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Evaluation of the intraocular scattering through brightness reduction by glare using external diffusers to simulate cataracts

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In this work, we evaluate the feasibility to determine the intraocular scattering by measuring the brightness reduction by glare. A haploscopic system based on the brightness comparison has been developed. This system allows to compare the brightness of a test with a steady glare source in the field of vision, and another one without it. Our goal is to study the sensibility of the proposed methodology to quantify the intraocular scattering. In this first approach, we use physically and psychophysically characterized external diffusers to simulate different degrees of cataracts. The results have been shown in terms of the glare index. This index increases as the level of filter scattering rises, and even more when the diffuser is set up on only one eye. Besides, the system allows to discriminate among slightly different levels of scattering. The repeatability of the results and the resistance to fraud of the methodology have been analyzed.

Keywords: brightness, glare, intraocular scattering.

1. Introduction

The light coming into the eye is scattered by different ocular media producing straylight that affects the quality of the image on the retina. This effect becomes important for patients who have developed cataracts as well as for those who have undergone refractive surgery [1]. Besides, the aging produces a progressive impairment in the ocular media revealing an increase in the intraocular scattering. Cataracts could be a consequence of either an alteration in the fiber structure or an abnormal aggregation of proteins in the lens [2]. In both cases there is a proliferation of inhomogeneous particles, which increases the intraocular scattering projecting a veil of light over the retinal image which is degraded. The intraocular scattering is much stronger when there are intense light sources in the visual field – disability glare. The effect of glare on the visual functions has been especially studied through the contrast threshold changes [3]. The veil produced by the presence of glaring sources is added to the retinal image reducing the effective contrast. One of the first works in this field [4] arrived at the empirical model that accounts for this effect in terms of the veiling luminance L_v

$$L_v = \frac{kE}{\theta^2} \tag{1}$$

where E is the illuminance produced by the glaring source at the subject cornea, in lux, θ is the eccentricity of the light source expressed in degrees and k is a constant. This equation has a validity range from 1° to 30° and it is valid for people up to 40 years old when using $k = 10$. The deviations of the normal values of k reflect individual variations in each subject [5] depending on factors such as age and iris pigmentation [6]. The equation for disability glare [7] finally adopted by the CIE (Commission Internationale de l'Éclairage) for the same angle range and taking into account the age effect is:

$$L_v = \frac{kE}{\theta^2}\left[1 + \left(\frac{\text{Age}}{70}\right)^4\right] \tag{2}$$

with $k = 10$.

Another way of quantifying the intraocular scattering is by determining the optical quality of the human eye by means of the point spread function (PSF) [8], in which the pedestal of this function has a direct correspondence with the L_v/E value of the luminance veil equation [9, 10].

This work is based on previous investigations about the glare effect on the brightness of a test. The first results were obtained by way of an experimental arrangement based on haploscopic vision with steady glare [12, 13]. In the past years, Colombo and her colleagues developed a methodology that allows the study of the transient glare effect displaying the stimuli in a sequential way [14–16]. All these works showed an effect of brightness reduction in foveally seen stimuli. Though the model of veil luminance was developed based on glare effects on the contrast threshold, FRY and ALPERN [13] suggested that the same veil could be the cause of brightness reduction. Taking into account this hypothesis as well as their own data of brightness reduction, they arrived at the following expression similar to (1)

$$L_v = \frac{69.8\,E}{\theta^{2.5}} \tag{3}$$

Even though it is well known that brightness perception depends on both the retinal illuminance and the retinal and cortical processes [17–19], it has been shown that the glare effect on brightness perception could be associated to the veiling luminance when the stimulus is an increment and the surround is dark [14, 20]. If the equation for disability glare of the CIE could be applied to brightness reduction, then the evaluation of this reduction could account for an increase in the intraocular scattering. We consider the use of a measurement based on the brightness comparison very valuable, since this measurement is more connected with daily life than threshold conditions. This is why this kind of measurement could be a good indicator of the real effect on perception of dazzling scene.

Our aim is to find out if the phenomenon of brightness reduction by glare could be sensitive enough to quantify the intraocular scattering. In order to achieve this, a haploscopic version of the previous system [14–16] has been used. This version of the system allows us to measure this phenomenon using steady glare. Due to the variety of kinds and densities of the cataracts, it is difficult to establish a controlled scale. This is why in this first approach we use external diffusive filters to simulate the different degrees of cataracts. First, the filters were characterized physically and psychophysically. Then, a group of observers were evaluated in order to determine whether the developed methodology of brightness comparison (BCM) allowed the discrimination among the different conditions evaluated.

1.1. Physical and psychophysical characterization of filters

In order to find filters that simulate the scattering of early and advanced cataracts, a preliminary experiment was done. It was about physical and psychophysical characterization of commercial filters: BPM1 and BPM2, which are usually used for photography, and Lee 258 and Cinegel3020 (C3020) of Rosco, which are generally used for illumination. We measured the scattering profile of these filters – the point spread function (PSF), the visual acuity (VA) and the contrast sensitivity (CS) of people wearing those filters [21].

1.1.1. Physical characterization

In order to measure the PSF, a scatter meter was used to measure the intensity of light spread as a function of the angle between its propagation direction and the propagation direction of the incidental beam [22] (Fig. 1). This system has a HeNe laser of 5 mW

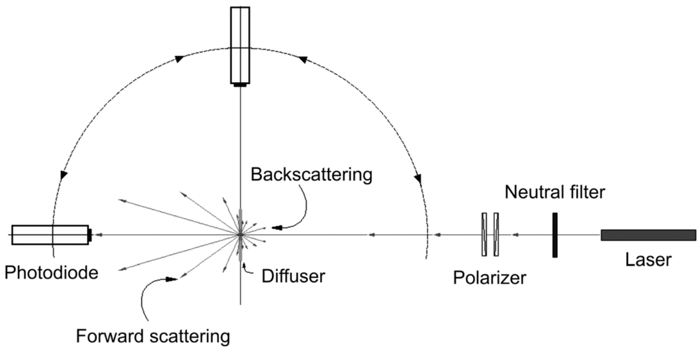

Fig. 1. Experimental layout used for physical characterization of diffuser filters.

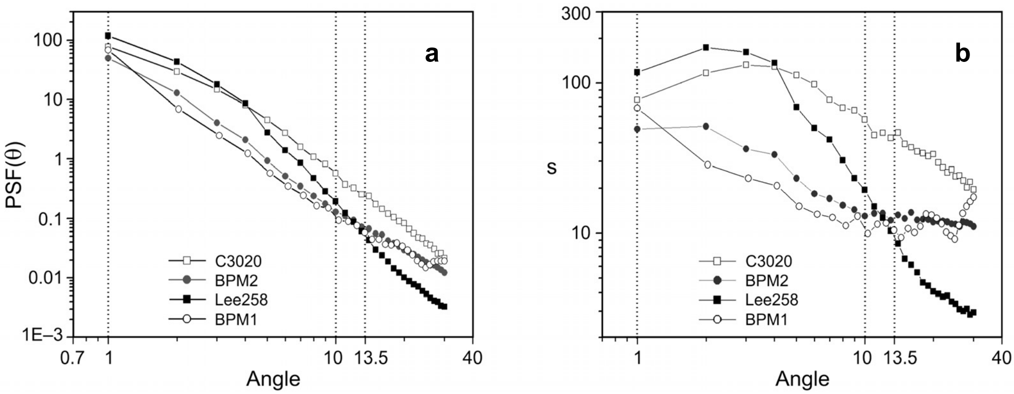

Fig. 2. The point spread function (PSF) as a function of the angle, for all the filters used (**a**). Values calculated of the straylight factor S as a function of the angle (**b**).

as a source and a Spindler & Hoyer photodiode type E2V as a sensor. The highest intensity applied to the sample was regulated by means of a neutral density filter and two polarizers.

In the optical system, the laser source and the filter remain in the same position during all the experiment, in such a way that the beam of light is perpendicular to the surface of the filter. The sensor can be placed on different angular positions in order to measure the scattered light. The measurements were made from 1° to 30°.

Once the PSF of each filter was obtained, the straylight value S was computed as:

$$S = \mathrm{PSF}\ \theta^2 \tag{4}$$

In Figure 2**a**, the PSF of the filters evaluated can be seen, and in Fig. 2**b**, the function S of these filters is shown. The slopes of the fitted straight lines between 3° and 30° are: –2.89 for C3020, –2.43 for BPM2, –2.15 for BPM1 and –3.92 for Lee258 (Fig. 2**a**). It is known that the variation of S as a function of θ is similar to any kind of cataracts with a slope of –2.12 [11, 21], approximately. As the filter Lee258 deviates from the normal pattern of cataracts, it was discarded.

The transmittance was also measured at 0° for the four filters tested (Tab. 1). As a result, values higher than 60% were found in accordance with other studies [21].

Table 1. Transmittances of the evaluated filters.

Diffuser	Transmittance
BPM1	0.706±0.003
BPM2	0.648±0.012
Lee258	0.934±0.008
C3020	0.879±0.006

1.1.2. Psychophysical characterization

In order to test the psychophysical behavior of the filters as cataract simulators, we quantified their effects by means of the compensation comparison method [23], based on the direct compensation method [24] that has a good performance to be compared with other glare testers [25]. In this work, we adopted a commercial version of this system that is used for clinical applications (C-QUANT by Oculus). Ten observers from 22 to 37 years old, with normal or corrected vision, participated in the experiment. The monocular measurements were performed with BPM1, BPM2 and C3020 filters for both eyes. In addition, a measurement without a filter was carried out for the eyes of all the subjects. Figure 3 shows the average of the log of the stray light parameter ($\log S$) for each diffuser.

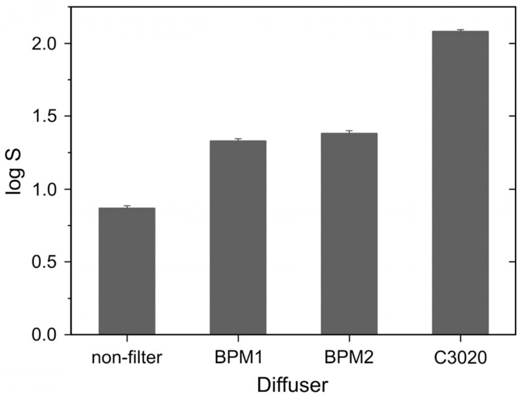

Fig. 3. Measurement average of $\log(S)$ for 4 degrees of scattering.

In order to analyze the results, an ANOVA and the post Tukey test were performed. The ANOVA reveals that at least one of the levels is significantly different from the others ($p < 0.05$). Then, the Tukey test shows that the means obtained with the BPM1 and BPM2 filters are not different ($p > 0.05$), but they are different from the means obtained without a filter and with C3020 filter ($p < 0.05$). Despite the distinction made by DE WIT *et al.* [21] between BPM1 and BPM2, we find out that they may be used indistinguishable.

After this, the reduction of the VA and the CS was measured. For BPM1 there is data from the literature [21] showing that there is no reduction in the VA and only 5% reduction in the mean CS, without specifying the spatial frequencies evaluated. For C3020 we carried out the measurements on our own. 16 eyes were measured to determine the loss of VA and a 52% loss was found. 9 eyes were measured to determine the loss of CS for spatial frequencies of 1, 2, 4, 8, 12 and 24 c/deg with our own computerized system [26]. Remarkable reductions of CS – from 60% for 1 c/deg up to 84% for 2 c/deg, with a mean fall of 75% – were found. The smallest reduction of VA and CS found with the BPM1 filter goes with the measurements done in eyes with early cataracts [27]. However, the values found for the filter C3020 were lower than the highest values found when diagnosing a cataract [28]. Taking into account all our measurements as well as previous results, we decided to use the BPM1 as a simulator of early cataracts and the C3020 as a simulator of more advanced ones.

2. Methods

2.1. Apparatus and stimuli

The stimulus consisted of two semicircles slightly separated. In order to simultaneously compare the brightness of these two fields, we developed a haploscopic configuration as FRY and ALPERN [13] and SCHOUTEN and ORNSTEIN [12] did in their studies. In this haploscopic layout, a mask was placed at a proper distance from the eyes so that each eye looked only at one of the two semicircles (Fig. 4), which are seen as parts of only one circle. The distance between the stimuli and the eyes of the observer was 55 cm. The experiment was done with the head of the subject placed on a chin rest.

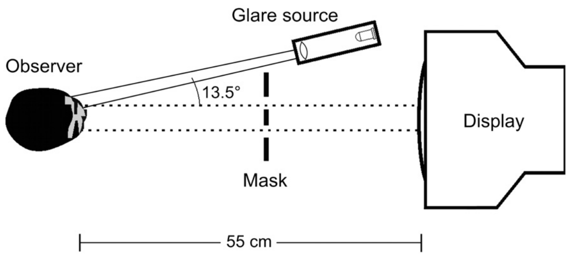

Fig. 4. Experimental set up.

The stimuli were presented on a 19" Samsung SyncMaster 955DF TRC monitor electronically modified for having a high gray level resolution [26]. The display was programmed on Matlab using the psychophysics toolbox [29, 30].

The stimuli were achromatic and each semicircle subtended an angle of 5.6°. The luminance of one of the semicircles was 10 cd/m^2 – the reference stimulus (Rs) – and it was seen by the eye that was being evaluated. The luminance of the other semicircle – the comparison stimulus (Cs) – could hold values in a range of 0.01–89 cd/m^2 and it was seen by the other eye. The luminance of the surround was 0.04 cd/m^2. Two little circles were added to the stimuli in the nasal position to facilitate

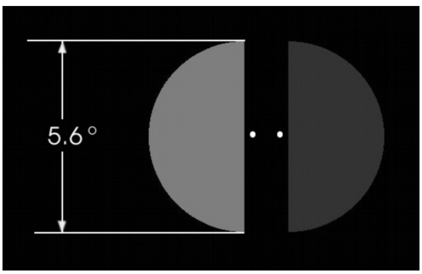

Fig. 5. Stimuli used.

the stereoscopic fusion, avoiding an overlap between the semicircles and achieving the stabilization of the stimuli (Fig. 5).

2.2. Glare

An eccentrically placed glare source illuminated the eye that looked at the reference stimulus – "the evaluated eye". This source was placed at 13.5 temporal degrees. The illuminance of 40 lux measured on the cornea was obtained. In order to avoid glare beams falling on the optic disk, the position of the source was 5° above the horizontal plane that contained the foveal line. The glare source was a LED. When we used a single white LED, the subjects reported a chromatic induction effect on Rs while Cs was perceived as achromatic. This chromatic difference between the fields prevented the brightness comparison from being done in an appropriate way. Therefore, we used a tricolor LED which contained red, blue and green components in a single 5 mm package. As the intensity of the three components could be independently manipulated, we managed to minimize the color effect and compensate the color induction.

2.3. Procedure

We developed a procedure to get the luminance of the Cs that matches the brightness of the Rs: the matching luminance L_m. The procedure consisted of two steps: the first one was a coarse adjustment to find the range for L_m, and the second one was a fine process to determine the value of L_m. The subject attended a sequence of trials during each session. Each trial consisted of a simultaneous presentation of the reference and comparison stimuli during 0.8 s. After that, the subject had to state which one was brighter.

The coarse adjustment was made using the method of the limits. Fifteen values of the comparison stimulus luminance L_c in a range of 1.74–89 cd/m^2 were shown to the subject. The sequence was manipulated to make the task easier at the beginning, and then the difficulty became greater. As a result, we had a first estimation of L_m. This first step also served as training for the subjects.

In the second step a QUEST adaptive method was adopted [31]. This bayesian method needs *a priori* value that was given by the L_m estimation of the first section. During this phase the number of trials varies according to *a posteriori* standard deviation value. When the standard deviation was lower than 0.1, the test concluded and L_m was the last value obtained.

Subjects were not aware of any of the two phases of the experiment.

2.4. Conditions

The experiment was carried out with three levels of scattering: eyes without a filter and two levels representing different degrees of cataracts. The last two were obtained by means of the BPM1 and C3020 filters, which were placed in front of the subject's eyes.

The experiment was done placing the filters either on both eyes (simulating a symmetric condition of eye diseases) or on only one eye (simulating an asymmetric

Table 2. Filtered condition and its equivalent cataract condition.

Condition	Equivalent to
Non-filter	Normal vision
BPM1	Incipient cataract in both eyes
C3020	Advanced cataract in both eyes
BPM1 EE	Incipient cataract only in the "evaluated eye"
C3020 EE	Advanced cataract only in the "evaluated eye"
BPM1 CE	Incipient cataract only in the "comparison eye"
C3020 CE	Advanced cataract only in the "comparison eye"

condition of eye diseases). In this way the "evaluated eye" looked at the Rs and the "comparison eye" looked at the Cs. Measurements were also made under the same experimental conditions but without glare. Table 2 summarizes the experimental conditions.

2.5. Subjects

Six male subjects participated in the study; two of them were aware of the objective of the study, while the others were *naïve*; all were trained. The subjects had normal vision and were between 23 and 39 years old (mean 30.5).

3. Results

In order to compare the results, we computed a glare index (GI) as a stimulus luminance relation:

$$\mathrm{GI} = \frac{L_r'}{L_m} - 1 \tag{5}$$

where L_r' is the luminance of comparison stimulus under non-glare condition and L_m is the luminance of comparison stimulus under glare condition. It is worth noting that L_r' is the value of L_m when the glare source illuminance is zero, which does not always equal the reference luminance L_r, because the eyes do not always have the same transmittance. This is the reason why we used L_r' to compensate the asymmetry between the eyes.

The GI is based on the V index used by FRY and ALPERN [13]. V is defined as follows:

$$V = \frac{L_m}{L_r'} - 1 \tag{6}$$

In the Fry and Alpern's experiment, the glare source beams illuminate the eye that is looking at the comparison stimulus. Therefore, the brightness in that eye is reduced and a higher L_m is necessary to match the brightness. In consequence V is increased.

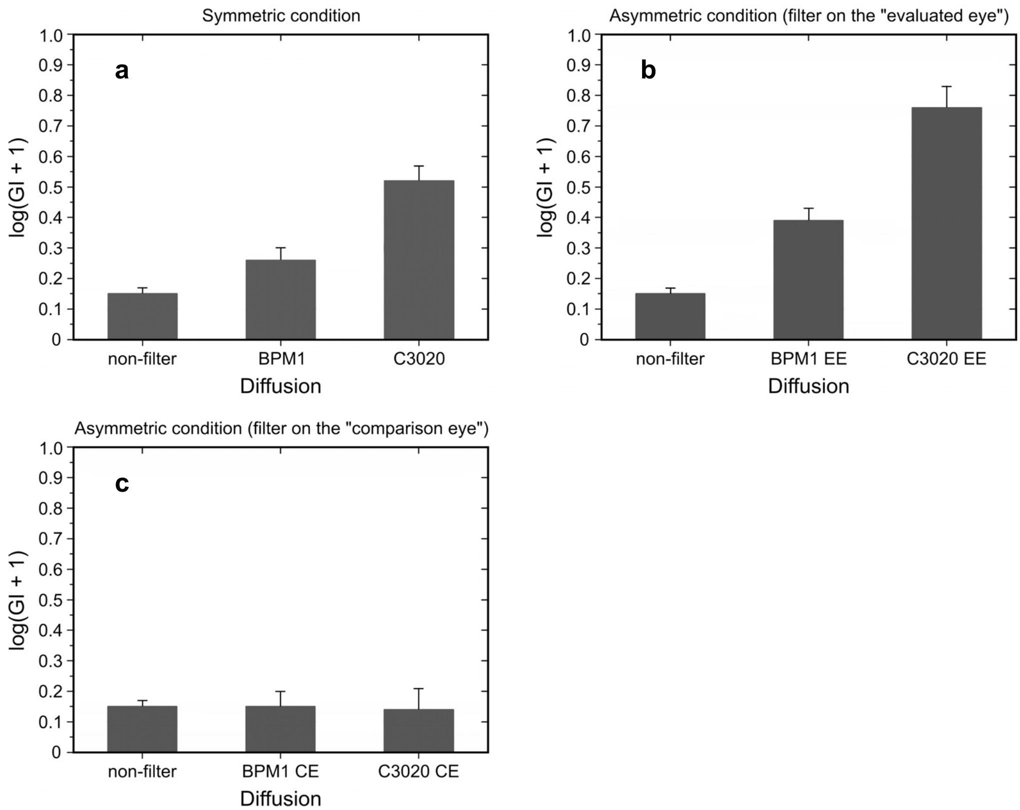

Fig. 6. Plot of $\log_{10}(\mathrm{GI} + 1)$ means for symmetric conditions; this is without filter and with equal filters (BPM1 or C3020) on both eyes (**a**). Plot of $\log_{10}(\mathrm{GI} + 1)$ means for asymmetric conditions; this is without filter on both eyes (non-filter) and with filter (BPM1 or C3020) on only the "evaluated eye" (**b**). Plot of $\log_{10}(\mathrm{GI} + 1)$ means for a naked eye evaluated when the other, the "comparison eye", wears either one of the filters or none (**c**). The bars are the standard errors of the data.

By contrast, in our experiment the glare source illuminates the eye that was looking at the reference stimulus – "evaluated eye". Therefore, the brightness in that eye was reduced and hence a lower L_m was necessary to match the brightness, and GI was increased. Hence GI is equivalent to V:

$$\mathrm{GI} \equiv V \tag{7}$$

We used $\log_{10}(\mathrm{GI} + 1)$ instead of GI because it was simpler to work with positive values.

Figure 6**a** shows the average of the six subjects' data for three experimental conditions: naked eyes (non-filter) and both eyes wearing the filters BPM1 or C3020 (symmetric conditions). It can be seen that the $\log_{10}(\mathrm{GI} + 1)$ value increases as the diffuser level rises showing that the index used accounts for the level of the external scattering. Figure 6**b** shows the means obtained when the BPM1 and

C3020 filters are kept only in the evaluated eye (asymmetric conditions). As expected, these means show the same trend as the ones shown in Fig. 6**a**, but the values obtained for symmetric conditions are nearly 33% lower than those obtained for asymmetric conditions. Finally, Fig. 6**c** shows the means obtained when the "evaluated eye" is naked, but keeping the BPM1 and C3020 filters in the eye without glare – the "comparison eye". In this case no variation was obtained.

An analysis of variance (ANOVA) general linear model and the post Tukey's test were carried out. The effect of three factors was evaluated: the subject, the "evaluated eye" and the "comparison eye". Results showed that the subject effect was null ($p > 0.05$), so it did not introduce bias. Results also showed that considering the factor "evaluated eye", at least one of the conditions was significantly different from the others ($p < 0.05$). In addition, the Tukey's test showed that each of the conditions evaluated in that eye was significantly different from the remaining ones ($p < 0.05$). As a conclusion, the system allows us to discriminate among the three experimental, symmetric conditions (BPM1, C3020, non-filter). This result shows that the system could discriminate among these three scattering levels in subjects with cataracts in both eyes.

Regarding the effect produced by the factor "comparison eye", at least one of the conditions considered was significantly different from the others ($p < 0.05$), although the variability was higher than that found in the effect produced by the factor "evaluated eye". The Tukey's test allowed us to assert that the BPM1 scattering condition was not significantly different from the other two conditions ($p > 0.05$), the C3020 scattering condition showed a small but significant difference from the condition without a filter ($p < 0.05$ [0.03]). This result allows us to analyze what would happen when a healthy eye is measured and the comparison eye has a high degree of scattering (for example a monocular cataract). In other words, the effect of the scattering level of the "comparison eye" on the measurement of the scattering level of a healthy eye is neglected when the scattering is low, but the factor "comparison eye" could produce a bias when the scattering is high. In this case, the error appears as an underestimation that, in clinical terms, would not introduce false positives in the evaluation of a healthy eye.

If we analyze the values of L_r' and L_m used to compute GI in every condition, generally a major brightness reduction is produced in the asymmetric condition than in the symmetrical one, as it is expected. This is due to the fact that the symmetrical condition introduces a degree of major dimness as a consequence of the additional light reduction that is produced by the filter on the "comparison eye". Nevertheless, this difference is larger in the glaring condition (L_m) than in the condition without glare (L_r'). This explains the difference found between symmetric and asymmetric conditions.

These results show that when the comparison is made with the filter placed on the eye looking at the comparison stimulus, the measurement done in the healthy eye is not affected. This demonstrates the efficacy of the compensation operation proposed in (5).

In order to evaluate the properties and the reliability of the system, we made some contrasts with published data about other systems. To do this, we followed some of the items proposed by VAN RIJN *et al*. [25].

One of the parameters analyzed was the repeatability, which was estimated as the ratio between two standard deviations and the range of values measured. Table 3 shows these relations for each condition, being the adopted range for $\log_{10}(\mathrm{GI} + 1)$ from 0 to 1. If these values are compared with those obtained for VAN RIJN *et al*. [25], we find that the repeatability has the same order or better than the best values found for both Straylight Meter's versions (0.21 and 0.26), except for the asymmetric condition using the C3020 filter. This indicates that our system reaches the current standards in ophthalmologic research.

T a b l e 3. Repeatability relation for the several difusion conditions.

Diffuser	Non-filter	BPM1	C3020	BPM1 EE	C3020 EE	BPM1 CE	C3020 CE
Ratio	0.08	0.20	0.23	0.20	0.34	0.32	0.28

It is also possible to analyze the resistance to fraud. On the one hand, the coefficient of repeatability (RC) of the measurements is computed for all the observers with "naked eyes". As a result RC = 0.11. On the other hand, the coefficient of repeatability is computed for only one observer (MD) who made 5 determinations. As a result RC = 0.19. Since the repeatability of the measurements in a subject is not better than the repeatability among observers, it is possible to say that the equipment presents resistance to fraud [25].

4. Discussion

We present a new system that allows us to quantify the intraocular scattering on the basis of a psychophysical methodology of brightness evaluation (BCM). The experimental system is based on a haploscopic arrangement and the measurements are more rapid than those based on stimuli sequentially presented [14–16].

In this work, we assess the ability of this system to discriminate different degrees of cataracts. In order to achieve this, we perform measurements in healthy eyes by simulating cataracts using external diffuser filters previously characterized. The filters were chosen following criteria from the literature [21, 27, 28] and our own tests. The filter BPM1 worn by a healthy eye simulates an early cataract and the filter Cinegel 3020 simulates a more advanced cataract.

The results obtained show that the determination of the index $\log(\mathrm{GI} + 1)$ allows us to discriminate among the different scattering conditions evaluated, even when both eyes have the same degree of cataracts (symmetry) or when they have a different degree (asymmetry). However, due to the fact that the methodology is based on the comparison between the brightness perceived by the "evaluated eye" and the brightness perceived by the "comparison eye", the results show a tendency to have higher values of scattering when the "comparison eye" is free from cataracts.

The differences found between the symmetric condition and the asymmetric one show the difficulty in implementing this system in the ophthalmologic clinic. Due to this difficulty and to the fact that most cataracts are bilateral, the next step would be to determine the asymmetry degree that this system could successfully evaluate.

Nevertheless, the results are consistent with the levels of scattering previously determined with a physical scatter meter. What is more, we have stated the repeatability of the results of this system as well as its resistance to fraud. Thus, we can conclude that by using filters the brightness comparison methodology is sensitive to changes in the ocular scattering and could have a potential to be used in patients. In this way we show that this methodology, which is based on brightness comparison, is very valuable since this measurement is more connected with daily life than threshold conditions.

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