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Effect of interocular differences on binocular visual performance after inducing forward scattering

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Abstract

Purpose: To assess binocular visual performance by means of binocular summation on visual function after inducing monocular forward scattering, and to study the influence of interocular differences on ocular parameters.

Methods: Seven young healthy subjects were recruited. Four Bangerter foils and five fog filters were used to induce monocular forward scattering. To analyse the impact of the scatter, visual acuity, contrast sensitivity, visual discrimination capacity and distance stereoacuity were measured binocularly with the filter placed over the dominant eye. Additionally, interocular differences were calculated for four ocular parameters: the Objective Scatter Index (OSI), Strehl ratio (SR), modulation transfer function cut-off (MTF cut off) and straylight (log[s]). Binocular summation was determined for these visual functions.

Results: A statistically significant deterioration in visual acuity, contrast sensitivity and stereoacuity was seen for all of the filter conditions with respect to the natural state (baseline), with the largest change being recorded for the Bangerter foils. Similarly, the interocular difference for the three retinal image quality parameters (OSI, SR and MTF cut-off) and log(s) increased significantly for the Bangerter foil condition, but not for the fog filters (except log(s)). Binocular summation declined gradually with the Bangerter foils, but not for the fog filters. Statistically significant correlations were found, that is, the greater the interocular differences, the lower the binocular summation of the visual functions and the greater the distance stereoacuity.

Conclusion: Increased forward scattering in the dominant eye resulted in interocular differences, which reduced the overall binocular visual performance, including the binocular summation of several visual functions and distance stereoacuity. The results suggest that marked interocular differences in ocular parameters should be avoided in cases of ocular pathology, amblyopia and emmetropisation procedures (such as refractive surgery) or a monovision correction for presbyopia.

KEYWORDS
Bangerter foils, binocular summation, fog filters, induced forward scattering, interocular differences, retinal image quality

INTRODUCTION

Assessing binocular visual performance is an important aspect of a visual examination. In order to evaluate binocular vision, the effect of binocular summation on different visual functions,[1–9] as well as stereopsis,[10–18] has been examined. Binocular summation is defined as the superiority of the binocular system with respect to monocular viewing in terms of visual function.[2,19] Stereopsis is the ability of the binocular visual system to perceive depth. Binocular performance may be reduced by ocular disease, such as cataract[20] or age-related macular degeneration (AMD),[21] as well as other ocular disorders such as amblyopia[22] or following refractive surgery.[23] Many factors can influence binocular performance, for example, interocular differences, that is, differences between the two eyes for a specific monocular visual parameter, thereby affecting binocular summation.[10,13,24–27] So et al.[28] reported that interocular differences in visual acuity result in a deterioration in stereopsis. Further, increased interocular differences in scatter levels will negatively affects stereopsis.[29] Jimenez et al.[30] observed that interocular differences in corneal asphericity following refractive surgery could reduce binocular visual performance, even if the subjects were emmetropic post-surgery. Furthermore, in the binocular visual system, sensory ocular dominance (i.e., where one eye is preferred to the other for a perceptual visual task related to the sensory visual system[31]) is an important parameter and considered in keratorefractive[32] and cataract surgery,[20,33] in addition to the correction of presbyopia with a monovision technique[34,35] Here, typically the dominant eye is corrected for distance viewing due to the facility to suppress blur in the non-dominant eye,[34] thereby creating an interocular difference (anisometropia).

A further phenomenon to consider with regard to interocular differences is intraocular light scattering (forward scattering). This produces a veiling luminance on the retina causing a deterioration in retinal image quality.[15] It will increase straylight and induce disability glare, as seen in ocular disease such as cataract[36] and AMD.[21,37] As a result, many visual functions are impaired, including contrast sensitivity[38–40] and visual discrimination capacity at night (perception of halos).[21] To our knowledge, there is a lack of studies examining different degrees of interocular differences, and their consequent effect on binocular summation. In particular, it would be worthwhile evaluating retinal image quality and, more concretely, ocular parameters quantifying forward scattering, such as straylight or others, and their impact on binocular visual performance. This analysis could also be of interest in clinical applications such as refractive surgery,[23,41] monovision corrections[9] and ocular disease.[37] In this context, various levels of visual degradation and interocular differences can be simulated using Bangerter foils and fog filters (such as the Black Pro-Mist 2; tiffen.com).[42–46] Bangerter foils are most commonly used to treat amblyopia in children, penalising the visual acuity of the non-amblyopic eye.[47,48] Additionally, the Black Pro-Mist 2 fog filter has been shown to simulate early cataract by inducing forward scatter.[38,44] Taking into consideration the aforementioned studies, it might be assumed that when interocular differences in some visual parameters increase, such as those that assess intraocular scattering and straylight (which are particularly relevant in clinical practice), then binocular summation will deteriorate for several visual functions including stereopsis. Accordingly, the aim of this study was to assess binocular visual performance after penalising the dominant eye to differing degrees. To induce this penalisation, we used a variety of Bangerter foils and fog filters to increase monocular forward scatter and, thereby induce interocular differences. The monocular-induced light scatter through the ocular media will degrade the quality of the retinal image, while straylight (scattered light reaching the retina) will create a luminous veil and disability glare as a consequence of the reduced contrast retinal image. These monocularly induced changes will generate interocular differences. We assessed binocular visual performance through binocular summation for various visual functions such as visual acuity, contrast sensitivity and visual discrimination capacity (perception of halos), as well as distance stereoacuity. We further investigated the effects of varying degrees of monocular degradation and interocular differences in several ocular parameters such as intraocular scattering and straylight. Finally, we analysed the correlation between binocular summation and interocular differences in the ocular parameters listed above, as well as between distance stereoacuity and the same interocular differences.

Key points

- The impairments produced by penalising filters before the dominant eye reveal important factors in binocular visual performance.
- Increased monocular forward scattering produces greater interocular differences, which jeopardise the overall binocular visual performance. Specifically, deteriorations in binocular summation and stereopsis correlate with these interocular differences.
- Marked interocular differences should be avoided to preserve adequate binocular performance in stereopsis and binocular summation.

METHODS

Subjects

The study was approved by the Human Research Ethics Committee of the University of Granada (921/CEIH/2019). Before participating in the experiment, all participants signed an informed consent form in accordance with the Declaration of Helsinki. A total of seven young healthy subjects were enrolled in this crossover study (three females, four males) with a mean age of 27.7 ± 6.5 years. Participants took part in 10 sessions (baseline and one condition for each filter) scheduled on different days. Each session lasted about one hour. Due to the number of sessions, the number of participants had to be limited. The inclusion criteria were corrected decimal visual acuity ≥1.0 (better than logMAR 0.0) for each eye, distance stereoacuity of 40 arc sec or less as evaluated using the differentiated stereo D8 polarised test[16] and no pathological conditions or pharmacological treatment that could influence visual performance. A complete eye examination, including objective and subjective refraction, using the endpoint criterion of maximum plus for best visual acuity was undertaken for each eye and binocularly at distance (5.5 m) and near (40 cm) under photopic lighting conditions. The mean (±SD) refractive error (spherical equivalent) was −1.74 ± 2.39 D, ranging from −6.87 to 0 D. Finally, the subjects' sensory ocular dominance was determined by using one line above their achieved best distance visual acuity and alternately introducing a +1.50 D spherical lens before each eye. The sensory dominant eye was the one where the +1.50 lens created the most blurred vision during binocular viewing.[49]

Filters

Nine filters were assessed, with the filter placed before the dominant eye (as occurs, for instance, in the treatment of amblyopia). It is anticipated that penalising the sensory dominant eye will create smaller interocular differences when compared with penalising the non-dominant eye, thereby allowing us to evaluate a range of interocular differences. Four Bangerter foils (Ryser Optik, ryseroptik.ch) corresponding to grades 0.8, 0.6, 0.4 and 0.3 (BF_0.8, BF_0.6, BF_0.4 and BF_0.3) were used to reduce the retinal image quality. Each filter value corresponds to the theoretical visual acuity in decimal notation obtained when viewing through the foil (assuming an initial visual acuity of 1.0 [0.00 logMAR] or better), although this correspondence should be carefully considered as shown in other works.[46,50] Therefore, grades 0.8, 0.6, 0.4 and 0.3 should correspond to visual acuities of 0.10, 0.22, 0.40 and 0.52 logMAR, respectively. We also evaluated the Bangerter foil grade 0.2 (0.70 logMAR), but found this caused monocular suppression due to the excessive visual difference between the two eyes.[51] Bangerter foils are widely used to treat amblyopia in children,[48,52] as well as to deteriorate visual quality[45,50,53–55] for example, to simulate the scatter produced by cataracts.[50] They act as diffusers and have a structure of microelements (microbubbles) that produce image distortions,[46,50] thereby degrading visual acuity and contrast sensitivity.[45,55,56] The 0.8, 0.6, 0.4 and 0.3 Bangerter foils used here are characterised by a bubble density of 3.40, 3.41, 3.76 and 3.44 bubbles/mm^2, respectively,[50] but also present variability in the size of their bubbles (diameters between 0.2 and 0.4 mm).

In addition, five fog filters as used in photography were included: the Black Pro-Mist 2 (Tiffen, tiffen.com); the Fog A and the Fog B filters (HOYA, hoyafilter.com); a combination of the Fog A and Fog B filters (Fog_A + B) and the B + W Fog_1 filter (Schneider, schneiderkreuznach.com/en). The Black Pro-Mist 2 filter (BPM2) has been shown to be valid for simulating the effects of early cataract.[44,50] These photographic filters are generally characterised by their structure and grain size: the Black Pro-Mist 2 filter has the largest grain size but also the greater variability in terms of the size and form of the grain (30–100 µm), whereas the Fog_1 filter presents the smallest grain size[50] (Figure 1), with diameters from 5 to 15 µm. The Fog B filter produces a more enhanced fog effect than Fog A, which has a larger grain size,[50] but a lower grain size than the BPM2. These photographic filters produce an effect similar to dense fog.

The Bangerter foils were fixed directly onto plano ophthalmic lenses, mounted in identical optical frames, while each of the five fog filters was assembled into Knobloch K-2 shooting glasses (Knobloch Optik, knobloch-schiessbrillen.de), thereby allowing us to fix the lens-holder with the fog filter in front of the eye. All of the filters were analysed using the OQAS II (Optical Quality Analysis System II, Visiometrics, visiometrics.com), after being fixed onto an artificial eye (TOPCON, spherical refraction −5.5 D). This procedure allowed us to assess objectively the optical quality of an artificial eye both without a filter, and wearing each of the filters used in the present study, thus avoiding inter-individual variability and allowing us to support the results from the human observers.[50]

Visual function and ocular parameters

Visual acuity, contrast sensitivity and stereoacuity

Visual acuity, contrast sensitivity and stereoacuity were evaluated using the Pola VistaVision monitor (DMD MedTech, dmd.it/). Visual acuity (VA) was determined by the endpoint criterion of maximum plus for best visual acuity, in decimal notation, both monocularly and binocularly, using the VistaVision Visual Acuity Chart at a distance of 5.5 m under photopic lighting conditions. Stereopsis was evaluated by means of stereoacuity measured at 5.5 m under photopic lighting conditions using the differentiated stereo D8 polarised test of the Pola VistaVision stereotest, which uses polarised vertical lines to evaluate eight disparities from 300 to 10 arc sec. For

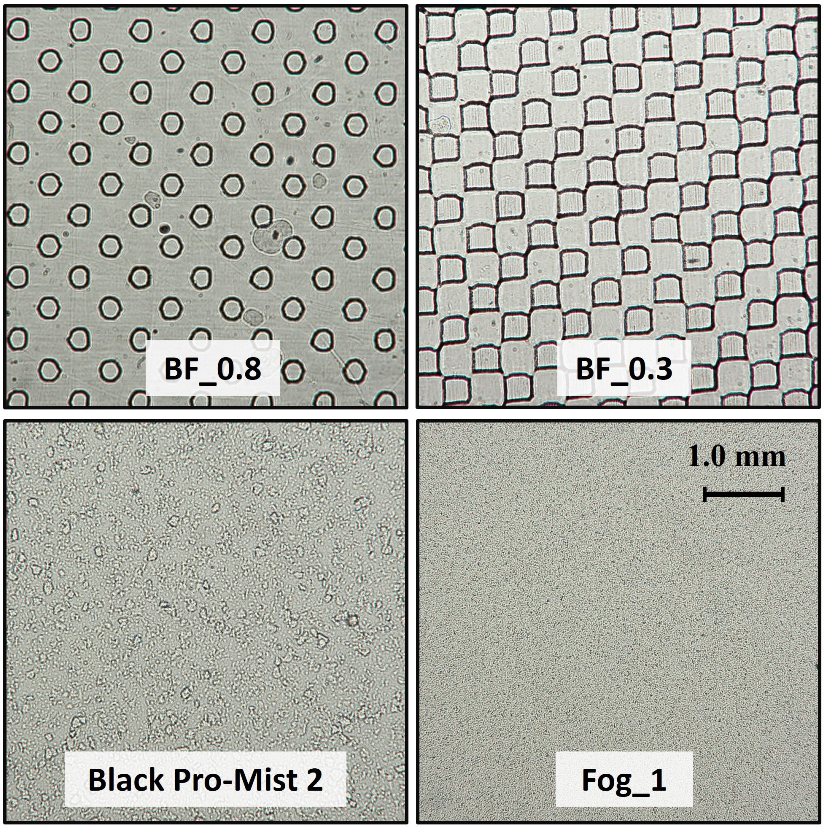

FIGURE 1 Macro photographs of the structure in the BF_0.8 and BF_0.3 Bangerter foils and Black Pro-Mist 2 and Fog_1 photographic filters

each disparity, five vertical lines were displayed simultaneously in a row on the monitor. One of the five vertical lines showed disparity and the task of the subject, who wore polarised glasses, was to perceive it stereoscopically. For this purpose, the subject had to indicate which of the five lines was perceived to be in front of the monitor (crossed disparity). This stereotest accurately evaluates the stereopsis.[16] The contrast sensitivity function (CSF) was evaluated using the VistaVision contrast sensitivity test (DMD MedTech, dmd.it/)[50,57] through sinusoidal grids in which the observers had to indicate whether the grid inclined to the right, left or vertical, with the contrast of these grids being decreased until it could not be determined by the subjects. Six different spatial frequencies, that is, 0.75, 1.5, 3, 6, 12 and 18 cycles per degree (cpd), were assessed both monocularly and binocularly at 3 m.[57] The test had a background luminance of 60 cd/m^2 and was performed under mesopic lighting levels. For each condition, the contrast sensitivity for all of the spatial frequencies tested was averaged. In fact, some authors have shown that binocular summation for this visual function does not vary with the spatial frequencies measured.[58]

Retinal image quality

Retinal image quality was assessed using the OQAS II (Optical Quality Analysis System II, Visiometrics, visiometrics.com), a double-pass device that has been validated in clinical practice.[37,59] Three parameters were measured: the Objective Scatter Index (OSI),[36,59] the Strehl ratio (SR)[27,50] and the modulation transfer function cut-off (MTF cut-off).[9] The OSI is an objective parameter quantifying the intraocular scattering, which affects the retinal image quality; the higher the OSI value, the greater the intraocular scattering. The OSI was calculated for an artificial pupil size of 4 mm and analyses the light intensity within an annular area of 12 and 20 arc min ('near-angle' scattering) with respect to the central peak of the double-pass image (intraocular scattering is located in the outer part of the point spread function [PSF]). The Strehl ratio is defined as the ratio between the 2D-MTF (modulation transfer function curve in two dimensions) area of the eye and the diffraction-limited 2D-MTF area, ranging from 0 to 1; the higher the value, the fewer the ocular aberrations and less scattering. The MTF is calculated from the PSF based on the double-pass image (ocular aberrations dominate the central peak). The MTF cut-off represents the spatial frequency corresponding to a theoretical MTF value of 0 (the noise produced by the charge-coupled device [CCD] camera is considered in the calculation of the parameter). The MTF and Strehl ratio data were referenced to a 5-mm-diameter pupil. We measured and evaluated the retinal image quality monocularly for each eye under low ambient illumination, beginning with the baseline conditions (without a filter), followed by each Bangerter foil and fog filter in random order. Three measurements were made and averaged for each experimental condition.

Visual discrimination capacity

The visual discrimination capacity under low-illumination conditions was evaluated using the Halo test (DIGIBUG Institutional Repository of the University of Granada, digibug.ugr.es), based on the Halo v1.0 software, displayed on a monitor at a distance of 2.5 m from the observer. This visual test has been used in clinical applications for ocular disease[21,60] and after refractive surgery,[23] but also under challenging circumstances to quantify night-vision disturbances.[61–63] The test comprises detecting peripheral luminous stimuli in different positions with respect to a central stimulus with high luminance. This central stimulus is the source of the halo perception and other night-vision disturbances (glare, starbursts, etc.). At the end of the test, a visual disturbance index (VDI) is obtained. This index represents the ratio between non-detected stimuli and all the peripheral stimuli presented to the subject: the higher the VDI the lower the visual discrimination capacity for the particular illumination condition and, therefore, the stronger the halo perception. Further information on this device can be found elsewhere.[21,61]

Intraocular straylight

Intraocular straylight was assessed under low-illumination conditions using the C-Quant straylight meter (OCULUS, oculus.de). This device uses a psychophysical compensation comparison method between two test field halves (randomly chosen). As a result, it produces two flickering stimuli that differ in modulation depth: one results from straylight while the other is a combination of straylight and compensation light.[64] This ocular parameter has been widely used in clinical studies[44,65,66] and introduced into the visual characterisation of daily tasks.[57,67] Specifically, the visual parameter log(s) is obtained at the end of the test, where *s* represents the straylight and quantifies the ratio between the scattered and non-scattered light; the higher the value of log(s), the greater the forward intraocular straylight and the consequent increase of the luminous veil over the retinal image. Furthermore, the log(s) parameter increases with age and in line with the values given by the normal straylight formula,[68] that is, 0.90 in young healthy eyes; 1.03 at 50 years of age and 1.42 at the age of 80. Three measurements were taken to improve the accuracy and reliability of this parameter, and only those values with a standard deviation of less than 0.08 were considered.

Procedures

Each participant took part in multiple sessions (baseline and one condition for each filter evaluated), none of which exceeded one hour to avoid visual fatigue. The order of the visual test measurements was randomised, to prevent any learning effects. The different sessions (corresponding to the baseline and each filter condition) were also randomised. We measured all the visual functions described above (VA, CSF, stereoacuity and visual discrimination capacity) both monocular and binocularly, as well as the ocular parameters (OSI, SR, MTF cut-off and straylight). Participants performed the visual tests using their best optical correction. For the binocular measurements, we evaluated the baseline condition with no filter, or with the filter in the corresponding lens-holder, checking that it was correctly aligned with the eye. The filter was placed over the sensory dominant eye.[69] Interocular suppression was checked at distance (5.5 m) for all the filters using the Worth-4-dot test. Suppression was only found for the 0.2-grade Bangerter foil, and consequently, this foil was removed from the study.

Interocular differences

Interocular differences (ID) were determined between the non-dominant and dominant eye of the subject. We calculated the ID (in absolute values) for all of the retinal image quality parameters (OSI, MTF cut-off and SR)[27,70] and straylight (log(s)). In this study, we determined the ID between the natural condition (non-dominant eye) and the dominant eye with the associated filter. Finally, an overall interocular difference score (OIDS) was obtained by averaging the z-scores of all the ocular parameters studied (in each of the experimental conditions). For all the variables, the more positive the score, the greater the interocular differences. Z-scores have been widely used[18,36,57,63] and are a measurement of how many standard deviations an individual value lies away from the group mean.

Binocular summation

Binocular summation (BS) assesses the binocular visual performance.[7,27] We evaluated the BS for three visual functions through their corresponding parameters, that is, VA, CSF and VDI.

The binocular summation for the visual acuity, BS_{VA}, was calculated using Equation (1), dividing the binocular visual acuity, VA_{bin}, by the best monocular eye, VA_{best_mon} (the higher of the two monocular values).

$$BS_{VA} = \frac{VA_{bin}}{VA_{best\_mon}} \quad (1)$$

Similarly, the binocular summation for the CSF, BS_{CSF}, was determined according to Equation (2), dividing the binocular CSF value, CSF_{bin}, by the best monocular value,[27,69,71] CSF_{best_mon}

$$BS_{CSF} = \frac{CSF_{bin}}{CSF_{best\_mon}} \tag{2}$$

Next, the binocular summation for the VDI, BS_{VDI}, was calculated using Equation (3), dividing the lowest monocular value, VDI_{best_mon}, by the binocular VDI value, VDI_{bin}, since the VDI decreases when the discrimination capacity increases.[9]

$$BS_{VDI} = \frac{VDI_{best\_mon}}{VDI_{bin}} \tag{3}$$

A binocular summation ratio above 1 indicates positive binocular summation, proving the superiority of the binocular system with respect to monocular viewing, whereas a value of less than 1 shows the superiority of the better eye measured monocularly, and inhibition of the binocular system.

Finally, in line with the OIDS calculation and other studies,[18,36,57,63] an overall binocular summation score (OBSS) was also calculated for the visual functions analysed (VA, CSF and VDI), and for all of the filter conditions. To do this, we averaged the *z*-scores of these visual function variables for each filter condition. In this study, the lower the OBSS values, the lower the binocular summation and the lower the binocular visual performance.

Statistical analysis

For data analysis, we used the SPSS 23.0 software package (IBM, ibm.com). We checked the normal distribution of all the parameters (Shapiro–Wilk test). An ANOVA test for repeated measures with Bonferroni correction was used to analyse the means and variances of the visual parameters (VA, CSF, stereoacuity, OSI, SR, MTF cut-off, log(s) and VDI) under all the filter conditions. Finally, the Pearson correlation coefficient (*r*) was used to study the relationship between the overall interocular difference score of the ocular parameters (OIDS) and the overall binocular summation score of the visual functions (OBSS). We also analysed the relationship between distance stereoacuity and the interocular differences of the ocular parameters (OIDS) using the Pearson correlation coefficient. A statistical significance level of 95% was applied for all tests ($p < 0.05$).

RESULTS

Table 1 shows the mean binocular values of VA, CSF, VDI and distance stereoacuity for the baseline (natural condition) and each filter condition. In all results, the binocular condition reflects the non-dominant eye without a filter and the dominant eye wearing the filter. Comparing the baseline to all of the filter conditions (Bangerter foils and fog filters), statistically significant deteriorations were found for three visual parameters: VA (Bangerter foils, $F_{1,6} = 15.0$, $p = 0.01$ and fog filters, $F_{1,6} = 7.0$, $p = 0.04$); CSF (Bangerter foils, $F_{1,6} = 12.48$, $p = 0.01$ and fog filters, $F_{1,6} = 6.06$, $p = 0.04$) and stereoacuity (Bangerter foils, $F_{1,6} = 12.989$, $p = 0.01$ and fog filters, $F_{1,6} = 7.68$, $p = 0.03$). Comparing each condition to the worst result (with BF_0.3), we found significant VA impairments in all the conditions ($F_{1,6} = 8.59$, $p = 0.03$) except for BF_0.6 ($F_{1,6} = 3.93$, $p = 0.10$) and BF_0.4 ($F_{1,6} = 2.53$, $p = 0.16$). Similarly, for distance stereoacuity, we also found impairments for all conditions ($F_{1,6} = 9.03$, $p = 0.02$) except for BF_0.4 ($F_{1,6} = 1.15$, $p = 0.33$). Stereoacuity at distance was strongly impaired by the Bangerter foils and less so with the fog filters. For the CSF, the worst situation was determined using the BF_0.4 foil, which showed a significant difference compared with BF_0.8 ($F_{1,6} = 6.46$, $p = 0.04$) and all the fog filter conditions ($F_{1,6} = 6.47$, $p = 0.04$).

For the VDI, the best results were found binocularly in the baseline and Fog_1 condition, but statistically significant differences were observed with the BF_0.6 ($F_{1,6} = 9.07$,

TABLE 1 Mean values (standard deviations) of the binocular visual functions: Decimal equivalent visual acuity (VA), averaged contrast sensitivity function (CSF), distance stereoacuity and visual disturbance index (VDI) for the different Bangerter foils and fog filters used

		VA	CSF	Stereoacuity (arcsec)	VDI
Baseline	(no filter)	1.3 (0.1)	166 (4)	20 (8)	0.13 (0.04)
Bangerter foils	BF_0.8	1.1 (0.1)	139 (14)	83 (90)	0.18 (0.09)
	BF_0.6	1.1 (0.1)	137 (17)	104 (64)	0.23 (0.12)
	BF_0.4	1.1 (0.2)	127 (17)	180 (98)	0.26 (0.13)
	BF_0.3	0.9 (0.2)	134 (24)	231 (122)	0.19 (0.09)
Fog filters	BPM2	1.2 (0.2)	146 (14)	36 (24)	0.15 (0.08)
	Fog_A	1.2 (0.2)	144 (18)	36 (17)	0.13 (0.03)
	Fog_B	1.2 (0.2)	143 (15)	39 (21)	0.16 (0.05)
	Fog_A + B	1.2 (0.2)	155 (12)	34 (19)	0.13 (0.05)
	Fog_1	1.2 (0.2)	154 (8)	39 (22)	0.13 (0.04)

$p = 0.02$), BF_0.4 ($F_{1,6} = 11.92$, $p = 0.01$) and Fog_B ($F_{1,6} = 10.06$, $p = 0.02$) conditions. The worst VDI result was for BF_0.4, resulting in significant impairment compared to baseline ($F_{1,6} = 11.92$, $p = 0.01$), and all the fog conditions ($F_{1,6} = 9.12$, $p = 0.02$), but not compared with the other Bangerter foils. Finally, for all of the visual parameters, no statistically significant differences were seen when comparing the fog filters ($p > 0.99$). Therefore, for the different visual parameters measured, significant deteriorations were revealed for all of the filter conditions with respect to baseline, with the worst condition being with the Bangerter foils.

Figure 2 shows the mean OSI values for the artificial eye and the subjects' eyes. Mean interocular differences for OSI are also included. For the artificial eye, the mean OSI values for the baseline and all the fog filters were equal to 0 with the exception of BPM2 (OSI = 0.1). For the baseline condition, statistically significant differences were obtained when compared to all the Bangerter foils ($p < 0.001$). These foils gradually increased the OSI value, with the worst condition being found for the BF_0.3 foil. Statistically significant impairments were observed when comparing the Bangerter foils with each other, with the exception of the comparison between BF_0.8 and BF_0.6 ($p > 0.99$). For the subjects, statistically significant differences were found between the baseline and all of the Bangerter foils ($p < 0.001$) but not with the fog filters ($p > 0.99$). For the Bangerter foils, OSI was progressively impaired from BF_0.8 to BF_0.3, with statistical differences between BF_0.8 and BF_0.6 ($F_{1,6} = 6.47$, $p = 0.04$).

Table 2 shows the mean interocular differences for the three retinal image quality parameters (SR, MTF cut-off and OSI) and straylight (log(s)). The Strehl ratio (SR) and the MTF cut-off are two related parameters calculated from the MTF. The straylight (log(s)) is methodologically different from that obtained with the OQAS device, although some studies have found a positive correlation between OSI and log(s).[50] For the SR and MTF cut-off, significant increases were observed between the natural condition and all of the Bangerter foil conditions ($F_{1,6} = 8.92$, $p = 0.02$), but not when comparing baseline to any of the fog filter conditions ($F_{1,6} = 0.93$, $p = 0.37$). In fact, on average, decreases in the interocular differences for the SR and MTF cut-off were found for all the fog filters with respect to the no filter condition (except for Fog_1 in the MTF cut-off), where the most significant difference was obtained when comparing the BPM2 filter and the natural condition for the MTF cut-off parameter ($F_{1,6} = 14.54$, $p = 0.01$). In addition, for the SR and MTF cut-off, the interocular differences increased progressively from the BF_0.6 to the BF_0.3 foils, but not between the BF_0.8 and the BF_0.6 foils ($F_{1,6} = 1.21$, $p = 0.32$). Similarly, for the OSI, significant increases in the interocular differences were found with all the Bangerter foils with respect to the baseline ($p < 0.001$). On average, the interocular differences of the OSI increased progressively from BF_0.8 to BF_0.3, but not statistically between BF_0.6 and BF_0.4 ($F_{1,6} = 2.04$, $p = 0.20$). On the other hand, the interocular differences for the BF_0.3 condition were significantly higher than the other filter conditions for the OSI ($p < 0.001$), being marginally significant when compared to BF_0.4 (for MTF cut-off, $F_{1,6} = 5.93$, $p = 0.05$ and for OSI, $F_{1,6} = 5.78$, $p = 0.05$). For the interocular differences in all the fog filter conditions, no statistical increases were observed compared to baseline ($F_{1,6} = 0.88$, $p = 0.38$). In terms of straylight, the interocular differences of log(s) were significantly lower for the baseline compared to the Bangerter foils and fog filter conditions ($p < 0.001$). Ultimately, compared to the baseline (no filter) condition, the interocular differences for the three retinal image quality parameters increased significantly for the Bangerter foils but not with the fog filters.

Table 3 indicates the mean values of binocular summation (BS) for the visual functions VA, CSF and VDI for the different experimental conditions. For VA, positive binocular summation ($BS_{VA} > 1$) was observed for the baseline and the fog filter conditions, except for BPM2. The

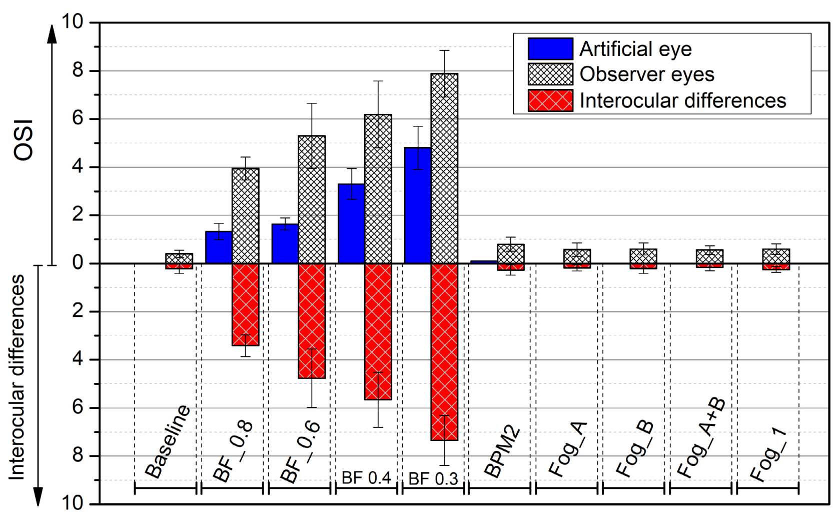

FIGURE 2 Mean OSI (Objective Scatter Index) values for the artificial eye and observer eyes for all the experimental conditions (baseline and the different filter conditions). The mean interocular differences for the OSI in observer eyes are also included. BF, Bangerter foils; BPM2, Black Pro-Mist 2

TABLE 2 Mean (standard deviations) interocular differences for the ocular parameters analysed: Strehl ratio (SR), modulation transfer function cut-off (MTF cut-off), objective scatter index (OSI) and straylight (log(s)) under the various experimental conditions (baseline and wearing each of the Bangerter foils and fog filters)

		Interocular differences			
		SR	**MTF cut-off (cpd)**	**OSI**	**log(s)**
Baseline	(no filter)	0.08 (0.05) *$p = 0.02^{a}$* *$p = 0.37^{b}$*	10.9 (5.9) *$p = 0.02^{a}$* *$p = 0.37^{b}$*	0.21 (0.20) *$p < 0.001^{a}$* *$p = 0.38^{b}$*	0.06 (0.04) *$p < 0.001^{a,b}$*
Bangerter foils	BF_0.8	0.15 (0.07)	29.4 (10.2)	3.41 (0.46)	0.37 (0.16)
	BF_0.6	0.14 (0.06)	28.2 (8.5)	4.77 (1.22)	0.54 (0.05)
	BF_0.4	0.16 (0.07)	31.4 (8.2)	5.66 (1.14)	0.72 (0.06)
	BF_0.3	0.17 (0.07)	33.2 (9.1)	7.35 (1.04)	0.69 (0.10)
Fog filters	BPM2	0.04 (0.04) *$p = 0.08^{c}$*	4.1 (4.2) *$p = 0.01^{c}$*	0.27 (0.21) *$p = 0.67^{c}$*	0.29 (0.08) *$p < 0.001^{c}$*
	Fog_A	0.06 (0.05)	6.0 (4.2)	0.19 (0.13)	0.35 (0.15)
	Fog_B	0.07 (0.05)	8.0 (4.7)	0.21 (0.21)	0.43 (0.09)
	Fog_A + B	0.05 (0.05)	6.5 (6.7)	0.16 (0.14)	0.64 (0.12)
	Fog_1	0.06 (0.05)	11.3 (6.4)	0.25 (0.12)	0.79 (0.13)

Note: p-Values comparisons: a, baseline-Bangerter foils; b, baseline-Fog filters (except BPM2) and c, baseline-BPM2.
Abbreviation: Cpd, cycles per degree.

TABLE 3 Mean binocular summation (standard deviations) for the visual parameters: decimal equivalent visual acuity (VA), contrast sensitivity function (CSF) and visual disturbance index (VDI) with the different Bangerter foils and fog filters used

		Binocular summation		
		VA	**CSF**	**VDI**
Baseline	(no filter)	1.14 (0.07)	1.31 (0.20)	1.33 (0.43)
Bangerter foils	BF 0.8	0.97 (0.07)	1.09 (0.19)	1.17 (0.50)
	BF 0.6	0.96 (0.13)	1.08 (0.22)	0.90 (0.25)
	BF 0.4	0.91 (0.13)	1.00 (0.21)	0.81 (0.26)
	BF 0.3	0.80 (0.11)	1.05 (0.23)	1.14 (0.51)
Fog filters	BPM2	1.00 (0.09)	1.15 (0.20)	1.33 (0.36)
	Fog A	1.05 (0.13)	1.13 (0.17)	1.46 (0.36)
	Fog B	1.05 (0.10)	1.11 (0.15)	1.15 (0.12)
	Fog A + B	1.02 (0.13)	1.22 (0.21)	1.44 (0.31)
	Fog 1	1.03 (0.06)	1.22 (0.23)	1.47 (0.25)

Note: 'No filter' represents the natural condition (baseline).

highest mean BS value was obtained in the baseline condition, which was statistically higher than all of the filter conditions ($F_{1,6}$ = 6.09, p = 0.04). Binocular summation for VA decreased gradually from BF_0.8 to BF_0.3, revealing inhibition of this parameter with all of the Bangerter foils ($BS_{VA} < 1$).[72] Considering CSF, positive binocular summations ($1 < BS_{CSF} < 2$) were found for all conditions except BF_0.4, the greatest being for the baseline condition 1.31 (0.20). In fact, statistically significant differences were observed for the baseline binocular summation compared to all of the Bangerter foil conditions ($F_{1,6}$ = 9.8, p = 0.02), and also compared with the fog filters ($F_{1,6}$ = 8.83, p = 0.03). On the other hand, statistically significant differences were observed between the lowest binocular summation value (BF_0.4) and BF_0.8 ($F_{1,6}$ = 7.53, p = 0.03), as well as all of the fog filters ($F_{1,6}$ = 6.63, p = 0.04). Finally, for the CSF, binocular summation gradually decreased with the Bangerter foils (except for BF_0.3). Similarly, for the VDI, binocular summation gradually deteriorated with the Bangerter foils (except for BF_0.3) with respect to baseline, being below 1 for the BF_0.6 and BF_0.4 conditions. Nonetheless, improvements in binocular summation were found for all of the fog filters except for Fog_B; the highest value of BS being recorded when wearing the Fog_1 filter. As a result, binocular summation declined with the Bangerter foil conditions, mainly affecting the VA and VDI values. By contrast, binocular summation values for the fog filters remained above 1. In fact, fog filters placed on the dominant eye did not lower binocular summation, providing even better binocular summation results for the VDI compared with the baseline condition (except for FogB).

Figure 3 shows the relationship between the overall interocular difference score (OIDS) and the overall binocular summation score (OBSS). A statistically significant negative correlation was found between the OIDS and OBSS ($r = -0.51$, $p < 0.001$), revealing that the higher the OIDS, the lower the OBSS. As a result, a tendency was observed despite the spread of data, namely, the higher the interocular differences for the ocular parameters analysed, the lower the binocular summation for the visual functions measured and, therefore, a stronger deterioration in binocular visual performance.

Figure 4 shows the relationship between the overall ocular parameter interocular difference score (OIDS) and distance stereoacuity (SA). A significant positive correlation ($r = 0.65$, $p < 0.001$) was found between OIDS and SA, revealing that the higher the OIDS, the greater the distance stereoacuity. As a result, the greater the interocular differences for the ocular parameters analysed, the higher the stereoacuity values and, therefore, a stronger degradation in stereoscopic perception at distance.

DISCUSSION

This study allowed an overview of binocular visual performance under natural conditions and after simulating various degrees of degradation on the dominant eye with Bangerter foils and fog filters. Taking into consideration all of the visual functions analysed binocularly, VA, CSF and stereoacuity showed statistically significant deterioration with all of the filters with respect to the baseline condition. For visual discrimination capacity in low ambient illumination, using the VDI metrics, we found statistically significant degradation mainly with the Bangerter foils (BF_0.6, BF_0.4). For the ocular parameters (MTF cut-off, Strehl ratio, OSI and log(s)), the increase in scattered light (induced by the filters) deteriorated the optical quality of the eye, resulting in a degraded retinal image.[50] Thereafter, binocular summations were calculated for these visual functions (VA, SC and VDI), indicating a lower binocular summation (BS < 1) only for Bangerter foils in some cases, that is, in terms of visual acuity (BF_0.8, BF_0.6, BF_0.4 and BF_0.3), and VDI (BF_0.6 and BF_0.4). We found that, on average, the binocular summation for VA and CSF diminished with respect to the baseline condition for all the filter conditions. Binocular summations for the VDI deteriorated with the Bangerter foils and the Fog B filter. Thus, the interocular differences also increased with all of the Bangerter foils for the ocular parameters (MTF cut-off, Strehl ratio and OSI), but also for straylight (log(s)), compared with the baseline condition. For the OSI and log(s) parameters, the higher the degree of deterioration with the Bangerter foil, the greater the interocular differences. For the fog filters, no increments in interocular differences were observed for the ocular parameters measured with the OQAS (MTF cut-off, Strehl ratio and OSI), in contrast to the straylight (log(s)) assessed using the C-Quant device, where important increases in the interocular differences were found with these filters. Several important points concerning these two devices must be taken into consideration. Firstly, the discrepancy could be due to methodological differences.

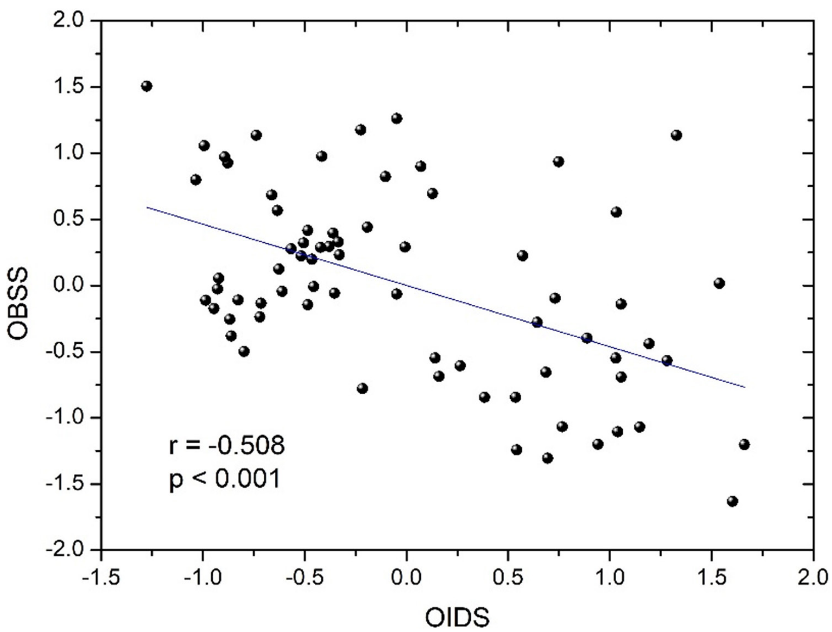

FIGURE 3 The overall interocular difference score (OIDS) of the ocular parameters analysed as a function of the overall binocular summation score (OBSS) of the visual function

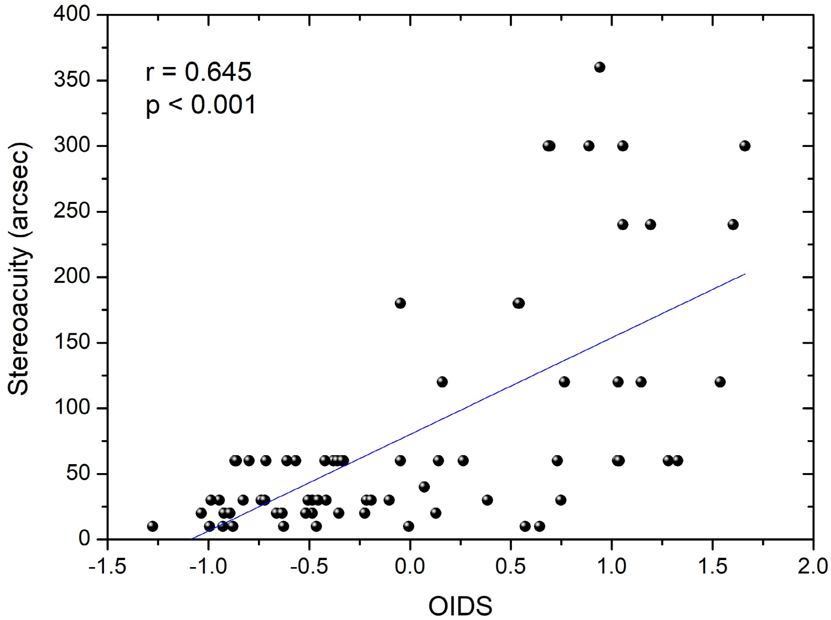

FIGURE 4 The overall interocular difference score (OIDS) of the ocular parameters analysed as a function of distance stereoacuity (arc sec)

In fact, the OQAS double-pass device provides objective measurements whereas the C-Quant device supplies the log(s) parameter through the compensation comparison method. Secondly, the OSI measured with the OQAS analyses the double-pass retinal image of a point source of light corresponding to the ratio between the light intensity (annular area of 12 and 20 arc min) and the intensity reaching the central peak (1 arc min).[50,73] However, retinal straylight measured with the C-Quant device is for a visual angle of 5 to 10 degrees. Thirdly, another important difference could involve the light used in these two devices: the OQAS uses a near-infrared light ($\lambda = 780$ nm), while the C-Quant has a white light source, for which visual sensitivity peaks at 550 nm.[50] For the OQAS device, the infrared light is more suitable for estimating measurements of retinal image quality than visible light, also providing additional comfort to the patient.[21,74,75] Even if there are certain limitations with the OQAS device, such as the artefact created by infrared light diffusion in the choroid causing back reflection,[75] the OQAS has been demonstrated to be useful in several clinical applications.[21,37,74,76–78] Finally, the structure of the fog filters could also influence the results: the Fog_1 filter is the smallest-grained fog filter, while the BPM2 is the largest-grained.[50] Uniform small grain filters produce 'wider-angle' scattering. For low-moderate levels of induced forward scattering, the OQAS device quantifies the 'near-angle' scattering, and with the contribution of its infrared light reaching the background, this device is limited and less sensitive to forward wide-angle scattering due to the small grain size (<40 μm) and uniformity induced by the fog filters.[50] By contrast, the log(s) parameter measured with the C-Quant is more sensitive to the wide-angle forward scattering of the fog filters, inducing higher interocular differences.[50]

As is well established, the scattering from very small particles (diameters of less than 1/10 wavelength of the incident light) is predominantly Rayleigh scattering, while for particles larger than a wavelength, Mie scattering predominates.[79] In young and well-pigmented human eyes, intraocular scattering for short and medium visible wavelengths is predominantly Rayleigh scattering.[80] However, this theory is limited when considering multilamellar bodies in the lens (particles from 1 to 6 μm), which have been reported in older transparent lenses and age-related cataracts, where the Mie scattering theory is more appropriate.[79] In the present study, the particle sizes of the filters used varied from a few microns (5–20 μm in the Fog_1 filter) to around a few hundred microns for the Bangerter foils (the highest size being around 400 μm). Therefore, all of the fog filters and Bangerter foils analysed in the present study (using infrared light centred at 780 nm, and white light) produced light scattering consistent with the Mie scattering theory.

Conversely, statistically significant correlations were found when comparing the interocular differences in the ocular parameters (OIDS) to the binocular summations for the visual functions (OBSS) and stereoacuity. In fact, the higher the interocular differences for the ocular parameters (OSI, RS, MTF cut-off and log(s)), the lower the binocular summation for the different visual parameters investigated (VA, CSF and VDI). Distance stereoacuity correlated with all of the interocular differences measured, demonstrating deteriorating stereoacuity with increased interocular differences for the ocular parameters cited above. As it is well established, intraocular scattering affects contrast sensitivity, visual acuity and stereopsis: the higher the intraocular scattering, the lower the contrast sensitivity and the poorer the stereopsis. Intraocular scattering is responsible for deterioration of the visual parameters and retinal image. These findings are line with Zhao et al.,[29] who found deteriorated stereoacuity induced by three different scatter filters placed binocularly before the eyes (Pro-Mist 1/2, Pro-Mist 1, Pro-Mist 2), suggesting a mutual influence between incremental interocular differences in scatter and deterioration of stereoacuity. Similar to Zhao et al., who assessed interocular differences in scattering on stereopsis, the present study evaluated and provided additional information to characterise objectively the scatter level induced (by means of ocular parameters such as OSI, RS, MTF cut-off and log(s)). A wide range of interocular differences induced by Bangerter filters (higher interocular differences than the BPM filters) and fog filters was examined. As a result, the increased forward scattering induced by these filters on the dominant eye produced greater interocular differences that deteriorated overall binocular visual performance.

Moreover, inhibitions in these binocular summations (BS < 1) were found for all the Bangerter foil conditions for visual acuity and Bangerter foils 0.6 and 0.4 for the binocular-discrimination capacity (VDI), resulting in no improvement in the binocular visual system. In fact, the perception and binocular-discrimination capacity proved to be worse than in the monocular state, indicating a major limitation when inhibiting binocular summation inherent in our visual system. By contrast, for Bangerter foil 0.3, binocular summation for the contrast sensitivity function and VDI were above 1, but this was not the case for the binocular summation for visual acuity. This may be explained by two reasons: the time spent on the visual task and the ensuing monocular partial suppression. Indeed, in this study, the longest visual tasks were the assessment of contrast sensitivity (CSF) and visual disturbances (VDI), compared with the short time to measure visual acuity. Another important point is that Bangerter foil 0.3 caused greater forward scattering than all the other filters measured. Even if the interocular suppression was verified by the Worth-4-dot test, we could not exclude the possibility of partial monocular suppression in the eye wearing the Bangerter foil 0.3 during the lengthier visual tasks.[51] Another explanation could be the adaptation of the binocular system to induced retinal blur, as caused by the Bangerter foil 0.3. In fact, Plainis et al.[81] found that binocular summation increased after inducing different degrees of defocus (retinal blur), suggesting activation of a larger population of neurons under binocular stimulation. Furthermore, when the image quality of the two eyes is dissimilar (as occurs with the Bangerter foils), stereopsis is reduced significantly.[41] The present study agrees with these findings. Castro et al.[27] found that the greater the interocular differences in the Strehl ratio, the more reduction in binocular summation of the contrast sensitivity function, showing a high degree of correlation ($r^2 = 0.80$) between them. An important factor to consider is that the test sensitivity used for evaluating the CSF in that investigation was higher than in the present study, which could affect any comparison of the results. Likewise, Jimenez et al.[14] found descending correlations between binocular summation for the CSF and the interocular differences in the higher-order aberrations, demonstrating deteriorating visual performance with such interocular differences. In fact, Sabesan et al.[7] confirmed higher values of binocular summation correcting the higher-order aberrations, and determined neural adaptation with ocular aberrations. Moreover, Nitta et al.[82] reported that subjects with a strong imbalance in sensory dominance had lower binocular summations for contrast sensitivity, and confirmed that ocular dominance is crucial for clinical applications, such as the monovision procedure used to correct presbyopia. This is in line with the present findings, that is, considering several levels of interocular differences (induced by the different filters) in various ocular parameters (OSI, RS, MTF cut-off and log(s)), we found consequent decreases in the binocular summation of the different visual parameters investigated (VA, CSF and VDI). These simulated deteriorations, particularly with the Bangerter foils and the BPM2, confirmed that incremental change in straylight and intraocular scattering produce deterioration of binocular summation for the visual functions investigated (visual acuity, contrast sensitivity and visual discrimination capacity). These results could be useful in clinical practice, where the visual evolution in several ocular diseases[21,37,59,74] (keratitis, AMD, cataracts, etc.) and ocular surgeries[23,58,76–78] (photorefractive keratectomy, LASIK, cataract removal, etc.) may occur in one eye first, thereby contributing to the interocular differences (due to the forward scattering), producing binocular imbalance and a successive decrease in binocular visual performance. In particular, the visual parameters measured in this study are inherent in patients with cataract where, due to the lens opacity, straylight and intraocular scattering increase, thereby disrupting the retinal image quality and binocular visual performance.[42,73,83,84]

Stereoscopic perception allows the visual system to see the surrounding environment in depth, and is paramount in critical complex tasks such as driving.[18,36,57] We produced a large range of interocular differences, primarily using Bangerter foils and the BPM2 filter before the dominant eye. These relationships are in line with other studies. For example, Li et al.[51] reported that penalising the dominant eye with a Bangerter foil reliably decreased stereoscopic depth perception for all strengths of filter. Additionally, Perez et al.,[46] when characterising Bangerter foils, identified the degradation caused by these filters. Odell et al.[53] also selected Bangerter foils to induce monocular blur, and confirmed a consequent progressive degradation of stereoacuity thresholds. Interocular differences in blur sensitivity appear to be a useful factor in grading eye dominance; binocular viewing conditions being modified by increases in interocular differences.[85] Considering possible correlations between interocular differences and binocular visual performance, Castro et al.[86] analysed interocular differences in optical quality (higher-order aberrations and Strehl ratio) on the maximum disparity (the total range of stereoscopic perception) under mesopic conditions, and found an important correlation between these interocular differences and the incremental change in stereothresholds. Other studies[14,70] have confirmed that the higher the interocular differences, the less effective the binocular summation and the lower the maximum disparity. An important impact caused by increased interocular difference following LASIK surgery was investigated by Jimenez et al.,[41] where they found that an incremental increase in interocular differences in corneal asphericity caused a significant deterioration in stereopsis. However, in the present study, the wide range of filters used (Bangerter foils and fog filters) made it possible to produce and simulate different levels of stereoacuity deterioration, providing a better understanding of stereopsis as well as binocular visual performance.

Finally, in the baseline condition, the dominant eye corresponded with the best monocular visual performance rather than the non-dominant eye. In the present study, filters were placed before the dominant eye as occurs, for instance, in the treatment of amblyopia, penalising and partially or completely occluding the dominant (non-amblyopic) eye, which produces blurred images of varying degrees.[47,87] In this manner, penalising the sensory dominant eye created initially lower interocular differences compared to penalising the non-dominant one, but still allowed us to evaluate a range of interocular differences. However, we found low interocular differences in the baseline condition and, consequently, one might expect to find similar tendencies by placing the filter before the non-dominant eye.[88]

Some limitations in the present study should be taken into account. Firstly, suppression when wearing the different filters was evaluated using the Worth-4-dot test. We are aware that this may not be the most sensitive test to assess suppression, although the stereopsis tests gave us useful information about sensory fusion. Secondly, the number of subjects tested was limited. However, we should also highlight strengths of the study: a wide range of filters were tested, which induced different levels of forward scattering in the eye. Consequently, this allowed us to analyse a wide range of interocular differences through different ocular parameters and visual functions, as well as to study their effects on binocular visual performance.

In summary, the various impairments applied to the dominant eye revealed an important factor in the study of binocular visual performance. The increase in forward scattering, induced mainly by the Bangerter foils and the BPM2 fog filter before the dominant eye, produced greater interocular differences which jeopardised the overall binocular visual performance. Specifically, this caused a decrease in binocular summation (VA, CSF and VDI) and reduced distance stereopsis, which correlated with the increased interocular difference. In this regard, the present study reveals that it is important to avoid considerable interocular differences in ocular parameters such as optical quality (OSI), intraocular scattering and straylight (log(s)) to preserve adequate binocular visual performance (stereopsis and binocular summation).

These findings could be very useful in terms of specific aspects of binocular vision such as refractive surgery or ocular disease when they first affect one eye, or in techniques for the treatment of presbyopia (monovision contact lenses), amblyopia and emmetropisation, which could impact complex visual tasks such as driving.

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AUTHOR CONTRIBUTIONS

Francesco Martino: Conceptualization (equal); data curation (lead); formal analysis (equal); investigation (equal); methodology (equal); validation (equal); visualization (equal); writing – original draft (equal); writing – review and editing (equal). **José J Castro-Torres:** Conceptualization (lead); formal analysis (equal); investigation (equal); methodology (lead); resources (equal); supervision (equal); validation (equal); writing – original draft (equal); writing – review and editing (lead). **Miriam Casares-López:** Formal analysis (equal); investigation (equal); methodology (equal); validation (equal); visualization (equal); writing – review and editing (equal). **Sonia Ortiz-Peregrina:** Formal analysis (equal); investigation (equal); methodology (equal); validation (equal); visualization (equal); writing – review and editing (equal). **Carolina Ortiz:** Investigation (equal); methodology (equal); validation (equal); visualization (equal); writing – review and editing (equal). **José R Jiménez:** Conceptualization (equal); investigation (equal); resources (equal); supervision (equal); writing – review and editing (equal).

CONFLICT OF INTEREST

The authors declare no competing interests.

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