Binocular summation and visual function with induced anisocoria and monovision

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Abstract: The advances in new techniques for correcting presbyopia, such as a small aperture combined with monovision, require an in-depth study of binocular aspects. In this work, we have studied binocular visual performance of 12 subjects after inducing different degrees of anisocoria combined with two different add powers in the non-dominant eye. We have analysed visual performance in terms of the visual-discrimination capacity (a function to evaluate the strength of bothersome halos) and the contrast-sensitivity. The results show a deterioration of the binocular vision when inducing anisocoria and with any add power, with a higher perception of halos, a lower contrast sensitivity and poorer binocular summation of these visual functions on increasing anisocoria. This deterioration is clinically acceptable in the case of low add power, since positive binocular summation is maintained in contrast sensitivity, and visual discrimination is not altered.

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OCIS codes: (330.0330) Vision, color, and visual optics; (330.1400) Vision - binocular and stereopsis; (330.1800) Vision - contrast sensitivity; (330.4595) Optical effects on vision; (330.6100) Spatial discrimination.

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perforated with 5-11 μm diameter of 3.8 mm and a central aperture of 1.6 mm and has no refractive power. The inlay is efficient and safe [5, 6]. The intrastromal corneal inlay is an opaque ring with an outer of focus in the eye receiving the implant (normally the non-dominant eye) and it appears to be therefore in recent years research has considerably intensified in terms of developing new techniques, surgical or otherwise, for the compensation/correction of this condition. Given the growing percentage of the older population, any compensation or correction technique is apt to be used by a great number of people. Beyond reading glasses, there has been a continuous search for surgical solutions. However, there is no perfect method of fully correcting presbyopia. Among the surgical techniques, the implantation of an intrastromal corneal inlay with a small aperture is growing in use [1–5]. This has the advantage of extending the depth of focus in the eye receiving the implant (normally the non-dominant eye) and it appears to be efficient and safe [5, 6]. The intrastromal corneal inlay is an opaque ring with an outer diameter of 3.8 mm and a central aperture of 1.6 mm and has no refractive power. The inlay is perforated with 5-11 μm holes, which are randomly arranged, allowing nutritional flow through the inlay to sustain stromal tissue. Usually the inlay is implanted in the patient’s non-dominant eye, centred on the coaxially sighted corneal reflex and combined with a + 0.75D
micro-monovision. It is well known that the correct positioning of the inlay is critical to achieving good vision. One of the advantages of this surgical technique is that it is minimally invasive and easily reversible.

After this correction technique, the binocular visual performance in these subjects is not expected to be as effective as that of normal observers. Binocular vision with implanted corneal inlays can be affected by induced anisocoria on introducing the inlay, since the differences between the pupil sizes can be notable and affect binocular vision depending on the observation conditions. Some authors have simulated binocular visual performance to check for potential improvement provided by corneal inlays. For this, they employed a binocular adaptive optics vision analyser in a group of subjects to study stereoacuity [3] and binocular through focus visual acuity [4, 7]. These researchers found that, under photopic conditions, a small aperture combined with monovision can yield stereoacuity values similar to those attained under normal binocular vision.

The study of the contrast-sensitivity function in subjects implanted with the KAMRA inlay is also important. For example, Lin et al. [8] recently reported that the postoperative contrast sensitivity was mildly reduced monocularly and minimal reduction binocularly, maintaining these reductions comparable to or better than postoperative results from other surgical vision-correction procedures.

Another important aspect after surgical processes is that night-vision disturbances can appear. Many subjects mention problems such as halos and/or glare under low-illumination conditions after submitting to different surgical techniques [9, 10]. The objective measurement and quantification of night-vision disturbances is a highly demanded matter for the optimization of surgical emmetropization techniques. Usually, the visual-discrimination capacity under low-illumination conditions is used to quantify the night-vision disturbances. However, there are no studies to show how anisocoria influences visual-discrimination capacity, or how it alters the binocular summation of this visual function. Therefore the need arises not only to study the effect of this function with induced anisocoria but also to analyse the effect of monovision.

In this work, we propose quantifying the changes in binocular visual function due to different pupil sizes (simulating corneal-inlay implantations) and their effects in night-vision disturbances and in the contrast-sensitivity function, two important functions to evaluate visual performance. For this, in a group of subjects with healthy eyes, we used different artificial pupil sizes and measured their effects on the halos, using a test that enabled the quantification of night-vision disturbances. We also added the effect of monovision in order to simulate the real conditions of the subjects after this operation. We also studied the effect on the binocular contrast-sensitivity function, and we calculated the binocular summation corresponding to these two important visual functions in order to compare the visual performance under binocular conditions vs. monocular ones. One of the positive points of simulation experiments with young subjects having healthy eyes is that we avoid the effect of the surgical act and we can measure exclusively the effect on vision of having different pupil sizes in each eye. Our aim is to delve into the study of binocular visual function after inducing anisocoria, since the quantification of these visual changes can help us to understand what might be expected after corneal inlays are implanted and how to optimise the variables involved.

2. Methods

2.1 Subjects

A total of 12 subjects were studied, with ages ranging from 22 to 35 years and a mean age of 24.3 ± 4.0 years. Subjects gave their informed consent in accordance with the Helsinki Declaration. Admission criteria for the experiment were: astigmatism not greater than ± 1.0 D, decimal visual acuity ≥1.0 with best correction for both eyes and no pathological disease or
condition that could limit visual performance, such as any ocular suppression. The mean refractive error (spherical equivalent) was \(-0.63 \pm 2.12\) D. All the observers had normal stereopsis according to the Randot stereotest (40 arcsec or lower).

2.2 Procedures

Subjects performed the psychophysical tests (contrast-sensitivity and visual-discrimination capacity) with best correction, monocular and binocularly, under natural conditions. Furthermore, artificial pupils of diameters 2, 3, and 4 mm, were used. Tests were administered for each condition (monocular: right and left eye, and binocular) with the three artificial pupils sizes. Artificial pupils were placed in the trial frame, using the posterior lens holder (back side), with the hole centered. The anterior lens holders (front side) were used for the optical correction (spherical and cylindrical lenses). The trial frame was adapted to each subject and then the interpupillary distance was adjusted. The interpupillary distance was measured under the experimental conditions of our psychophysical tests. For this, we used an Essilor Digital CRP pupillometer in which we adjusted the distance to the test (2.5 m for the CSF and discrimination-capacity test). We also checked the interpupillary distance using an ophthalmic ruler, positioning the subject at 2.5 m from the test monitor. Then, we checked that the subject had correct fusion and binocular vision, presenting a stereopsis test (viewing with polarizers) on an optotype chart monitor at the test distance.

Data from psychophysical tests and objective measurements were made with no dilation or cycloplegia to maintain natural conditions and thereby avoid shift of the pupil center caused by these drugs.

To study the effect on binocular visual performance after inducing a simple anisocoria or combined with monovision, observers did visual tests using the artificial-pupil with the larger diameter in the dominant eye (DE) and the smaller one in the non-dominant eye (NDE), the latter with no add power, with an add power of \(+0.75\) D (a value considered as optimum defocus in a corneal inlay modelling [3, 11]), and finally with an add power of \(+1.25\) D, a value used in traditional monovision [12]. Ocular dominance of all subjects was checked with the Miles test [13].

Therefore, the visual tests were performed under different experimental conditions: both eyes monocularly and binocularly (natural, 2, 3, and 4-mm pupil size); binocularly inducing an anisocoria or a small aperture monovision using the artificial pupils (three different combinations: 4-mm DE/3-mm NDE; 4-mm DE/2-mm NDE; and 3-mm DE/2-mm NDE); and finally, for each anisocoria combination, simulating a combined monovision (small aperture and add power in the NDE), using two values of add power, \(+0.75\) and \(+1.25\) D. A total of six combinations were examined: 4-mm DE/3-mm NDE + \(+0.75\) D; 4-mm DE/2-mm NDE + \(+0.75\) D; 3-mm DE/2-mm NDE + \(+0.75\) D; 4-mm DE/3-mm NDE + \(+1.25\) D; 4-mm DE/2-mm NDE + \(+1.25\) D; and 3-mm DE/2-mm NDE + \(+1.25\) D).

Measurements were performed in six sessions after several initial training sessions. These sessions were held on different days to avoid observer fatigue. In the setting up of the psychophysical tests to measure the CSF and VDI, we confirmed that for the same subject, the results remained stable over the day and on different days. A total of seven tests were run in each session: 4 CSF tests and 3 discrimination-capacity tests (or vice versa). The tests were randomly performed under the different conditions.

2.3 Contrast-sensitivity function (CSF)

Contrast sensitivity (CS) was evaluated using Gabor patches of vertical gratings displayed on a Samsung SyncMaster 753DFX CRT monitor (15 inches). Visual stimuli were generated by the ViSaGe MKII stimulus generator (Cambridge Research Systems Ltd, Rochester, UK) [14, 15], and conducted with the software package Metropsis designed for that hardware. The test monitor was calibrated with the colorimeter ColorCAL (Minolta, Japan), especially developed for the specifications of the software and hardware.
The spatial frequencies tested were: 0.7, 1.5, 3.0, 6.2, 10.1, and 15.7 cycles per degree (cpd), using Gabor patches of vertical gratings in all cases. The average luminance level of the monitor was 30 cd/m² and the test was performed in dim surroundings. The test method used was the four alternate forced choice (4AFC) in which the stimulus is presented in one of four positions on the screen (upper left, upper right, lower left, and lower right). The observer position was fixed at 2.5 m using a chin and a forehead rest to minimize head movements. From this position, the grating subtended 0.40 deg. A black cross, as a fixation target, was displayed on the centre of the monitor. Grating was presented, in the different locations, to 1.20 deg from the fixation target. For each spatial frequency, the contrast threshold was determined with an up-down staircase procedure with four reversals. The contrast threshold was defined by the average of the last three reversals. Spatial frequencies were tested in a random order. For each observer, a session was performed after a 2-min dark adaption time to the luminance of the stimuli.

This CS test, with the use of a CRT monitor, offers a greater contrast range (lower contrast levels) than do the usual tests, whether printed (CSV-1000, Pelli-Robson chart, etc.) or displayed on an optotype chart monitor, which uses LCD technology. This test has been used in clinical applications, such as refractive surgery [16]. On the other hand, the 4AFC method enables a less biased estimate of contrast-sensitivity threshold than when other methods are used (Yes/No, Left/Right/Vertical), maintaining the central-vision condition.

2.4 Visual-discrimination capacity (halos)

We also measured visual performance in terms of the visual-discrimination capacity, a visual function which allows us to evaluate the strength of bothersome halos. For this, we used a freeware software (Halo v1.0) developed at University of Granada (http://www.ugr.es/~labvisgr/) to quantify the visual-discrimination capacity of observers by simulating the effects of halos [17]. This test has been successfully applied in basic and clinical research to measure night-vision disturbances [17–19]. In this test, the subject was shown a central high-luminance stimulus over a dark background on a monitor and, progressively, peripheral luminous stimuli were shown around the central stimulus at different positions and distances from the main stimulus.

Experimental sessions began with a 3-min adaptation period to darkness, followed by 1-min adaptation to the central high-intensive light (a small stimulus of 0.34 deg and a luminance of 170 cd/m²). After this adaptation period, peripheral stimuli (0.06 deg, 35 cd/m²) distributed around the central stimulus were randomly presented to the observer (peripheral stimuli were distributed along 12 semi-meridians around the central stimulus). Exposure time (on-period) was 0.8 s and the time between stimuli (off-period) was a random value between 1.0 and 2.5s, to avoid learning effects. This time configuration was found to be suitable in previous experiments. The monitor was also optimised in brightness and contrast controls to minimize background luminance. The central light served to fix the patient’s gaze. The patients were seated with the head supported by a chin and head rest, and the test was made monocularly for both eyes and binocularly. The test distance was 2.5m. The patient’s task was to press the left button of the mouse whenever a peripheral stimulus could be discriminated. This information was stored for calculating the visual-disturbance index, a parameter which quantifies the strength of halos and other night-vision disturbances. Each peripheral stimulus was presented 3 times (3 was the weight of the stimulus) in the session. The visual-disturbance index, VDI, was computed as:

\[
VDI = \frac{\sum_{i=1}^{N} (p_i r_i^3)}{3 \sum_{i=1}^{N} r_i^2},
\]

where \(r_i\) is the distance from the centre of the central stimulus to the centre of the i-peripheral stimulus; \(p_i\) is the number of times over the total weight (\(p_i \leq 3\)) that the i-peripheral stimulus
was not discriminated by the subject, and \( N \) the total number of different stimuli. The higher the amount of peripheral stimuli discriminated, the lower the VDI. The VDI takes values of between 0 and 1 (the lower the VDI, the better the discrimination capacity). On the other hand, the greater the index, the lower the visual-discrimination capacity, and therefore the subject has more difficulties in discriminating the peripheral stimuli near the central stimulus, indicating a greater influence of halos or night-vision disturbances. More information on this test can be found in different papers [17–19].

### 2.5 Binocular summation for visual functions

To compare binocular with monocular data in the visual functions studied, we calculated binocular summation, a metric used to characterize binocular visual performance [20–24]. Binocular summation for the CSF was calculated dividing the binocular CSF by the best monocular CSF Eq. (2). For each observer, binocular summation was provided as the average of the binocular summation determined for each spatial frequency, since binocular summation does not differ significantly with spatial frequency [25].

\[
BS_{CSF} = \frac{1}{6} \sum_{i=0.7}^{10.7} \left( \frac{CSF_{bin}}{CSF_{best\_mon}} \right)_i.
\]  

(2)

Where \( BS_{CSF} \) is the binocular summation for the CSF; \( CSF_{bin} \) is the binocular CSF; \( CSF_{best\_mon} \) is the best monocular CSF (the highest value of the two monocular CSF’s); and the subindex \( i \) corresponds to the \( i \)-spatial frequency, for the six spatial frequencies checked, from \( i = 0.7 \) to 10.7cpd.

Regarding the night-vision disturbances, as the discrimination capacity increases, the VDI decreases. Therefore, to report the binocular summation for the VDI, we divided the lowest monocular VDI between the binocular VDI Eq. (3).

\[
BS_{VDI} = \frac{VDI_{best\_mon}}{VDI_{bin}}.
\]  

(3)

Where \( BS_{VDI} \) is the binocular summation for the VDI; \( VDI_{best\_mon} \) is the best monocular VDI (the lowest value of the two monocular VDI’s); and \( VDI_{bin} \) is the binocular VDI. Binocular summation definition [Eq. (3)] for VDI is consistent with the binocular-summation concept used in different binocular-summation metrics, providing a value higher than 1.0 for normal binocular-vision conditions.

### 2.6 Ocular aberrometry

The data of ocular aberrations for both eyes were taken with an aberrometer based on a Hartmann-Shack sensor. We used the commercial aberrometer WASCA (Carl Zeiss Meditec AG, Germany) which provided the Zernike coefficients computed for \( \lambda = 555 \text{ nm} \). Aberrations were measured using optical fogging to achieve a non-accommodative state of the eye. From eye aberrations, we calculated the total RMS (root mean square) of higher-order aberrations from the third to sixth order as well as the RMS of spherical (square root of the sum of the squared coefficients of \( Z_4^0 \) and \( Z_6^0 \)) and coma aberrations (square root of the sum of the squared coefficients of \( Z_3^1, Z_3^{-1}, Z_5^1 \) and \( Z_5^{-1} \)), as other works have shown to characterize aberrations [26]. Data on aberrometry were computed using the software provided by the aberrometer, for different pupil diameters: natural, 5, 4, 3, and 2-mm pupil.

### 2.7 Retinal-image quality: Strehl ratio and MTF cutoff

Data on retinal-image quality were taken from an optical-quality device, OQASII (Optical Quality Analysis System II, Visiometrics SL, Tarrasa, Spain), an optical instrument based on the double-pass technique widely validated [27–29]. This device provides information on higher-order aberrations, diffraction, and scattered light, using an infrared laser diode (\( \lambda = \)
780nm) as light source. To characterize the retinal-image quality we took the Strehl ratio and the modulation transfer function (MTF) cutoff [19, 20].

The Strehl ratio is defined as the ratio between 2D-MTF area of the eye and the diffraction-limited 2D-MTF area, ranging from 0 to 1. A lower value indicates lower retinal-image quality due to a greater influence of ocular aberrations and scattered light. On the other hand, the MTF represents the loss of contrast produced by the eye’s optics on a sinusoidal grating as a function of its spatial frequency [29]. The MTF cutoff theoretically represents the spatial frequency, in cycles per degree (cpd), corresponding to an MTF value of 0. However, due to the noise introduced by the CCD camera, which collect the double-pass image, the MTF cutoff is the frequency (cpd) at 1% of maximum MTF. That is, the double-pass device uses a MTF threshold value of 0.01 for reporting the MTF cutoff [27, 29]. The definition used here for this parameter is not equal to the classical definition, which is calculated based on wavelength and pupil diameter [30]. In any case, a lower value of the MTF cutoff indicates worse optical quality of the eye.

Data on the optical quality of the eye were referred to different pupil diameters: 2-, 3-, 4-, and 5-mm pupil. Data were taken from both eyes with no pupil dilation to maintain natural conditions.

2.8 Data analysis

We used the software package OriginPro 8.6 for the data analysis and for the graphical representation. An analysis of variance (ANOVA) was used to analyse the mean values between different experimental conditions (natural, anisocoria, and anisocoria combined with add power in the NDE) and then a post hoc comparison (level of significance of 0.05).

3. Experimental results and discussion

Results of the retinal-image quality and ocular aberrations are shown in Table 1. Mean values of the RMS for spherical, coma and high-order aberrations (HOA) as well as the MTF cutoff and the Strehl ratio are provided for pupil diameters of 5, 4, 3, and 2 mm. The RMS of ocular aberrations for natural pupil (mean pupil diameter of 6.5 ± 0.9mm) is also included. After performing the statistical analysis, we found that the RMS for ocular aberrations with a natural pupil was significantly higher (p<0.05) compared with the data computed for 5, 4, 3, and 2 mm of pupil diameter. Regarding the retinal-image quality, by means of the MTF cutoff and the Strehl ratio, we found similar results comparing pupil diameters from 5 to 2 mm, since the retinal-image quality deteriorated as the pupil diameter increased. It was found that with 2 mm of artificial pupil size, both the mean HOA RMS as well as the spherical aberration increase with respect to values found at 3 mm, although this change was not significant (p>0.05). Some authors have shown that as the pupil becomes smaller the coefficients of the HOA undergo considerable variance due to the fitting error [31]. This does not occur with a double-pass device, where data are taken using artificial pupils rather than by fitting. When we compared the optical quality corresponding to the various pupil sizes, we found no significant difference for anisocorias of 1 mm (p>0.05), but differences proved significant for anisocorias of 2 or 3 mm (p<0.05).
Table 1. Mean values (standard deviation included) of the RMS of ocular aberrations (spherical, coma, and higher-order aberrations, HOA), MTF cutoff and Strehl ratio, for different pupil diameters

|                     | Natural pupil | 5 mm       | 4 mm       | 3 mm       | 2 mm       |
|---------------------|---------------|------------|------------|------------|------------|
| RMS HOA (µm)        | 0.529 ± 0.294 | 0.227 ± 0.172 | 0.143 ± 0.126 | 0.098 ± 0.072 | 0.103 ± 0.045 |
| RMS Spher (µm)      | 0.180 ± 0.121 | 0.073 ± 0.049 | 0.038 ± 0.025 | 0.033 ± 0.021 | 0.042 ± 0.034 |
| RMS Coma (µm)       | 0.328 ± 0.247 | 0.145 ± 0.173 | 0.095 ± 0.120 | 0.068 ± 0.068 | 0.068 ± 0.043 |
| MTF cutoff (cpd)    | -             | 29.35 ± 10.17 | 34.30 ± 9.23 | 40.16 ± 8.36 | 43.55 ± 7.87 |
| Strehl ratio        | -             | 0.170 ± 0.050 | 0.197 ± 0.056 | 0.232 ± 0.059 | 0.254 ± 0.056 |

Table 2 presents the results of the visual-discrimination and contrast-sensitivity functions in dim surroundings. Mean values of the visual-disturbance index (VDI) and contrast sensitivity (CS), both binocular and monocular, are shown under natural conditions (mean pupil diameter of 6.1 ± 0.9mm) and with artificial-pupil diameters of 4, 3, and 2 mm. The VDI was significantly higher under natural conditions (p<0.05), both binocularly as well as monocularly, compared with artificial pupil diameters of 4, 3, and 2 mm, indicating an improvement in the discrimination capacity with these artificial pupil sizes. This result was to be expected given the deterioration in the optical quality of the eye due to ocular aberrations and intraocular scattering as the pupil size enlarged (Table 1). Such differences were greater monocularly (p<0.001) compared with the binocular results (p = 0.033). However, when artificial pupils were considered, non-significant differences were found for the binocular mean comparisons 4 mm to 3 mm, 4 mm to 2 mm, and 3 mm to 2 mm, although, on average, the VDI was lower when decreasing the artificial-pupil diameter from natural to 2 mm. The results were similar under monocular conditions, except for the 4 mm to 3 mm comparison, where the VDI for the 4-mm pupil was significantly higher (p = 0.016) than the VDI for 3 mm. Participants perceived more halo effects with natural pupils than using artificial pupils. This agrees with the results of Table 1, showing an improvement in optical quality as the pupil diameter diminished to 3 mm. This improvement in the optical quality of the eye affects the visual function, as demonstrated in other works, which correlated optical quality with visual performance [18, 19]. The monocular contrast sensitivity improved significantly as the pupil diameter decreased from natural to artificial pupils of 4 mm (p = 0.018) and 3 mm (p = 0.015), but not for the 2-mm pupil (p>0.05). In the same way, binocular contrast sensitivity improved significantly on shifting from natural conditions to pupils of 4 mm (p = 0.038) and 3 mm (p = 0.026). In view of the results (Table 2), binocular visual performance was better than monocular, both for the visual-discrimination capacity as well as for contrast sensitivity, indicating the superiority of the binocular system as opposed to the monocular case. It bears noting that the subjects with higher amounts of aberrations tended to benefit more from the inlay, as the binocular summation, for example, did not diminish as much as in the other subjects.

|                     | Natural pupil | 4 mm       | 3 mm       | 2 mm       |
|---------------------|---------------|------------|------------|------------|
| VDI (mon)           | 0.707 ± 0.246 | 0.448 ± 0.197 | 0.394 ± 0.184 | 0.414 ± 0.181 |
| VDI (bin)           | 0.562 ± 0.295 | 0.374 ± 0.233 | 0.354 ± 0.210 | 0.330 ± 0.180 |
| CS (mon)            | 29.9 ± 9.0    | 35.6 ± 13.5 | 36.2 ± 9.9  | 32.4 ± 8.6 |
| CS (bin)            | 52.3 ± 17.8   | 58.1 ± 14.2 | 59.2 ± 15.7 | 46.2 ± 11.4 |
Figure 1 represents a bar graph of the binocular VDI (VDIbin) under different experimental conditions: natural pupils; non-anisocoria using artificial pupils of 4, 3, and 2 mm; and inducing different anisocorias with the artificial pupils (DE 4-mm pupil and NDE with a 3- or 2-mm pupil; or DE 3-mm and NDE with 2 mm). The three conditions of anisocoria were also analysed with two different add powers in the NDE, + 0.75 and + 1.25D. It was found that with pupils of the same size in both eyes (no anisocoria) of 4, 3, and 2 mm, the binocular VDI took lower values, indicating a greater visual-discrimination capacity than under conditions of induced anisocoria, except in the case of having both pupils of natural size (6.1 ± 0.9mm), a situation in which this discrimination capacity substantially diminishes. When anisocoria of 2 mm (4mm DE /2mm NDE) was induced, the binocular VDI was greater (worse discrimination capacity) than with an anisocoria of 1 mm (4mm/3mm, 3mm/2mm). This was because the differences in optical quality between the two eyes are significant when the two pupil diameters differed by 2 mm but not when they differed only by 1 mm (Table 1). The VDI for the condition DE 4mm/NDE 2 mm was significantly higher than for the VDI under the binocular conditions of 4 mm (p = 0.006), 3 mm (p = 0.003) or 2 mm (p = 0.002). Similar results were found for the condition DE 3 mm/NDE 2 mm, but for DE 4 mm/NDE 3 mm, for which no significant differences were found (p>0.05) compared to the non-anisocoria conditions. However, with add power in the NDE, the VDI was significantly higher in all cases compared with the VDI under conditions of non-anisocoria, this difference being more pronounced for the greater add power (+ 1.25 D). That is, the visual-discrimination capacity significantly deteriorated on introducing an add power of + 0.75 D in the NDE, increasing this deterioration with an add power of + 1.25 D. However, there were no significant differences (p>0.05) between the VDI with an add power of + 0.75 D and the VDI with an add power of + 1.25 D. On the other hand, there were no significant differences between the binocular VDI under natural conditions compared with any binocular VDI with any add power in the NDE. Given the improvement in the visual-discrimination capacity on reducing the pupil diameter, it should be taken into account that this is counteracted by the deterioration in binocular summation on inducing anisocoria.
Results on binocular summation for the visual functions studied are shown in Table 3. Under natural conditions, the mean binocular summation both for the contrast sensitivity as well as for the visual-discrimination capacity were higher than 1, indicating the superiority of the binocular system with respect to the monocular one. With all the artificial-pupil diameters, the binocular summation for the VDI diminished significantly with respect to the natural pupils (p<0.05), the combination 4 mm-DE/3 mm-NDE presenting less deterioration, this combination of artificial pupil sizes being the only one that results in binocular summation (BSVDI) greater than 1 on average. When an anisocoria of 2 mm was induced (DE 4 mm; NDE 2 mm), as well as in the case of 1 mm of anisocoria induced by pupil values of 3 mm-DE/2 mm-NDE, the average values of binocular summation for VDI were less than 1, implying lower binocular visual performance than in the monocular case (less efficient interaction of the monocular images to achieve binocular vision). This binocular summation also deteriorated in a statistically significant way (p<0.05) in all cases when applying an add power in the non-dominant eye, although we found no differences comparing the results for a lower add power (+ 0.75D) and a higher one (+ 1.25D).

Regarding the binocular contrast-sensitivity function, for each participant, the data were averaged for all spatial frequencies (CSbin). The mean contrast-sensitivity value was significantly higher under natural conditions (p<0.05) than in the rest of experimental conditions (except in the case DE-4mm/NDE-3 mm, where there were no significant differences), this trend being found both with or without any add power. These results agree with the findings of other authors who have shown a deterioration in the postoperative contrast sensitivity (monocular and binocular) after inlay implantation and without any add power [8]. With the two combinations of artificial pupils which induced an anisocoria of 1 mm (DE-4 mm/NDE-3 mm and DE-3 mm/NDE-2 mm), there were no significant differences in the average binocular CSF between the condition without any add power and that with a small one (+ 0.75D), or between the two values of add power. However, the binocular CSF was significantly lower with the highest add power compared with the case without add power (p<0.05). In the case of an anisocoria of 2 mm (DE-4mm/NDE-2mm), contrast sensitivity did deteriorate significantly with respect to the anisocoria of 1 mm. Comparing the two anisocorias of 1 mm without add power (DE-4 mm/NDE-3 mm and DE-3 mm/NDE-2 mm), we found no differences. In all the situations of induced anisocoria, the binocular CS was better without any add power, and diminished on increasing the add power in the NDE.

### Table 3. Mean values (standard deviation included) of the binocular visual-disturbance index (VDIbin) and contrast sensitivity (CSbin) with different anisocorias and different values of add powers (Add) in the non-dominant eye (NDE). DE: Dominant eye. BSVDI and of the CSF (BSCSF) are also included.

| Pupil (mm) | DE | NDE | Add (NDE) | VDIbin | BSVDI | CSbin | BSCSF |
|-----------|----|-----|-----------|--------|--------|-------|-------|
| Natural   | Natural | -   | 0.565 ± 0.298 | 1.305 ± 0.376 | 52.3 ± 17.8 | 1.473 ± 0.424 |
| 4         | 3   | -   | 0.393 ± 0.247 | 1.004 ± 0.331 | 54.8 ± 15.4 | 1.167 ± 0.319 |
| 4         | 3   | + 0.75D | 0.504 ± 0.264 | 0.778 ± 0.342 | 45.2 ± 16.1 | 0.982 ± 0.228 |
| 4         | 3   | + 1.25D | 0.546 ± 0.294 | 0.732 ± 0.277 | 42.7 ± 12.6 | 0.949 ± 0.263 |
| 4         | 2   | -   | 0.484 ± 0.233 | 0.801 ± 0.217 | 43.3 ± 11.8 | 1.056 ± 0.325 |
| 4         | 2   | + 0.75D | 0.563 ± 0.265 | 0.677 ± 0.134 | 38.4 ± 15.3 | 1.027 ± 0.350 |
| 4         | 2   | + 1.25D | 0.596 ± 0.292 | 0.655 ± 0.182 | 36.4 ± 11.4 | 0.937 ± 0.218 |
| 3         | 2   | -   | 0.457 ± 0.248 | 0.793 ± 0.211 | 48.9 ± 14.1 | 1.083 ± 0.365 |
| 3         | 2   | + 0.75D | 0.530 ± 0.268 | 0.690 ± 0.216 | 41.5 ± 12.6 | 1.036 ± 0.331 |
| 3         | 2   | + 1.25D | 0.576 ± 0.266 | 0.639 ± 0.243 | 37.3 ± 17.2 | 0.942 ± 0.398 |
Figure 2 shows the mean CSF’s for the natural condition and for the anisocoria of 2 mm under different conditions. The most deteriorated CSF corresponded to the anisocoria with the add power of +1.25D compared with natural pupils. In all cases, the mean CSF was deteriorated compared with the CSF under natural pupils. It bears mentioning that the CSF values that we measured in our laboratory are of the same magnitude as those published recently by Lin et al. [8] with the aim of providing a referent in the investigation of the impact of presbyopia-correcting ophthalmic procedures on contrast sensitivity.

With respect to binocular summation of the CSF (BS_{CSF}), as might be expected, we found the highest value in the case of the natural pupils in both eyes. When anisocoria was induced, both of 1 and 2 mm, the BS_{CSF} diminished significantly (p<0.05) with respect natural conditions, although the BS_{CSF} remained at values higher than 1 in all cases when we did not add any to the NDE. This indicates that the binocular system is more effective than under monocular conditions even when anisocoria was induced. Only for the combination of 4 mm/3 mm, was the BS_{CSF} significantly greater than with add power in the NDE. In no case were significant differences found on checking the BS_{CSF} results between the add power of +0.75 D and +1.25 D. On the other hand, with the add power of +1.25D, the binocular summation fell slightly below 1 in the three cases of anisocoria, indicating a slight inhibition of binocular visual performance as opposed to monocular vision. These results indicate that for contrast sensitivity, the effectiveness of the summation was stronger than for the visual-discrimination capacity.

Figure 3 shows, for the case of an anisocoria of 2 mm, the binocular summation for the CSF against the interocular difference in the Strehl ratio. The interocular difference was determined by the difference between the Strehl ratio of the dominant eye measured at 4 mm and the Strehl ratio of the non-dominant eye measured at 2 mm. A decreasing significant correlation was found (p<0.01), in such a way that the higher the interocular differences in the Strehl ratio, the lower the binocular summation for the CSF. This correlation was similar to that found in other studies [20], although the present work shows higher values of interocular differences due to the anisocoria, as well as a broader range of values for binocular summation, even becoming less than 1 when the interocular differences were greater.
To summarize our results, we can state that, of all the simulated situations, the best binocular vision performance in the functions studied corresponds to the case of 4 mm of pupil in the DE and 3 mm in the NDE with no add power, given that it is the only situation in which both the \( B_{S_{VDI}} \) and the \( B_{S_{CSF}} \) remained above 1, showing greater effectiveness of the visual system under binocular as opposed to monocular conditions. In all other cases, the perception and binocular-discrimination capacity proved worse than monocular, indicating a major limitation by inhibiting the binocular summation inherent to our visual system.

In this study, the visual functions were measured at an intermediate distance, and thus in future work it would be useful to evaluate both binocular summation of the CSF as well as the VDI in near vision, to check the benefits of this correction technique at different distances. Vilupuru et al. [33] analysed the mesopic contrast sensitivity for intermediate vision in patients implanted with the KAMRA inlay and compared it with respect to patients binocularly implanted with three different intraocular lenses (2 multifocal IOLs and 1 accommodating IOL). They found better binocular contrast sensitivity for the inlay patients, especially with glare, resulting in better visual performance. However, the effect of monovision in the small aperture technique was not analysed in their work.

As is well known, to place an artificial pupil in the eye represents a compromise between improved depth-of-focus, luminance, and optical quality. Plainis et al. [34] reported that artificial reduction in the pupil diameter of one eye and the consequent induced interocular differences in retinal illuminance cause interocular differences in visual latency. This visual latency can distort the perception of the position and path of moving objects, and thus can lead to hazard in some everyday tasks. Zheleznyak et al. [35], studying the impact on visual performance of modified monovision with monocularly induced spherical aberration to increase depth of focus, found a substantial benefit in through-focus visual acuity and binocular depth of focus as compared to traditional monovision. Thus, to take into account the real effects of the induction of anisocoria with artificial pupils, we also need to consider different aspects such as scene luminance, whether or not the task to be evaluated is in movement, the pupil diameter, optical quality of the eye, the Stiles-Crawford function of the individual, and of course, the centration of the inlay.

As binocular vision is the natural state of human vision, an analysis of the characteristics of visual performance studied in the present work (such as binocular summation of two important visual functions) is vital for characterizing our vision. These aspects are highly useful for optimising emmetropization techniques. For this reason, it is important to avoid generating interocular differences in patients, whether in terms of optical quality (HOA, scattering, Strehl ratio, etc.) or in visual performance through functions as important as discrimination capacity or CSF, since these asymmetries deteriorate binocular visual performance [20, 24, 35].
The clinical applicability of these results is important, as it has been demonstrated that the induction of certain anisocorias, combined or not with add power, can considerably limit the summation capacity characteristic of our binocular visual system. After inducing anisocorias, although the optical quality and visual quality of these eyes under monocular conditions proved optimal, we have demonstrated that when we study binocular visual functions, such as the discrimination capacity under low illumination conditions, or the contrast-sensitivity function, these deteriorate. Similarly, if we calculate the binocular summation corresponding to these visual functions, we find a deterioration that limits the capacity of our visual system. On the other hand, it is important to indicate the differences in these visual functions found in these subjects are possibly less after the real clinical application, because the long-term neural adaption effects can reduce interocular differences in latency [34].

Thus, in the case of a small aperture combined with a low add power in the NDE, the resulting deterioration is acceptable for subjects to have comfortable visual performance, as shown in some studies [3, 7], since a positive summation is maintained for the CSF and furthermore the visual-discrimination capacity is similar to that measured under natural conditions. Our results show that when we induce an anisocoria of 1 mm (DE 4 mm/NDE 3 mm), the visual discrimination capacity is similar to that found under conditions without anisocoria. Other authors [3] have also shown that the use of a small aperture in one of the eyes significantly reduces the negative impact of monovision on stereopsis to a value close to that achieved under natural vision condition.

These results should be taken into account when designing surgical treatments to compensate for presbyopia, as it is desirable not only to have good visual acuity both near up as well as far away after the surgery, but also to continue having the same binocular visual performance as before the operation. Nevertheless, the binocular deterioration that we have measured is similar to that reported in some works in which the visual function was analysed after different correction treatments for presbyopia [3, 5, 34], where it is demonstrated that these declines in certain binocular aspects are in general clinically minor for the subjects, considering that after surgery good near (and distance) vision is recovered without the need for optical compensation.

4. Conclusion

In this work, we have analysed how interocular asymmetries influence binocular summation, taking into account visual functions that have hardly been studied in clinical applications (binocular summation for the CSF) but also others not analysed to date, such as binocular summation for the visual-discrimination capacity, which provide new data for a complete study of the complex process of binocular vision. We have demonstrated that the interocular differences in optical quality and in visual functions, caused by the anisocoria induced, diminishes (although non-significantly) the binocular visual-discrimination capacity and the binocular contrast-sensitivity function. Nevertheless, this deterioration is similar to that reported in studies on surgical techniques for correcting presbyopia and provides acceptable clinical results if we take into account that it provides the subject good far as well as near vision under different lighting conditions. Thus it would be advisable for potential patients, before being subjected to these surgical techniques involving anisocoria and/or monovision, to be informed concerning the limitations in terms of binocular visual performance after surgery.

Funding

This work was supported by Ministry of Economy and Competitiveness (Spain) and European Regional Development Fund (ERDF) (Grant FIS2013-42204-R).

Acknowledgments

We thank David Nesbitt for translating the text into English.