographic light shaping diffuser (Light Shaping Diffusers, Luminit, LLC) that ensures spatially symmetric radial distribution of the light. The reason for choosing this spectrum is based on the dependence of ocular straylight with wavelength and the influence of ocular pigmentation [33]. The spatial (angular) distribution of the glare source was controlled by removable 3D-printed spatial masks designed with fixed outer radius (R_2=20 mm) and different inner radius (R_1) to range the glare angle between 3 and 14-degrees (data shown in Table 1). The luminous intensity of the source was set to provide a maximum illuminance at the pupil plane of 4511 Lux for the largest angular field of the spatial masks (i.e. 14º glare angle) and electronically controlled to modulate a fixed pulse width and total exposure time of 240 milliseconds to produce photo-bleaching.

The maximum photo-bleaching illuminance at the pupil plane was 4511 Lm/m^2 which is well-bellow the maximum permissible according to the American National Standards Institute (ANSI) Z136.1-2000 [34] that corresponds to 6.15 x 10^6 Lm/m^2 for an exposure time of 240 milliseconds. The glare source, visual stimulus and the retinal plane of the subject are conjugated by means of an achromatic doublet lens (f'=100 mm) and a 50:50 beam splitter as shown in Fig. 1. The glare angle is the subtended visual angle of the straylight source by means of the achromatic doublet lens. The visual stimuli were computer generated to subtend visual field of 7º and to provide contrast sensitivity levels corresponding to Michelson contrast values of 5 %, 10 %, 25 %, 50 % and 100 %, respectively. Contrast sensitivity images (shown in Fig.2, first row) were displayed using a smartphone (Samsung Galaxy A32) placed at a distance of the pupil plane equal to the focal length of the achromatic doublet lens. The visual channel optical pathway is coaxial with the glare source as shown in a real picture in Fig.1b. The background illuminance of the visual target (i.e. smartphone screen) was 170 Lm/m^2. The device was mounted on an optical board of 30 x 30 mm dimensions and coupled to a chinrest to ensure subject alignment during measurements.

Table 1 shows the maximum illuminances (E) values measured at the corneal plane corresponding to the different analyzed glare angles. Henceforth, we will refer to increasing angle of glare as increasing amount of straylight. Photometric measurements were carried-out at the exit pupil of the system using a luxometer (PCE-174 model).

Table 1. Glare angle of the glare source, inner radius of the spatial mask, measured illuminance at the pupil plane.

Field	*Inner R_1 (mm)*	*Glare Angle (º)*	*E (Lux)*
#1	2.62	3	1246
#2	4.38	5	2277
#3	6.14	7	3027
#4	9.72	11	4281
#5	12.47	14	4511

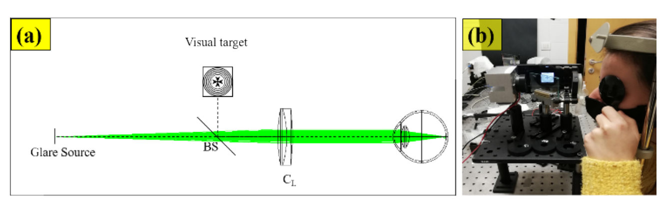

Fig 1. (A): layout of the total disability glare instrument. CL: Collimating lens; BS: Beam splitter. (B): Picture of a volunteer during a measurement session.

2.1 Experimental procedure and data analysis

Total disability glare instrument was designed to produce safely photostress after a short exposure time of 240 milliseconds as a function of the glare angle and contrast sensitivity levels of the visual stimulus. The measurement protocol starts occluding the contralateral eye to be examined and aligning the subject´s pupil by means of an articulated chinrest. Once the subject is aligned with the common optical axis of the glare source the visual stimulus, the ambient illumination is reduced to total darkness and then five minutes were allowed for scotopic adaptation.

The subjects were instructed by the examiner to fix the center of the visual stimulus, to perceive the contrast sensitivity as the visual reference baseline, and then press a bottom once the visual baseline is recovered after the light exposure. The timing starts when the examiner triggers the glare source and stops when the bottom is pressed by the subject after recovering the contrast sensitivity baseline. When one eye is measured, the same configuration is used for the contralateral eye. At the end of each measurement, five minutes waiting ensures total photostress recovery [29, 35]. For every subject, the recovery time was timed for 5 glare angular distributions (glare angles: 3º, 5º, 7º, 11º and 14º) and 4 Michelson´s Contrast levels (5%, 10%, 25 %, 50% and 100 %), the latter modified by remote control.

In this work, the maximum variability of the recovery time for each glare angle is defined as the contrast sensitivity recovery time (CSRT) parameter.
Contrast sensitivity images and retinal imaging simulation were computer-generated and computed using Matlab programming language (Matlab 2019b, The Mathworks Inc., Natick, MA), respectively. Those images generated for visual stimulus were stored in a remotely controlled smartphone. Statistical analysis and graphical representation were performed in Sigmaplot data analysis software (Systat Software, Inc, USA). Non-linear regressions were applied to fit the Recovery Time as a function of Michelson contrast to exponential decay functions. Spearman correlation was used to investigate the relationships between the experimentally fitted parameters and the glare angle, and between the CSTR parameter and glare angle. Finally, age groups (Subsection 3.3) were compared using paired t-test.

3. RESULTS

3.1 Disability glare vision simulation

If an intensely bright light source is present in the visual field, the contrast sensitivity is disrupted due to a superimposed retinal veil of light created by light scattering processes or intraocular straylight. This concept known as glare vision limits the retinal image quality, if the residual contrast sensitivity allows discriminating some spatial frequencies of the scene there exists adaptation glare and therefore visual function information [35]. If straylight is strong enough to turn the retinal contrast into negligible spatial resolution, vision enters the scotomatic glare or total disability glare regime.

This section presents theoretical simulation of retinal contrast sensitivity affected by straylight using non-sequential ray tracing. A model of the human eye based on the Liu Brennan model [36] was created in Zemax optical design software (Zemax OpticStudio, LCC, Arlington Capital Partners, Washington, DC, USA). The optical layout of the optical system coupled to the eye model is shown in Fig. 1. The glare source was simulated according to the experimental description of the total disability glare instrument (Section 2.2).

Fig. 2 shows the generated contrast sensitivity test images (mid row) shown at the subjects for different Michelson contrast levels. Test images were shown at the subject within a field of view corresponding to the maximum glare angle field (Fig.2c). For example, Fig. 2f shows a test image corresponding to 100 % Michelson contrast within a total visual field of 14º. Notice that total disability glare experiment induces temporal scotomatic vision (i.e. negligible contrast sensitivity vision). However, for the sense of understanding how glare vision is perceived, the optical simulations shown at the bottom row of Fig. 2 were carried-out for a fraction of the maximum illuminance of the straylight source and 14º glare angle (see Table 1). Then, glare vision images corresponding to the combined effect of the glare source (straylight) and visual target as viewed by the subject are shown.

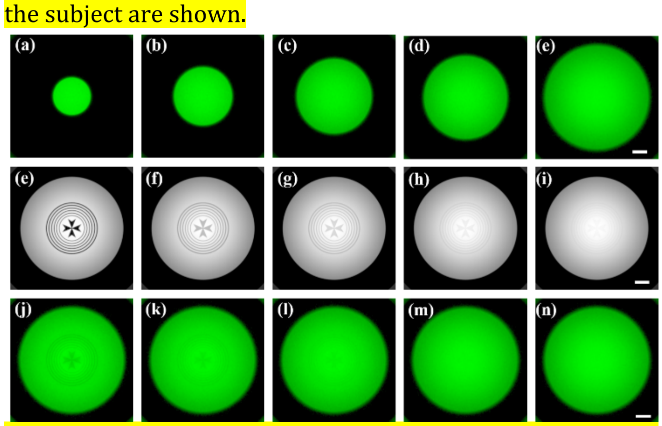

Fig. 2. Straylight source simulated for the glare angles shown in Table 1 (upper row); Contrast sensitivity test images for 100 %, 50 %, 25 %, 10 % and 5 % Michelson contrast levels, respectively (mid row); Simulated retinal images affected by straylight source with 14º glare angle aperture. Scale bar: 2º visual field. Images are shown with auto-scaled gray-level.

Results shown in Fig.2 simulate glare vision while some spatial frequencies can still be discriminated. Notice that for high contrast images, glare angles larger than 7º are required to produce total disability glare, which begins to be evident for mid and lower contrast levels (bottom row). Next subsections are focused on the temporal interval in which the vision recovers the normal vision after being induced total disability glare.

3.2 Recovery time as a function of the glare angle and stimulus contrast

Fig. 3 shows the recovery time (in seconds) for all participating subjects as a function of the contrast level of the observed stimulus and different glare angles.

the common behavior revealed a recovery time decaying as the contrast level of the stimulus increased, that is, for a given glare angle the lower the contrast of the scene the higher the time required to recover the baseline once total disability glare arises. The recovery time values as a function of the contrast were compared using t-test statistical analysis. For all glare angles, the recovery time was found to be statistically dependent on the contrast ($p<0.005$).

Fig. 4 shows the exponential decay function fittings from the data shown in Fig. 3. A statistical analysis (analysis of variance test) revealed significant dependence of the recovery time as a function of the glare angle for all groups with the exception of the responses for 5º and 7º glare angles. Results showed unequivocally that for both low- and high-Michelson contrast levels, the higher the glare angle, the lower the time required to recover the baseline contrast sensitivity vision.

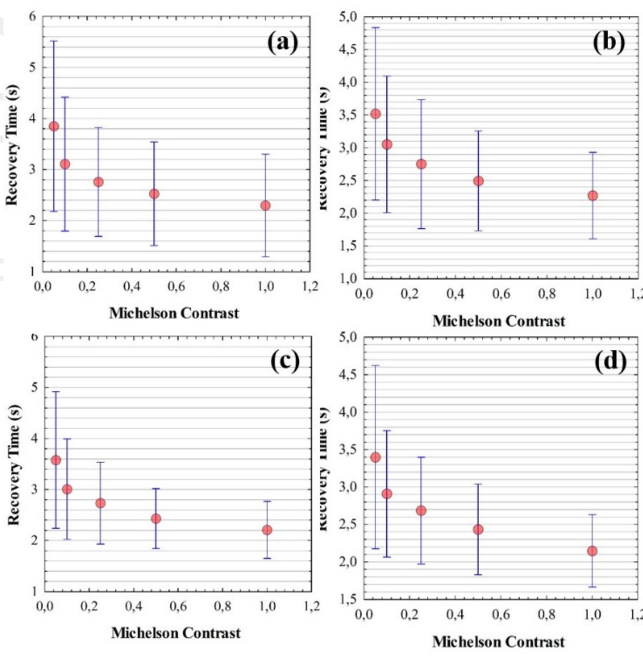

Fig. 3. Mean recovery time for all subjects (i.e. both groups) of the study as a function of the visual target contrast and at 3º (a), 7º (b), 11º (c) and 14º (d) glare angles.

For each glare angle, the exponential decay curves were fitted through the general equation:

$$RT(s) = K_0 + a \cdot e^{-b \cdot Contrast} \quad (1)$$

Where K_0 is an experimental constant (K_0=2.30) and the coefficients a and b being dependents of the glare angle and were extracted from the experimental fitting and plotted in Fig. 5. The statistical analysis revealed significant negative correlation (and within the confidence bands) between coefficients a (R^2=0.78, p=0.02) and b (R^2=0.82, p=0.01) and the glare angle of the source. Then, substituting the fitted correlations of a and b in Eq. (1) an experimental analytical expression to calculate the recovery time as a function of the contrast of the visual stimulus can be expressed as:

$$RT(s) = [2.30 + 2.25 - 0.07 \cdot \alpha(°)] \cdot e\text{^}[-(10.76 - 0.51 \cdot \alpha(\quad (2)$$

Where RT is the recovery time in seconds, α glare angle in degrees and C the Michelson contrast.

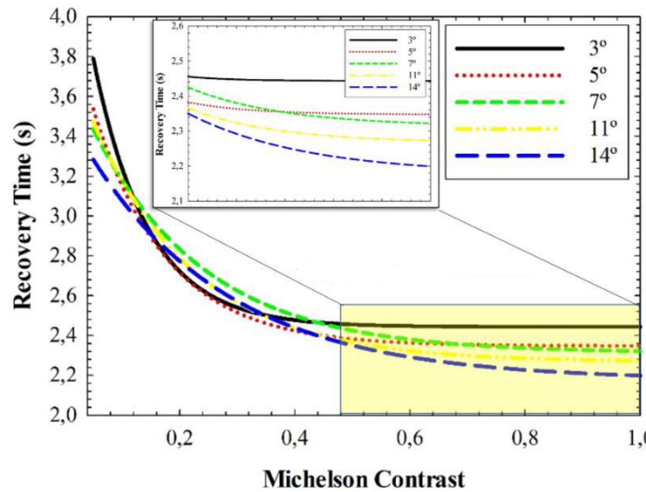

Fig. 4. Exponential decay fittings of the data shown in Fig. 3. The correlation coefficients were: R^2 (3º)= 0.95, p=0.04); R^2 (5º)=0.95, p=0.04; R^2 (7º)=0.95, p=0.03; R^2 (11º)=0.95, p=0.03 and R^2 (14º)=0.96, p=0.03, respectively. Upper plot is a magnification of the yellow shaded region. Graph legend is shown at the right upper corner.

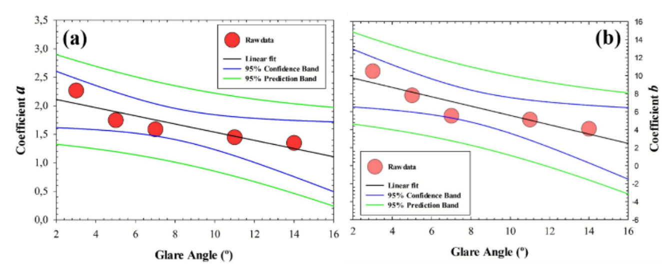

Fig. 5. Coefficients a and b extracted from experimental fitting of the Fig. 4 as a function of the glare angle.

Regarding the contrast sensitivity recovery time (CSRT) defined in Method, Fig. 6 shows the correlation between the CSRT parameter and the glare angle. A statistical analysis revealed that the CSRT parameter decreases as the glare angle increases. That is, the recovery time is significantly longer when the veiling glare density is maximum.

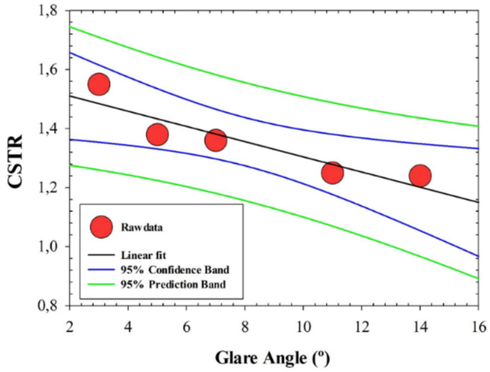

Fig. 6. CSRT as a function of glare angle. The data were mathematically fitted. Spearman correlation results: R^2=0.84; p=0.03.

3.3 Recovery time as a function of age

Healthy subjects present angular and contrast dependence in the recovery time after a photo-bleaching reaction. However, the data that supported those results did not separate between age groups, but just considering the natural temporal responses of recovering after temporal blindness. In that sense, it is well-known the increasing intraocular straylight and lower contrast sensitivity with age [19], therefore it is interesting to analyze the differences between the two age groups defined in Methods.
Fig. 7 shows the recovery time response as a function of the visual contrast test for all glare angles studied in this work (i.e. 3º, 5º, 7º, 11º and 14º glare angles). As shown in Table 1, there was no parity between both age groups. Then, in order to make possible a paired comparison, the group #1 corresponding to young volunteers (mean age 24.5 ± 6.5) was randomly reduced down to 30 eyes from which the average values are shown in Fig. 6. The statistical analysis was carried-out comparing both groups with paired t-test.

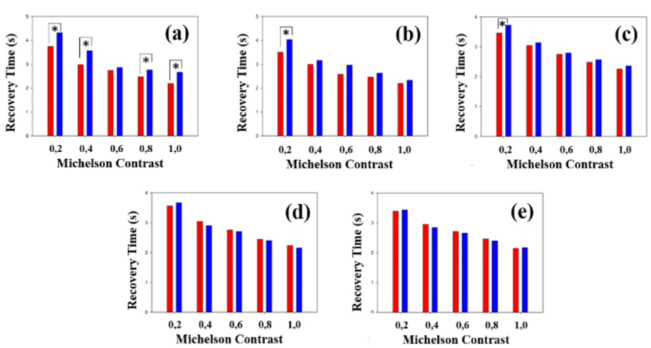

Fig. 7 Comparison of the recovery time between groups #1 (young people, red bars) and #2 (older people, blue bars) as a251 function of visual test contrast for 3º (a), 5º (b), 7º (c), 11º(d) and 14º (e) glare angles. Statistical significance: (*, p <0.05).

Those pairs of groups showing statistical differences were marked with asterisk. Results showed that for small glare angles the recovery time is significantly higher for older people (Fig. 7a) with independence of the visual contrast test with the exception of mid contrast level (50 % Michelson Contrast). For 5º and 7º glare angles, both groups showed significant differences for low-contrast (5% Michelson Contrast) vision only (Figs. 7b and 7c). As the glare angle increases the differences in recovery time between both groups disappears whereas both of them show a lower recovery time as the contrast increases for all glare angles.

3. DISCUSSIONS AND CONCLUSIONS

Glare vision is considered an important shortcoming in driving safety. Since the negative effects can range between difficulties to distinguish low-contrast objects in high ambient light levels and total blinding conditions.
Holladay conducted experiments to study visibility effects caused by a glare source exposition on the luminance discrimination threshold of the eye. His experiments showed that the luminance of the source multiplied by the exposure time was proportional to the recovery time [37]. Irikura et al. [38] found an equation in which the time required to recover half of the visual acuity after exposure to a glare source was proportional to the product of the luminance and the exposure time to the 0.29 power. However other factors such as contrast sensitivity, age or eye pigmentation play an important role in visual function in response to a disability glare phenomenon [10].
This work presents a cost-effective and ultra-compact optical system for the study of total disability glare as a function of the glare angle and the contrast of the visual stimulus. The visual perception and contrast sensitivity of the subject were employed as the baseline reference.
The recovery time was timed until the visual perception got back the baseline.

On the one hand, the recovery time significantly depends on the visual contrast test which distribution can be statistically fitted to an exponential decay function which parameters also depends on the glare angle. For a given glare angle, the lower the contrast of the scene, the higher the required time to recover the baseline contrast sensitivity vision. Those experimental results allowed to obtain an empirical expression to calculate the recovery time as a function of the glare angle and the contrast sensitivity.

On the other hand, this recovery time is also a function of the glare angle, that is, the larger the illuminated retinal field (higher glare angle) the shorter the required time to recover the baseline vision. This fact can be explained by the veiling glare density, even though the equivalent retinal luminance is supposed to be uniform across the angular field, the equivalence luminance o veiling glare density is maximum when the glare flash is projected on the central retina (3º glare angle) which is consistent with the Stiles-Holladay veiling glare general formula.

Finally, the comparison of two age groups revealed an increasing in the recovery time with age, in agreement with the reported dependence of disability glare with age [9, 10, 14, 39]. However, the influence of age in the recovery time was found to be statistically significant for shorter glare angles, being reduced (between two age groups) as the glare angle increased. This can be explained through the relationship between the recovery of sensitivity and visual pigment regeneration in cone vision [40, 41] and considering that macular pigment density decrease with increasing age [42].

To conclude, we found that total disability glare vision depends on contrast sensitivity. Time recovery after photo-bleaching also depends on the angular distribution of the straylight source that generates veiling glare luminance. This time required to recover contrast sensitivity baseline vision is larger in older people with statistical significance at shorter glare angles.

Future work will include deep analysis of all types of glare vision to explore those factors that characterize adaptation to glare and to study the dynamics of ocular straylight and its real impact in the contrast sensitivity vision.

Disclosures

The authors declare no conflicts of interest.

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Data availability. Data underlying the results presented in this paper are available upon request.

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