Phase-transfer function of the human eye and its influence on point-spread function and wave aberration

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The bidimensional phase-transfer function (PTF) of the human eye has been computed from aerial retinal images of a point test. These images were previously determined by using a recently developed hybrid optical–digital method. Actual PTF data have been obtained directly without linear variations with spatial frequency and have shown great variations among individual subjects. The influence of the PTF on the determination of the point-spread function and the wave-aberration function for emmetropized and slightly astigmatic subjects has been also evaluated. Finally, the effect of pupil size on the PTF was determined by computing these functions from the wave aberration. These results allow us to give a more thorough description of the optical image quality of the human eye and can be used as actual data in subsequent psychophysical studies.

INTRODUCTION

Several recent studies have examined the significance of the phase-transfer function (PTF) in the description of the image quality of optical systems.[1–3] This is especially important in systems with asymmetric aberrations in which, if the PTF is neglected, erroneous data on image quality will result. At the same time, the influence of the PTF of the human eye on the ability to discriminate differences in spatial phase[4,5] was also studied.[6] Here we present actual bidimensional PTF data computed from aerial retinal images of a point test. These images are obtained by means of a recently developed hybrid optical–digital method to determine the point-spread function (PSF) of the human eye.[7]

Generally, the optical image quality of the dioptrics of the human eye has been described in terms of the unidimensional modulation transfer function (MTF), which is usually obtained from measurements of aerial images of a line test formed by a double pass through the optical media of the eye.[8–10] But, because of the asymmetries of the wave aberration of the eye and the irregularities of the retina, it is more appropriate to use a point test to obtain bidimensional information. The hybrid optical–digital method permits recording of the aerial retinal image of a point test and computation of the bidimensional PSF's and MTF's for individual human eyes. Subsequently the wave aberration is retrieved from the PSF and the modulus of the pupil function by means of a phase-retrieval method.[11] These image-quality results obtained in foveal vision always show important asymmetries, even in the case of emmetropized eyes, in good agreement with previous studies.[12,13]

As is well known from Fourier optics,[14] if the PSF does not have revolution symmetry and is not centered at the origin, the PTF will not be zero for all spatial frequencies. However, in spite of the asymmetries present in the optical system of the eye, the PTF has not generally been taken into account in the determination of the image quality of the human eye. As far as we know, only Charman and Walsh[6,15] reported unidimensional PTF data previously, but their data included an arbitrary linear variation with spatial frequency owing to a lateral shift of the whole image that does not have any influence on optical image quality.

DETERMINATION OF THE PHASE-TRANSFER FUNCTION FROM THE RETINAL IMAGE

The hybrid optical–digital method for determination of the PSF of the human eye was described in Ref. 7. Its main characteristics were the use of the pinhole of a spatial filter as the object test, a He–Ne laser beam as the light source, and a calibrated TV camera that introduces the short-term retinal images into a digital image-processing system. An averaged aerial image $I(x'', y'')$ is obtained by adding a number of short-term images in order to get a simulation of the second pass as an incoherent imaging process.[7] In this way the averaged aerial image can be written as

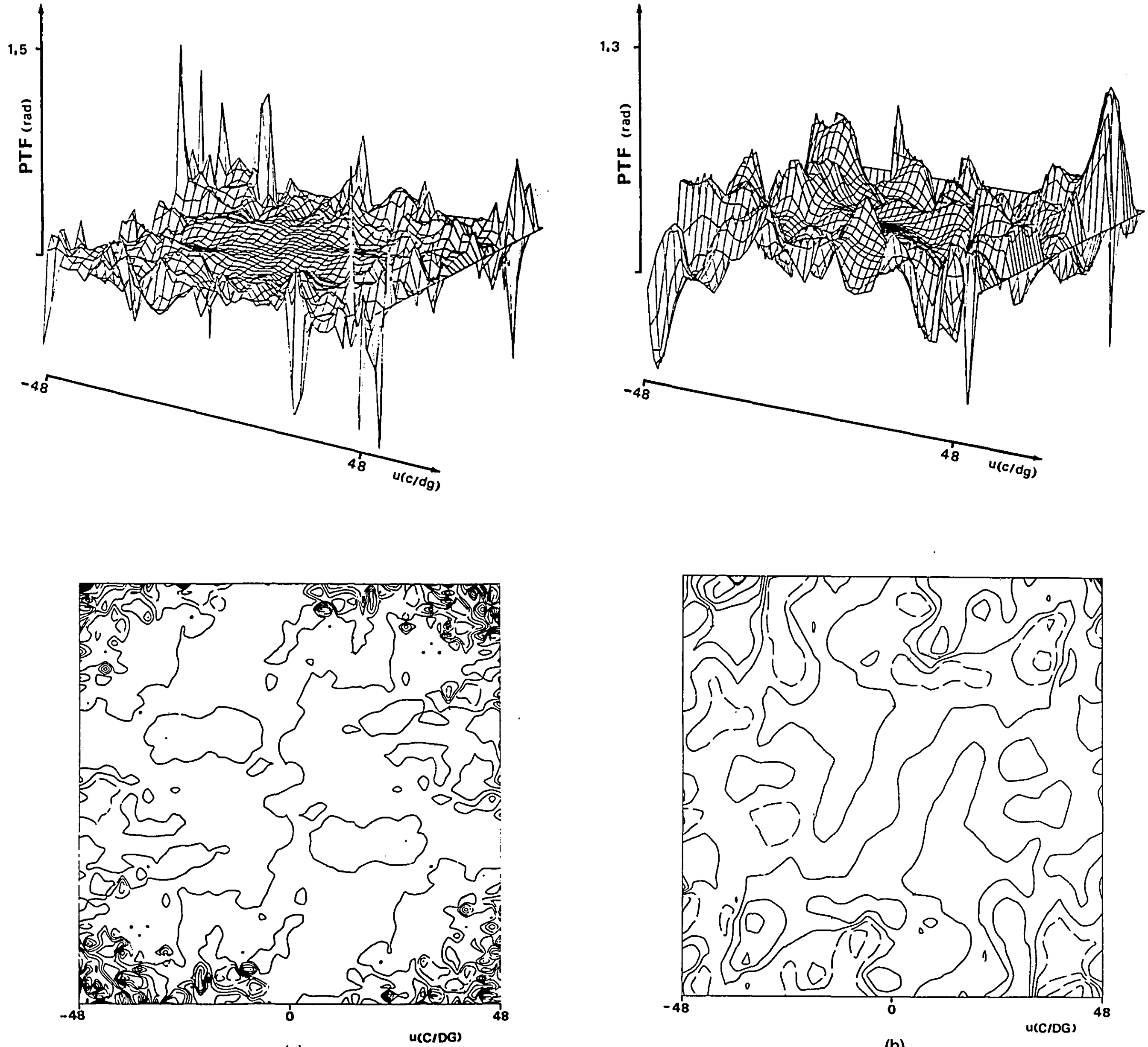
$$I(x'', y'') = P_s(x', y') \otimes P_s(x', y'), \tag{1}$$

where $P = (x', y')$ is the PSF of the optical system of the eye and $\otimes$ denotes convolution. The optical transfer function $H(u, v)$ is computed by the square root of the Fourier transformation of the averaged aerial image, and finally the PTF is

$$O_f(u, v) = \tan^{-1} \langle \mathrm{Im}[H(u, v)]/\mathrm{Re}[H(u, v)] \rangle. \tag{2}$$

Since the inverse tangent function is multivalued, the PTF has been computed with the restriction that $-\pi < O_f(u, v) < \pi$. Fortunately, despite the possibility of ambiguity in the phase determination, discontinuities in the principal value of the phase did not occur in the cases of emmetropized subjects. To compute the PTF in astigmatic eyes that show large asymmetries, a phase-unwrapping algorithm[16] was used.

Isometric and contour plots of the bidimensional PTF obtained and contour plots of the corresponding MTF's for two subjects are shown in Fig. 1 and 2, respectively. Subject JS has normal vision and 5-mm pupil diameter, and subject PA has vision corrected with a −1-D spherical lens and 6-mm pupil diameter. In order to evaluate the influence of



(a) (b)

Fig. 1. Isometric and contour plots of the PTF for subjects (a) PA and (b) JS.

the PTF on the retinal image, the modified PSF corresponding to the optical-transfer function with zero PTF has been calculated. A normalized error parameter, defined as

$$\epsilon = \frac{\iint |P_s(x', y') - P_s'(x', y')|^2 \mathrm{d}x' \mathrm{d}y'}{\iint |P_s(x', y')|^2 \mathrm{d}x' \mathrm{d}y'}, \qquad (3)$$

where $P = (x', y')$ is the actual PSF and $P' = (x', y')$ is the modified PSF, was also computed. The resulting error parameters are of the order of 0.03 for emmetropized eyes with 5–6 pupil diameter, but when slightly astigmatic eyes are considered, the error can reach 0.12. Figure 3 shows sections of the PSF with and without PTF consideration for subjects PA [Fig. 3(a)] and MA [Fig. 3(b)]. Figure 4 shows contour plots of the actual PSF [Fig. 4(a)] and the modified PSF [Fig. 4(b)] for subject MA, who has 6-mm pupil diameter and vision corrected with a −1-D spherical lens and has 0.5 D of residual astigmatism.

The influence of the PTF in wave aberration-functions has been also studied by retrieving these functions from PSF data by means of a phase-retrieval method recently presented.[11] A comparison between the wave-aberration coefficients determined from the actual PSF and from the retinal image of a point obtained without PTF consideration shows that all orders of coma terms vanish completely; one of the astigmatism terms decreases severely, and the symmetrical aberration coefficients practically do not change if the PTF is not taken into consideration.

PTF's corresponding to different pupil sizes were also computed from the wave-aberration function previously retrieved.[11] Figure 5 shows the contour plot at 10° intervals of the bidimensional PTF for subject MA with 6-mm pupil diameter [Fig. 5(a)] and with 3-mm pupil diameter [Fig. 5(b)]. For pupil sizes smaller than 2 mm the PTF is nearly zero at spatial frequencies of practical interest.

DISCUSSION AND CONCLUSIONS

The PTF describes the lateral shift of each spatial-frequency component of the image relative to the correct geometrical image position and causes image distortion.[1] Considering that the aerial retinal image of a point test is a real function with its peak at the origin, the PTF will be an odd function and will not have any linear variations with spatial frequency. This is an important fact because only the nonlinear parts of the PTF produce different lateral shifts of the Fourier components in the image and distortions affecting the image quality. Eventual linear variations cause only a bodily shift of the whole image and are completely unimportant in the case of the eye.

The unidimensional PTF data of Charman and Walsh[6,15] were derived only in vertical directions from wave-front results obtained by using an objective method based on the photographic recording of the retinal image of a grid.[13] A linear term was subtracted, with the objective of producing a produce PTF of zero at 15 cycles per degree (c/dg), to separate the linear term in the PTF from higher-order terms.

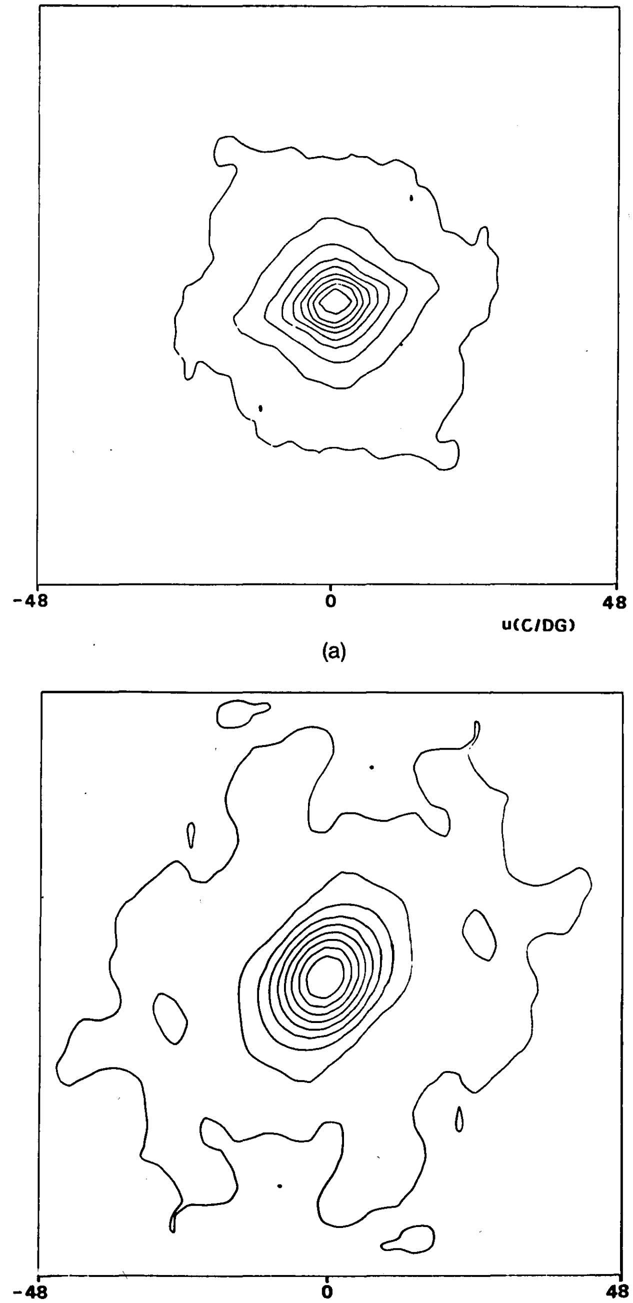


Fig. 2. Contour plots of the corresponding MTF's for subjects (a) PA and (b) JS.

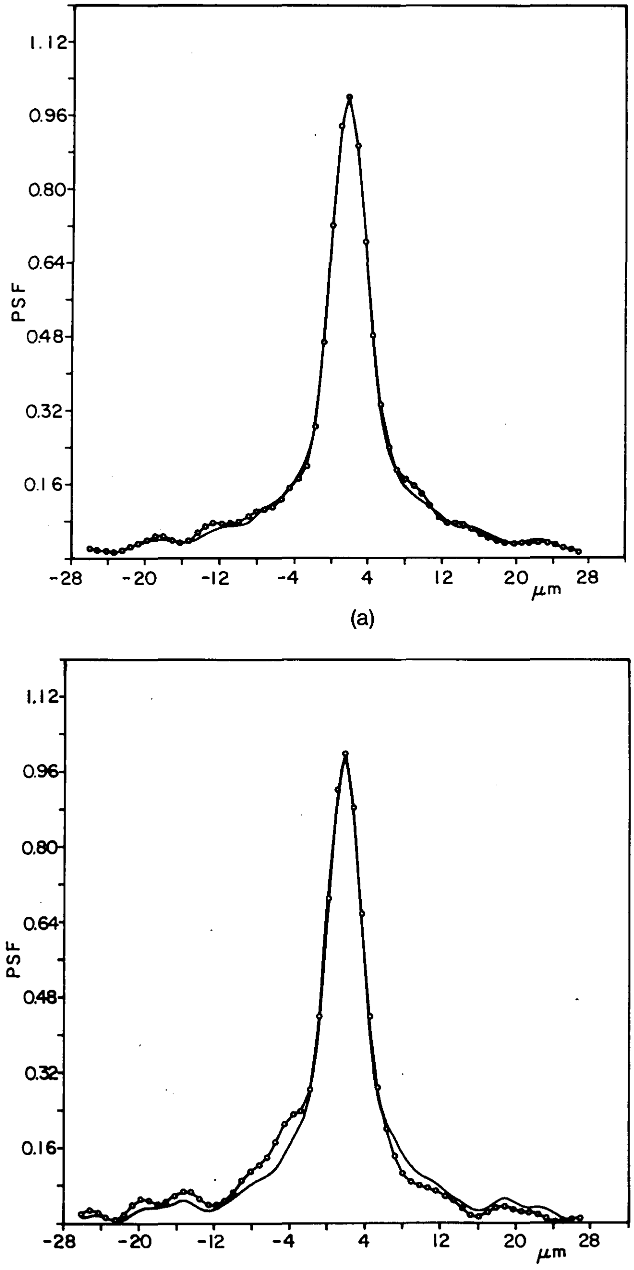
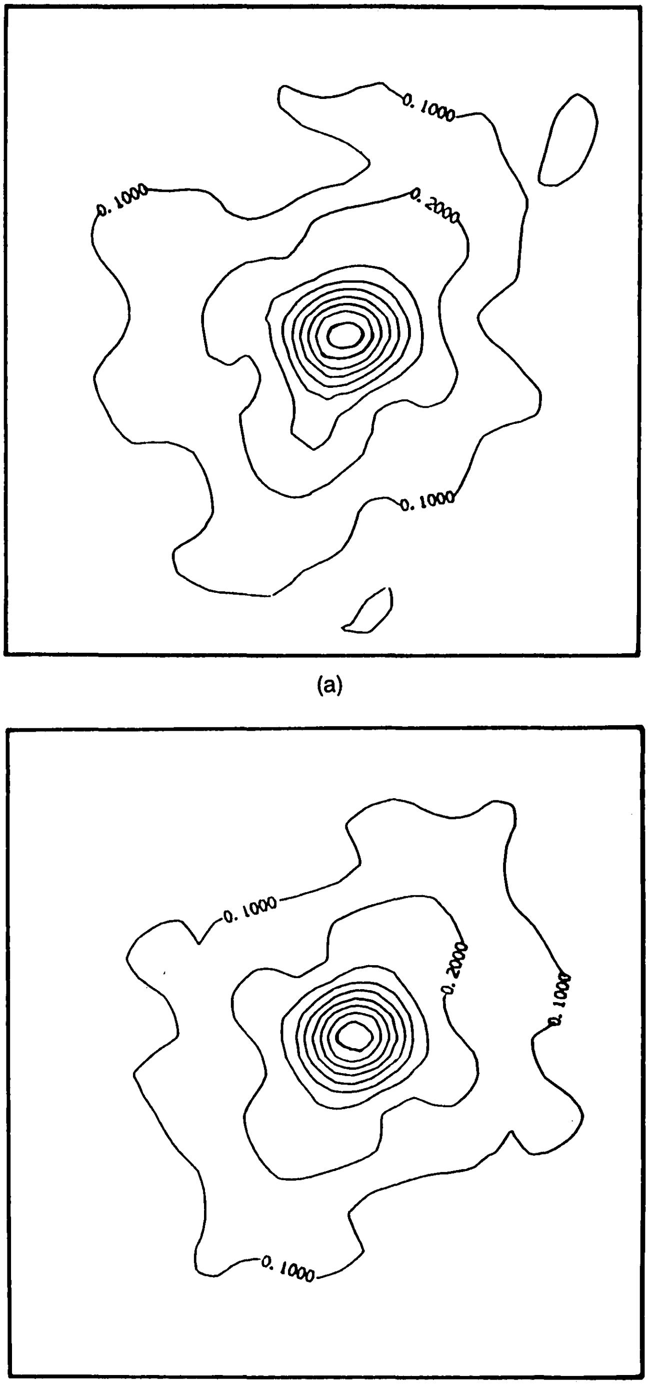


Fig. 3. Comparisons of sections of the actual PSF (circles) and the PSF obtained without considering the PTF (solid curves) for subjects (a) PA and (b) MA.



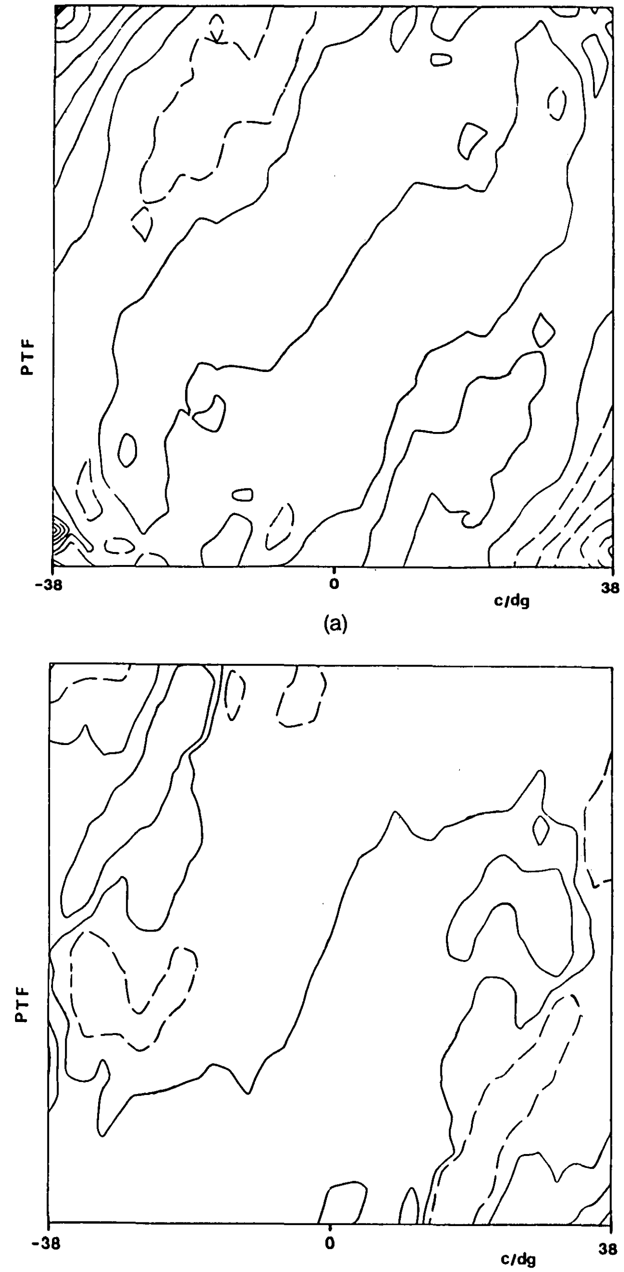
(a)

(b)

Fig. 4. Contour plots of (a) the actual PSF and (b) the symmetrized PSF obtained without PTF for subject MA.

This linear phase removal is a common problem in PTF determination, and different solutions have been proposed.[17] In our case, the correct solution was obtained directly by previous centering of the aerial retinal image.

As in previous PTF determinations, we also found a great dispersion of individual data, although we disagree on the maximum value of the PTF near the cutoff frequency. Our results show that with emmetropized eyes, and with large pupil diameters, the PTF did not exceed 60° at 50-c/dg spatial frequency. Moreover, Rosenbruck and Gerschler[2] showed that if the MTF is greater than 0.2, the PTF does not exceed $\pi/4$, even in the cases of highly asymmetric wavefront aberrations. In addition to a large variation in results among different subjects, higher absolute values of the PTF at high spatial frequencies have been observed. This is due to the residual noise present in the averaged aerial retinal image caused by incomplete averaging of short-term images.[7] However, this fact is not important because the corresponding MTF at those frequencies is practically zero. On the other hand, the nonzero PTF values at medium and low spatial frequencies arise from the obvious asymmetries present both in the retinal image of a point test[7] and in the wave aberration.[11] Moreover, the use of a pointlike test object in the hybrid optical–digital method avoids the intro-



(a)

(b)

Fig. 5. Contour plots at 10° intervals of the PTF for subject MA (a) with 6-mm and (b) with 3-mm pupil diameter.

duction of asymmetries in the optical image-quality results resulting from nonuniformities of the fundus reflection.

A normalized error parameter has been computed in order to permit the influence of the PTF on the retinal image to be estimated. This parameter gives us an estimation of the asymmetries of the wave aberration and reached 0.12 for slightly astigmatic subjects. By analyzing the wave-aberration functions retrieved from actual PSF data and from PSF's obtained without PTF's by means of a phase-retrieval method,[11] we found that if the PTF is not taken into account, then coma and one of the astigmatism coefficients are not included in the optical image-quality determinations in human eyes. Computations of the PTF for different pupil sizes have shown that the phase shifts begin to be appreciable when the pupil diameter is larger than 2 mm and reach important values with normal pupils.

These bidimensional PTF results complete the description of the optical image quality of the dioptrics of human eyes and can be used as actual data in subsequent psychophysical studies involving spatial phase discrimination.

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