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Visual acuity with computer simulated and lens-induced astigmatism

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The relationship between spherical and astigmatic refractive errors and their associated visual acuity is investigated in this work by means of two different approaches. In the first one, different refractive errors were induced in normal subjects by trial lenses. In the second one, defocused images were simulated numerically by the optical transfer function of a model eye and then judged by the same subjects. The amount of defocus (measured in terms of the modulus of the dioptric power vector) necessary to reduce the visual acuity to 0.1 logMAR and to 0.4 logMAR was computed with each method and then compared. We found that the visual system is clearly more tolerant to lens-induced defocus than for the computer simulated one. However, no significant differences in visual acuity were found for astigmatism of the same power but different axes in each method.

Keywords: visual acuity, simulated defocus, astigmatism, lens-induced defocus, power vector, Zernike polynomials.

1. Introduction

Visual acuity (VA) is a standard parameter by which the outcome of most clinical trials is judged. Several studies have described the relation between VA and refractive errors [1–10]. In most of these analyses either an artificial degradation of vision in normal subjects is produced with trial lenses [4–9], or letter acuity charts are blurred by numerically simulated defocus [8–10]. Both methods have advantages and disadvantages. The first one, also called the "observer method" [7], is mainly affected by optical factors (lens centrations, vertex distance, reflections on the lenses, chromatic aberration, *etc.*); the second one, also called the "source method" was claimed to substitute the previous one, principally in research activities, because it minimizes the variability of the results reported by different subjects. However, the source method could be affected by the model eye employed to obtain the retinal image. The so-called "neural adjustments to image blur" [11] also affect both methods in a different way. Because of their inherent differences, the VAs reported with both methods do not give, necessarily, the same value. In a pioneer study, SMITH *et al.* [7] found that both methods are correlated, but their differences were statistically significant, being the VA obtained with the observer method better than the one reached with the source method. Recently, a similar study was performed by DEHNERT *et al.* [8]. In this case, authors report no statistical differences between both methods, but contrary to the work of SMITH *et al.* [7], they found that VAs obtained with the source method were slightly better than those obtained with the observer method. In [7] and [8] only spherical defocus was considered. In another recent paper, OHLENDORF *et al.* [9] compared both methods inducing spherical and astigmatic blur. They found that both methods are correlated with minor differences between them for spherical defocus, but for astigmatism, the source method reduces VA much more than the observer method. GRACIA *et al.* [12] also found that VA measured under natural ocular high order aberrations was significantly higher than VA measured with simulated aberrated images.

In the light of these last reports it seems that there is a need for further investigation about the validity of the source method to substitute the observer method in reporting VA in the presence of spherical, and especially, astigmatic defocus. This is the purpose of this work. We investigate the effect on VA of astigmatic defocus produced by lenses and compare the results with those obtained with equivalent numerically simulated astigmatism. Simple myopic astigmatism (SMA), mixed astigmatism (MA) and myopic defocus were simulated using Fourier techniques and also generated with trial lenses. The amount of defocus, measured in terms of dioptric power vector, or blur strength B, necessary to reduce the VA of normal observers to 0.1 logMAR and to 0.4 logMAR was measured and compared.

2. Methods

Four subjects with no evidence of ocular disease participated in this study with an average age of 25 years. Only right eyes were considered. The summarized subjects' data are presented in Table 1. Pupil sizes were measured from photographs taken with a digital camera under the same experimental lighting conditions. During the experiment, pupil sizes and accommodation were not controlled artificially. For all subjects, compensated VA was 20/15 or better (logMAR < –0.1).

T a b l e 1. Subject's data.

Subject	Age [year]	Subjective refraction	Amplitude of accommodation [D]	Pupil diameter [mm]
E1	25	0.00/–0.50×90°	8.5	4.50
E2	26	–0.75/–0.50×180°	6.5	4.00
E3	24	0.00/0.00	7.5	5.00
E4	25	+1.00/0.00	8.0	4.50

Table 2. Combination of sphere S and cylinder C used to simulate different refractive errors; B is the modulus of the corresponding power vector.

SMA	MA	Myopic defocus
S/C (B)	S/C (B)	S/C (B)
0.00/+0.25 (0.18)	+0.25/–0.50 (0.25)	+0.25/0.00 (0.25)
0.00/+0.50 (0.35)	+0.50/–1.00 (0.50)	+0.50/0.00 (0.50)
0.00/+0.75 (0.53)	+0.75/–1.50 (0.75)	+0.75/0.00 (0.75)
0.00/+1.50 (1.06)	+1.00/–2.00 (1.00)	+1.00/0.00 (1.00)
0.00/+2.25 (1.59)	+1.25/–2.50 (1.25)	+1.25/0.00 (1.25)
0.00/+3.00 (2.13)	+1.50/–3.00 (1.50)	+1.50/0.00 (1.50)
0.00/+3.50 (2.48)	+2.00/–4.00 (2.00)	+2.00/0.00 (2.00)

The stimulus, consisting of a single line of optotypes (non-serif Snellen letters: C, D, E, F, H, K, N, P, R, U, V, and Z) [13] was presented to the observers at 5 meters on a computer monitor with a luminance of 125 cd/m^2. To minimize the effect of crowding, the distance between letters was set equal to the letter size [13, 14]. A random sequence of letters was used in each trial to avoid learning effect. The luminance response of the monitor was determined for different pixel gray levels in steps of 10 pixel gray levels. We found that for gray levels from 90 to 210, the response curve was almost linear.

Different levels of defocus were induced or simulated in each session, recording the values that reduced the B to 0.1 logMAR and to 0.4 logMAR, *i.e.*, when more than 50% of letters in a line were not identified. Table 2 summarizes the combination of powers used to simulate the different refractive errors. In each case the conventional script notation (S; $C \times \alpha$) was converted to power vector coordinates (M, J_0, J_{45}) and the norm of the power vector, or blur strength B, was computed using the following equations:

$$M = S + \frac{C}{2} \tag{1a}$$

$$J_0 = -\frac{C}{2}\cos(2\alpha) \tag{1b}$$

$$J_{45} = -\frac{C}{2}\sin(2\alpha) \tag{1c}$$

$$B = \sqrt{M^2 + J_0^2 + J_{45}^2} \tag{1d}$$

Measurements were performed in a quiet environment exclusively used for research activities with constant ambient lighting conditions 70 ± 10 lux and were repeated three times in different sessions. The time involved in each session was restricted to 45 minutes to minimize the effects of fatigue (three days elapsed between sessions).

Statistical analysis was performed using Statistical Product and Service Solutions (SPSS 14.0) for Windows software. The data were tested for normality of distribution

(Kolmogorov–Smirnov ($p > 0.05$ in all cases) and Levene normality test) and equivalence of variance (F-test).

2.1. Observer method or lens-induced defocus (LID)

In the LID method, SMA was induced over the individual refractive correction, using a positive cylinder at 0°, 45° and 90°. MA was induced also at 0°, 45° and 90° but using an equivalent Jackson cross-cylinder. Myopic spherical defocus was induced with positive spheres. In all cases, the back vertex distance was set to 12 mm.

2.2. Source method or computer simulated defocus (CSD)

In the CSD method, defocused images were simulated numerically using the standard Fourier techniques by means of the optical transfer function (OTF) computed for a simple model eye following the procedure sketched in Fig. 1 [8, 15]. First, the vector components corresponding to each induced refractive error Eq. (1) were converted to the second order Zernike aberrations coefficients using the following expressions [16]

$$a_3 = \frac{-J_{45} r^2}{2\sqrt{6}} \tag{2a}$$

$$a_4 = \frac{-M r^2}{4\sqrt{3}} \tag{2b}$$

$$a_5 = \frac{-J_0 r^2}{2\sqrt{6}} \tag{2c}$$

where a_4, a_3, and a_5 are the defocus and astigmatism Zernike coefficients in µm and r is the pupil radius that was set to 2.25 mm, which is the mean value of the four subjects under experimental conditions. Then, the pupil function that incorporates the complete information about imaging properties of the model eye is calculated as

$$P(x, y) = A(x, y) \exp\left[-i \frac{2\pi}{\lambda} \sum_j a_j Z_j(x, y)\right], \quad j = 3, 4, 5 \tag{3}$$

where $Z_3(x, y)$, $Z_4(x, y)$, and $Z_5(x, y)$ are the Zernike polynomials corresponding to astigmatism at 45°/135°, defocus, and astigmatism at 0°/180°, respectively. $A(x, y)$ is the circular aperture representing the eye pupil with a unit amplitude transmittance and $\lambda = 555$ nm is the wavelength of the light.

The PSF and the OTF were both numerically calculated by means of a Fourier transform algorithm (a detailed description of the method to compute the simulated

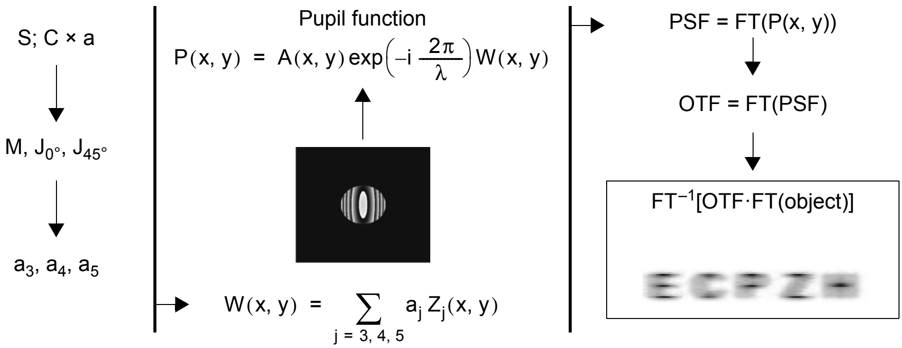

Fig. 1. Scheme of the computer simulated defocus (CSD) method (see the main text for details).

images can be checked in the Appendix of [8]). The images were presented in a matrix of 601×601 pixels. In this way, at the chosen viewing distance, one pixel subtended 5×10^{-5} rad (0.17 min arc) and the smallest detail for the 0.1 logMAR letter was 7.00 pixels. By multiplying the OTF with the Fourier spectrum of the set of letters and doing an inverse Fourier transform, the defocused image of the test is obtained and finally presented to the compensated eye.

The effect of diffraction when viewing the convolved image through a diffraction-limited natural pupil was not corrected by means of inverse filtering because it was considered negligible under the experimental conditions.

3. Results

Figure 2 shows the individual results of the amount of pure spherical defocus, measured as the modulus of the dioptric power, necessary to reduce the VA of the observers to 0.4 logMAR and to 0.1 logMAR. As can be seen, both the LID and CSD reduced VA to a similar degree. Note that, except for subject E2, all subjects needed slightly higher values of defocus with the LID method. There are no significant differences between both

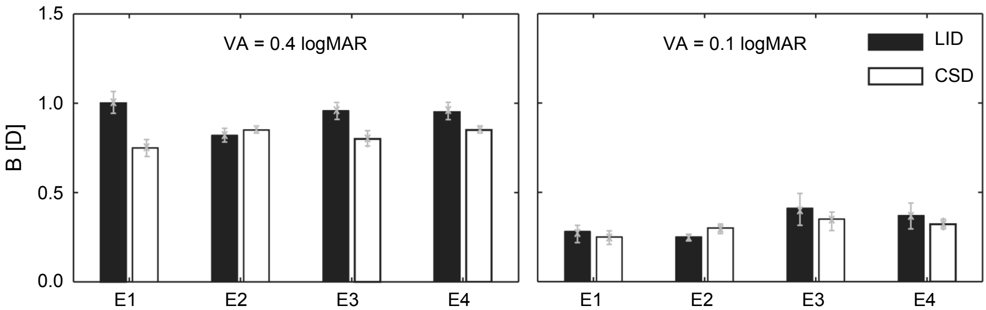

Fig. 2. Values of spherical defocus (blur strength B) necessary to reduce the VA to 0.4 logMAR and to 0.1 logMAR by the LID and CSD methods for different subjects. Standard deviations are shown.

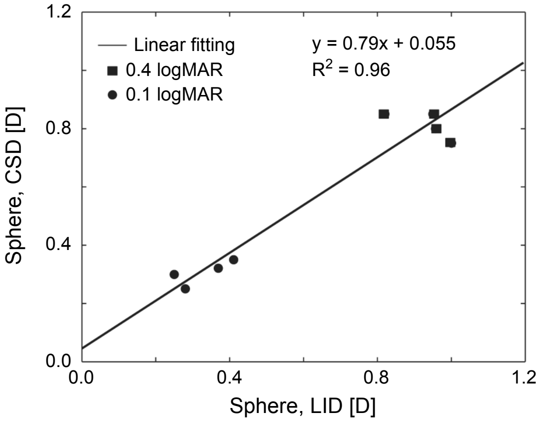

Fig. 3. Amount of sphere required for obtaining a drop of visual acuity to 0.1 logMAR and to 0.4 logMAR with the CSD method as a function of the amount of sphere required with the LID method for the 4 subjects of the study. Linear fit represents the fit for both groups together.

methods [VA: 0.4 logMAR ($F = 5.891$, $p = 0.051$) and VA: 0.1 logMAR ($F = 0.270$, $p = 0.622$)]. It should be noted that the p-value of 0.051 for 0.4 logMAR VA is very close to the limit of statistical significance $p = 0.05$. Considering that only 4 data points on each group were evaluated, a p-value of 0.051 indicates a strong trend. Also, the linear fit of the required amount of defocus introduced in the simulations as a function of the optical sphere required to obtain a certain level of blur (see Fig. 3) shows a slope of 0.79 ($R^2 = 0.96$). Therefore to achieve a comparable amount of blur, only a 79% of the amount of optical defocus is required in the computationally induced blur method.

The mean value of B necessary to reduce the VA to 0.4 logMAR is (0.92 ± 0.08) D for LID method, and (0.81 ± 0.04) D for CSD method. For 0.1 logMAR these values are reduced to (0.32 ± 0.07) D for CSD method and (0.30 ± 0.06) D for LID method. The inter-individual variability of results for spherical defocus was lower than 0.087 logMAR units.

In Figure 3 the CSD values were represented as a function of the LID values along with a linear fit. The linear fit shows that the CSD method only requires a 79% of the defocus required by the LID method to achieve the same level of blur.

Table 3 shows the mean values of B (for the three axes) needed to reduce VA to 0.1 logMAR and to 0.4 logMAR for different types of astigmatism. Figure 4 shows

T a b l e 3. Mean values of B (in diopters) necessary to reduce VA to 0.4 log MAR and to 0.1 log MAR with both methods.

VA	SMA		MA	
	LID [D]	CSD [D]	LID [D]	CSD [D]
0.4 logMAR	0.98 ± 0.17	0.80 ± 0.13	0.85 ± 0.05	0.73 ± 0.04
0.1 logMAR	0.40 ± 0.10	0.30 ± 0.05	0.32 ± 0.06	0.25 ± 0.03

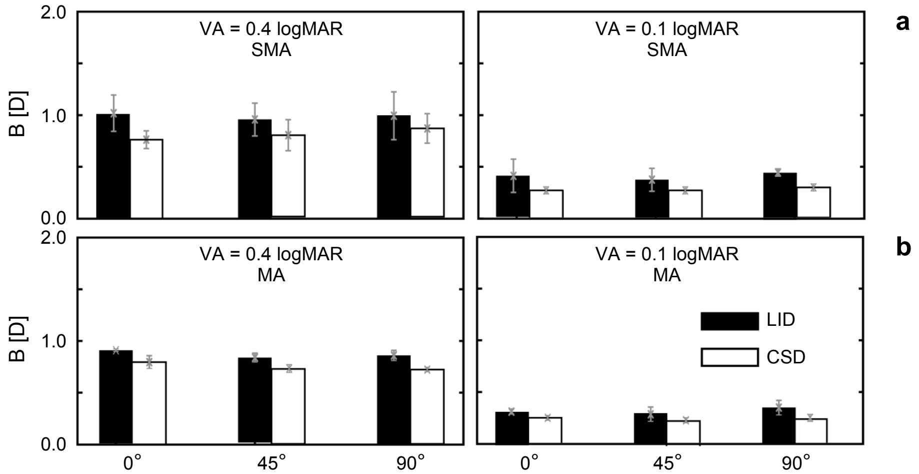

Fig. 4. Mean values of defocus (blur strength *B*) necessary to reduce the VA to 0.4 logMAR and to 0.1 logMAR; by the LID and CSD methods for SMA (**a**) and MA (**b**) at 0°, 45° and 90°. Standard deviations are shown.

the mean values obtained for all subjects. As can be seen, for all orientations of the cylinder axis, the subjects admitted higher values of astigmatic blur with the LID method than with the CSD method to attain the same VA score. The difference between both methods in this case is statistically significant ($p < 0.05$ in all cases). Related to this figure, it should be emphasized that, in spite of different appearance of the images reported by the subjects for different axis orientations, the values of *B* are nearly the same for the three axes considered. In fact, for each method, we found no statistically significant differences between the defocus generated at different axis of orientation for SMA, and MA ($p > 0.05$ in all cases).

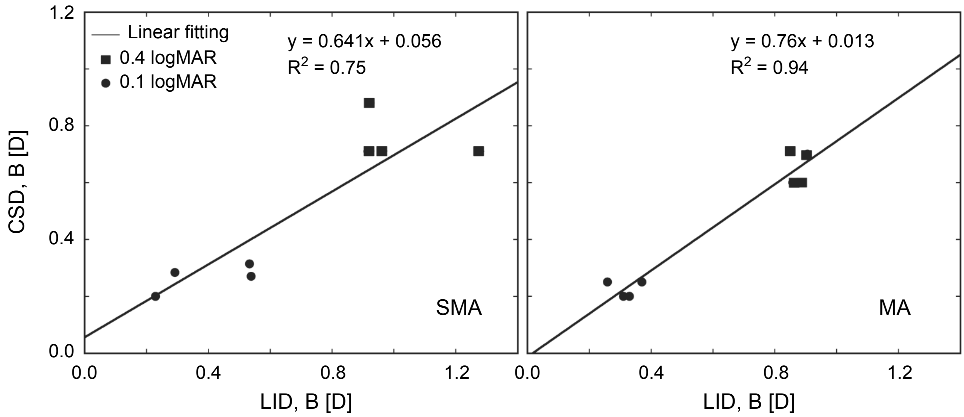

Fig. 5. Blur strength required for obtaining a drop of VA to 0.1 logMAR and to 0.4 logMAR with the CSD method as a function of the same parameter with the LID method for the 4 subjects of the study. Linear fit represents the fit for both groups together.

In Figure 5, the CSD values were represented as a function of the LID values for SMA and MA. The linear fit shows that for SMA and for MA, the defocus required by the CSD method to achieve the same level of blur than by the LID method is 64% and 76%, respectively.

4. Discussion and conclusions

Using spherical defocus, both the LID and the CSD methods degrade VA to a similar amount (no statistically significant difference). However, except for one subject, we found a tendency for the LID method to admit slightly higher values of blur power than the CSD method to obtain the same VA. Similar results were found by OHLENDORF *et al.* [9] and by DEHNERT *et al.* [8], but contrary to the present study, in this last case, slightly better acuities achieved with the CSD than with the LID method were reported.

As represented in Fig. 3, the CSD method only requires about 79% of spherical defocus required by the LID method to achieve the same level of blur. It means that a higher level of LID is necessary to obtain the same amount of generated blur. This result is also in line with the previous results [12].

The comparison between both methods is valid in spite of the fact that the pupil size was not controlled artificially in the LID method and it was kept constant for the image computation in the CSD method, because we assumed that pupil diameters of subjects of the same age under the same lighting conditions are almost constant [17]. However, although instructed not to do so, subjects maybe squinted their eyes slightly in the LID method, reducing the effective pupil size to improve their VA.

For astigmatic blur we found that the amount of tolerable defocus is also higher with the LID than with the CSD, but in this case a significant difference between both methods was obtained for the two tested VA. This result is also consistent with the findings of OHLENDORF *et al.* [9], but contrary to their result, we found that the differences between methods are more evident for SMA than for MA. Fluctuations of accommodation, which would not help in the case of the CSD method, can be the reason of this difference. As represented in Fig. 5, the linear fit shows that the for SMA and for MA, the defocus required by the CSD method to achieve the same level of blur than by the LID method is 64% and 76%, respectively.

Regarding the influence of the axis of the astigmatism, in this study we employed a wide range of different letters [13] to reduce the bias for certain axes of astigmatism because it is known that the design of the optotype affects readability of the letter charts [18, 19]. In this case, we found statistically no significant differences between the results obtained for induced astigmatism at different orientations with both methods. This result is consistent with our previous result for the lens-induced SMA [6] and later supported by OHLENDORF *et al.* [9]. On the other hand, ATCHISON *et al.* [20] found that the impact of astigmatism on VA when it is induced with a cross-cylinder (MA) is dependent on the orientation of its axis. However, in that work, simulations showed little effect of astigmatic meridian on the image quality of letters in the absence of other aberrations. Thus, the meridional dependence of astigmatic blur could be due to the interaction of the induced astigmatism with other existing high order aberrations of the eye [20, 21]. Related to this, Gracia *et al*. [22] explored the meridional visual improvement due to the optical improvements in the retinal image quality by measuring the CSF under natural aberrations and after adaptive optics corrections. They found a lack of correspondence in the improvements on the MTF (by a factor of 8 at intermediate spatial frequencies; which was isotropic) and on the CSF (by a factor of 1.4 at the same frequencies; which was lower at 45°/135°).

Moreover Viñas *et al*. [19, 23] recently have shown that the reduction in VA under induced astigmatism was higher for non-astigmats than for subjects with myopic astigmatism (≥0.75 D) when astigmatism was induced along the axis of their natural astigmatism. For non-astigmats, Gracia *et al*. [21] found that the induction of coma plus astigmatism (with an adaptive optics system) produces better VA scores than when only astigmatism is simulated. However, the group reported [24] that this improvement is highly dependent on the subject's own astigmatism and whether this is habitually corrected or not. This result suggests relevant neural adaptation effects in the eye normally exposed to astigmatic blur. In a recent paper, the same results have been found by myopes that show higher tolerance to retinal defocus compared with emmetropes [25].

In our work, the subjects were clinically non-astigmats and this effect seemed to be of little influence. On the other hand, individual ocular aberrations, that we do not considered in the case of CSD, but might interact with defocus in the LID method (improving the VA) may be responsible for the differences we found between the results obtained with both methods.

Additionally, the use of broadband light for the LID method can introduce additional cues to the visual system to enhance VA. On the other hand, monochromatic light 555 nm was used to simulate defocused images in the CSD method. However, since higher order aberrations were not measured in the subject's eyes (therefore they cannot be taken into account in the calculations) and since the luminous efficiency function is mostly symmetric around the maximum value, the inclusion of polychromatic light for the computationally blurred images was not expected to introduce these cues. Because of the limited number of participants in the study, it is not possible to draw any definite conclusions, but some tendencies are clear and they support previous research. Participants were young people with amplitude of accommodation in the range of 6.5–8.5 D. How the results obtained with induced MA can be extrapolated to people of other range of ages in still an open question that can be addressed in a further study with a larger population sample.

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