Simultaneous measurement of two-point-spread functions at different locations across the human fovea

Pablo Artal and Rafael Navarro

An experimental system for measuring simultaneously the retinal images of two-point tests has been developed. In particular we present one experiment in which one of the points is located at the center of the fovea and the other one is at 1 deg of eccentricity. At these two foveal locations the optical image quality is expected to be approximately the same, while the structure of the retina is known to be quite different. Our results of aerial images show small but systematic differences between the two-point-spread functions that are measured at 0 and 1 deg of eccentricity. The image quality is always slightly better in the center of the fovea with the differences more marked in the nasal and inferior orientations. That could be explained by a small but noticeable contribution of the retinal thickness to the optical aberrations of the eye. The possible increment of scattering caused by the increase in retinal thickness at 1 deg was barely measurable in our experiment. An indirect consequence is that retinal reflection has little practical influence on our particular double-pass measurements of the eye's image quality.

Introduction

The measurement of the optical image quality in the human eye has been a subject of interest during the last decades, and even now several questions remain. Apart from many practical and clinical applications, the eye's image quality is also a matter of basic research. In particular, since the optical system of the eye is the first step in the information gathering and processing that are performed by the human visual system, the eye's image quality is the necessary departure point in many spatial vision experiments and models.

A variety of techniques, either subjective or objective, have been applied to assess the eye's image quality. They range from studies of optical aberrations[1] to measurements of the optical transfer function (OTF).[2] At present objective methods based on the double pass of the light through the ocular media seem to be more convenient for measuring the image forming properties of the human eye, because they present several advantages. Bidimensional complete information can be obtained in a straightforward manner by a fast procedure in addition to the advantages that are derived from the objective nature of the method. However, some scepticism remains concerning the double-pass technique mainly because of the lack of a complete understanding and agreement on the nature of fundus reflection.

Since the early work of Flamant[3] many authors have measured the OTF of the human eye from aerial images of lines, edges, or gratings formed by a double pass through the optical media of the eye.[2,4] Among the different tests the one that consists of one point is the most appropriate, because it yields complete bidimensional information. It also avoids the possible influence of anisoplanatism when using an extended test. Based on the double-pass method of Arnulf *et al.*[5] for the cinematographic recording of the aerial image of a point tests, we developed an experimental system[6] that permits for the first time we believe the measurement of the retinal point spread function (PSF) and also the bidimensional OTF. This method is based on the recording of short-exposure aerial retinal images of a point source. The OTF is obtained by averaging a set of these images and then computing the square root of its Fourier transform, including the modulus [modulation transfer function (MTF)] and phase (phase transfer function).[7] The methodology was also extended to compute the wave aberration function[8] from the experimental PSF by using a phase retrieval procedure.[9] Since then we have continued working in two directions: on the one hand,

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The authors are with the Instituto de Optica, Consejo Superior de Investigaciones Científicas, Serrano 121, Madrid 28006, Spain.
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improving the experimental setup including better components and implementing much more accurate processing of the data.[10] This allows us to obtain two-dimensional OTF's with a higher signal-to-noise ratio, which permits the extension of a reliable range of measurement as far as the cutoff frequency and with an easier and more comfortable procedure.[11] On the other hand, we have been interested in designing new experiments based on the double-pass method in order to understand better the role of the retinal thickness on the eye's image quality and also its influence on double-pass measurements. In particular the fundamental question for our double-pass method is: how close is the correlation between the real retinal image, which is effective for the visual process, and that which we obtain by a double pass through the optical media?

We present a modified version of the double-pass experimental system, which has been implemented to obtain retinal images of a multiple test, which consists of an array of points. In particular we present results that correspond to aerial images of couples of twin points that are simultaneously recorded. In this particular experiment one point is located at the center of the fovea and the second one at 1 deg of retinal eccentricity. We have collected data from the four principal orientations (nasal, temporal, inferior, and superior). The simultaneous recording of the aerial image of the two points guarantees that the experimental conditions (i.e., pupil size, accommodation, eye position) are exactly the same, permitting the detection of quite small differences. At these foveal locations, with eccentricity that is this small, the image quality corresponding to the eye's optical system should be practically the same as in the foveal center, while the thickness and structure of the retina are at 1 deg substantially different from those of the center of the fovea. Consequently the possible differences between the two retinal images should be primarily attributed to the effect of a different retinal thickness and structure at each location. Results that show small differences between both images of a couple (at the foveal center and at 1 deg) indirectly mean that the effect of retinal reflection also has little influence. An indirectly derived consequence is relevant for our double-pass method. The results of image quality are highly correlated to the retinal image that is effective for the visual process.

We first describe the modified double-pass system; then we explain the experiment, which consists of the simultaneous measurement of two aerial PSF's, including a brief analysis of the results. We also discuss the contribution of the retina to the optical aberrations and scattering of the eye and its consequence on double-pass measurements of the eye's image quality. Finally we present the conclusions.

Retinal Aerial Images of Twin Points

In the particular experiment presented here the setup was modified by introducing an array generator[12] into the optical path that splits the incoming light beam into its different diffraction orders to form an array of points. This modification of the system permits the simultaneous recording of the retinal images of the two point sources separated by a given angular distance across the fovea.

Description of the Experimental System

The apparatus that is used to record the retinal images of the two point sources in the fovea is depicted in Fig. 1. A He–Ne laser with nominal power of 10 mW is used as the light source. The beam first passes through an optional neutral low-density filter (ODF) that is used to match the beam intensity to the optimum CCD camera sensitivity range for each particular experimental condition (pupil size, image quality, etc.). A second, high-density, filter (DF), with $D = 4$, attached to a rotary solenoid (R) attenuates the intensity of the beam allowing the subject to look at the point source comfortably. During the short exposure time this filter is removed and synchronized with the camera by acting as a flash shutter. The beam is expanded by a 20× microscope objective (M) and filtered by a 10-μm pinhole (P), which acts as the primary test object (O). The diverging beam is collimated by lens L_1 ($f' = 200$ mm).

The generation of the array of points, which is used as the final object test, is carried out by placing an optical Fourier plane array generator[12] in front of the collimator. Figure 2 shows the principle of this system: a phase diffraction grating splits the incoming beam into a series of diffraction orders, and a lens

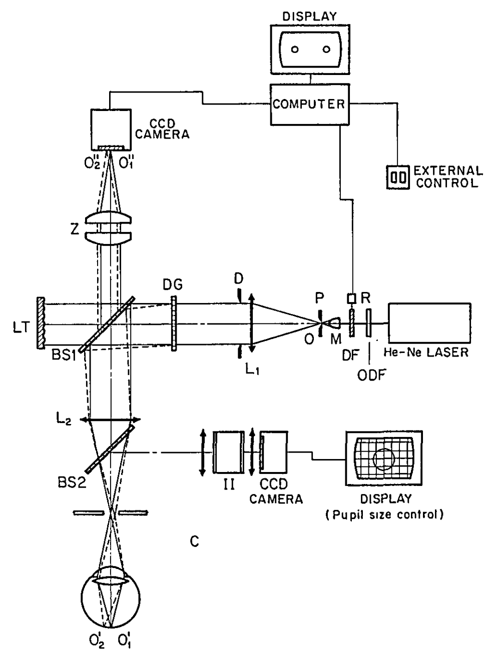


Fig 1. Experimental setup for recording simultaneously the retinal images of two point sources (O_1' and O_2'): ODF, optional neutral low-density density filter; DF, high-density filter; R, rotary solenoid; M, objective microscope; P, pinhole; DG, phase diffraction grating; BS1, BS2, pellicle beam splitters; C, spot; II, image intensifier system; Z, zoom lens; LT, light trapping; O, primary test object; L_1, L_2, lenses; D,

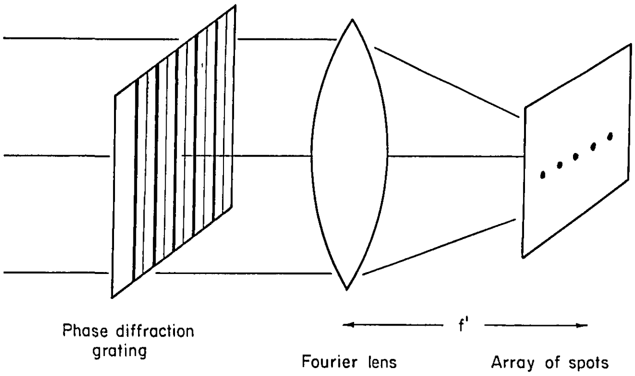


Fig 2. Schematic plot of a Fourier plane array generator that is based on a Foucault phase diffraction grating.

performs the Fourier transform by focusing the orders to an array of points. When necessary, as, for example, in far vision, the eye can be used as the Fourier lens, although this particular experiment was performed in near vision. After the diffraction grating (DG) and reflection in a pellicle beam splitter (BS1), lens L_2 ($f' = 300$ mm) forms a set of points in the accommodation plane, which is 3 diopters away from the eye. The diffractive component, a Foucault phase diffraction grating, was made as follows: a binary mask (rectangular grating) was plotted with a laser printer and photoreduced to obtain the required spatial frequency. The diffractive element was then constructed in bichromated gelatin to obtain a high diffraction efficiency and designed to generate an array of points with approximately the same intensity in the three central peaks. In the setup a field stop selects only two points on the array in the accommodation plane (C): the central (zero-order) point and one of two points that correspond to the first order. The diffraction grating is mounted on a rotary system to select the arrangement of the point couples (horizontal or vertical). During the measurement process the subject's eye is at a viewing distance of 3 diopters, forming the retinal images of both points O_1 and O_2 on his (or her) retina. While one of the points (O_1') is used as a fixation test, with its image in the center of the fovea, the position of the second point (O_2') is set to 1 deg of the retinal eccentricity with variable orientation.

A small fraction of the incident light is reflected in the fundus and passes again through the ocular media, lens L_2, and the beam splitters. The zoom lens Z ($f_z' = 60$–300 mm) forms the aerial images O_1'', O_2'' of the retinal O_1', O_2' on the CCD camera. The zoom lens permits a change in the magnification of the system from $\sim 3.6\times$ to $18\times$ (the ratio between the eye and the zoom focals). The aerial retinal images are digitized and stored on an AT computer by means of a frame grabber-image processing board (Matrox MV-AT). This system was previously calibrated with a horizontal pixel size of 13.2 μm and a vertical pixel size of 11.3 μm. Since the aspect ratio is not equal to one, it must be corrected during the posterior image processing procedure. The aerial images O_1'' and O_2'' are oversampled by more than twice the Nyquist frequency to avoid aliasing, since the interlaced scan of the camera causes the real vertical resolution to be half of the theoretical value.

The pupil size of this experiment was 4 mm. This pupil corresponds to a typical indoor reading situation, which assures a normal eye's image quality and permits a comfortable recording. Since the subject is in natural viewing conditions, including pupil and accommodation, it is necessary to control the pupil size during each short exposure. For this purpose an additional pellicle beam splitter (BS2) has been incorporated into the system permitting us to monitor the pupil in real time by an intensified camera [i.e., an image intensifier tube (II) together with a CCD camera]. The mean pupil size in the experiment was 4 mm with a standard deviation of 0.2 mm. The high-density filter is removed from the beam at the same time that the short-exposure images are grabbed. The actual duration of the laser exposure is ~ 100 ms, and the maximum laser power irradiance in the eye pupil plane is 0.1 mW/cm^2 in these particular experimental conditions. When taking into account the area of the PSF on the retina and the duration of the snapshot, the laser exposure is at least 1 order of magnitude below the American National Standards Institute laser safety standards.[13] (For direct viewing into a He–Ne laser beam the ANSI value is above 1 mW/cm^2 for an exposure time of 0.1 s.)

Experimental Procedure and Image Processing

We showed previously[6] that to average a set of short-exposure frames is equivalent to taking a long-exposure image. In both cases, since the retina acts as a reflecting moving diffuser, the speckle is blurred, breaking the coherence of the beam, which is necessary to insure that the second pass is an incoherent image process. A computer simulation showed[6] that to average 32 short-exposure images is an optimum procedure for computing the OTF with a good enough signal-to-noise ratio. In this research we recorded short-exposure aerial retinal images of twin-point couples. Each frame is first corrected for both bias and pixel sensitivity differences by subtracting the dark current image and dividing it by a flat-field white image. The resulting 512 × 512 pixel image with 8 bits/pixel is then displayed. At this point we accept the short-exposure image for averaging when it is within the optimum intensity range of the camera and reject either saturated or faint images. Frames are also discarded when they present an artifact (a result of blinkings, eye movements, or stray light). The selected images are added to the average. In practice the average of 32 frames is carried out in four separate series of eight images by computing the four independent partial averages. An example of a 512 × 512 pixel image containing the average retinal images at a couple of points (the foveal center on the left and 1 deg of eccentricity on the temporal side on the right) is presented in Fig. 3. Each of the two images is stored in a different 256 × 256 pixel subimage and processed

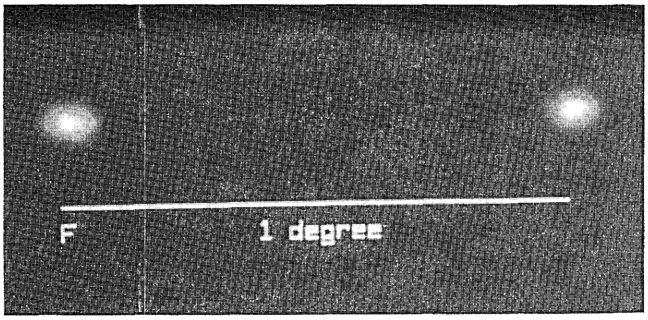


Fig. 3. Typical example of two simultaneously recorded average aerial images for the SA subject. F indicates the position of the center of the fovea, while the second image is at 1 deg of eccentricity in the temporal fovea.

separately by using an identical procedure to compute the two OTF's. The background light in the images resulting from the stray light coming from the setup (reflections in the lenses) is removed by subtracting the background average image. This is obtained by using a black diffuser in place of the eye. The pixel aspect ratio is corrected by computing on the y axis new samples by interpolation, and finally the images are slightly low pass filtered and multiplied by a circular window with Gaussian edges prior to the calculation of the OTF. The MTF is obtained by computing the square root of the modulus of the Fourier transform and the PTF by dividing the phase by two. The inverse Fourier transform of the resulting complex OTF gives an estimate of the retinal PSF. The standard error of the mean (SEM) in the MTF measurements is estimated by computing four MTF's from the four partial averages of the aerial images, which are obtained with only eight short-exposure images each.

Results: Aerial Retinal Images and MTF's

A complete set of experimental measurements consisting of four couples of average aerial retinal images at twin points, one at the foveal center and the second at 1 deg of the nasal, temporal, inferior, and superior retina, was taken in three young emmetropized subjects (22–29 years old) with normal vision. The amount of remaining astigmatism in each subject was < 0.12 diopter. Small differences between the results corresponding to the foveal center and those obtained at 1 deg are more marked in the aerial images than in the MTF's. This is because the double-pass aerial images are affected twice by the aberrations, while the MTF's are the really relevant data for vision since they include only the degradation that is introduced by a single pass, and consequently differences that could be substantial in the aerial images become smaller in the MTF.

Among the three subjects SA showed the greatest differences in image quality between the center and 1 deg in the fovea. A possible explanation for this is that subject SA could have a steeper foveal pit, which indicates a thicker retina at 1 deg. Figure 4 shows four pairs of simultaneously recorded aerial images for subject SA. One always corresponds to the center of the fovea (upper plot) and the second to 1 deg of eccentricity (lower plot) in the four different orientations: nasal (a), temporal (b), superior (c), and inferior (d). The results are shown as contour plots with the contour interval being 10% of the peak value. The contour plots that correspond to the other subjects are not represented here, but the differences within the image couples are always smaller than in the case of SA. These contour graphs present small but clear differences within all retinal image couples, with those obtained at 1 deg always spread more significantly. It must be noted that small variations in the aerial images are substantially marked on the contour graphs. We can also appreciate small differences between the four aerial images that correspond to the center of the fovea, since they were recorded independently (see Fig. 4). These variations are not statistically significant and illustrate the experimental incertitude of our measurements, which is mainly a result of the effect of the accommodation stimulus on the refractive state of the eye. As we have recently shown[14] a different stimulus of accommodation could produce small changes in the shape of the PSF. In this particular case the position of the second point test (horizontal or vertical) could slightly affect the recorded shape of the aerial image in the center of the fovea. In any case this illustrates why it is necessary to record the coupling of points simultaneously.

The two-dimensional MTF's were computed from the aerial images as mentioned before. Two examples of MTF's corresponding to the SA subject for the center and for 1 deg of nasal fovea (where the greatest difference was found) are plotted in Fig. 5. The contour plots in this case consist of ten contour lines ranging from 95% to 5% of the maximum of the modulation in a linear scale. Figure 5 shows that the two-dimensional shape of the MTF appears to be affected slightly by the retina, since the MTF is a little better at the center of the fovea. In addition, to allow an easier relative comparison, one-dimensional sections of the MTF's are also shown in Fig. 6. Each plot contains sections of the two MTF's that are obtained from a couple of aerial images. Their corresponding errors bars (the SEM) are also included to show the variability of the experimental measurements. We have included only three pairs of MTF sections for the sake of simplicity: a 1-deg nasal (a) and inferior (b) retina for subject MA, and a 1-deg superior (c) retina for subject SA, respectively. Figure 7 presents the average radial profiles of the four MTF's for the SA subject at the central fovea, and all orientations of 1 deg are plotted by using a logarithmic vertical axis. This set of MTF sections summarizes the most relevant results in order to analyze the effect of the retinal thickness. In general, for all subjects and orientations, the lower values of the MTF are always found at 1 deg of foveal eccentricity when compared with the central MTF. However, these systematic differences are small and always close to our experimental errors. Thus they are marginally statistically

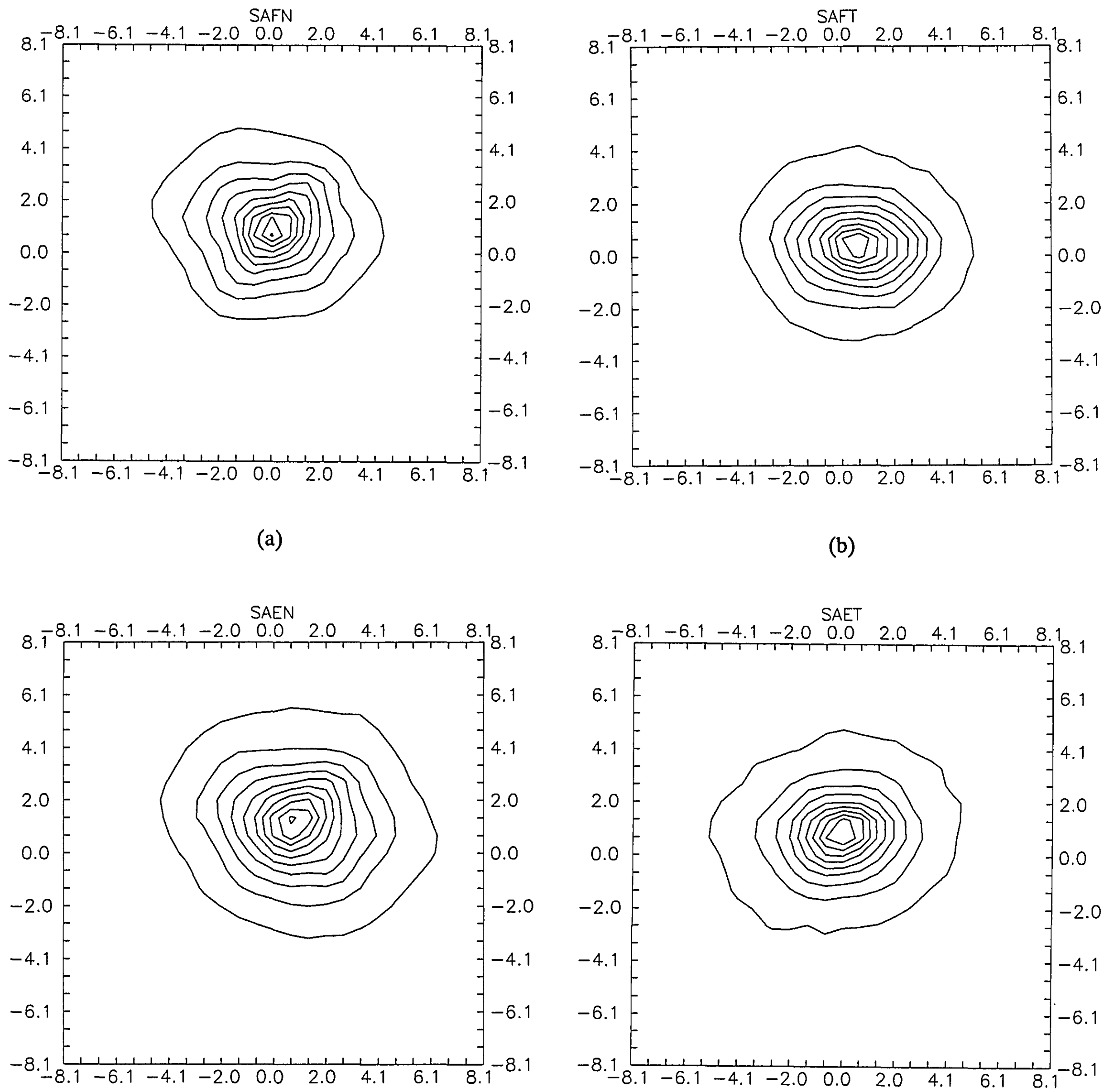


Fig 4. Couples of aerial images of a point test that is recorded in the center of the fovea (upper plot) and at 1 deg of eccentricity (lower plot) for the SA subject in the nasal (a), temporal (b), inferior (c), and superior (d) part of the fovea. The contour interval value is 10% of the maximum intensity of the image. The scale is expressed in minutes of arc.

significant. In fact only subject SA with nasal and inferior retinas showed significant differences that were greater than the error bars (SEM), and even in these cases this occurs only in the intermediate spatial frequency range. For example, the average difference in modulation between the two MTF's in Fig. 5 for 20 cycles per degree (c/deg) is 0.06, while the SEM is 0.05. Since this is one of the greatest differences that we found, it is clear that we are dealing with a marginally significant effect. The differences in modulation in the average MTF's of Fig. 7 are 0.024 for 20 c/deg and 0.018 for 30 c/deg.

A further analysis of the results can be performed in terms of the Strehl ratio,[8] which is a single parameter that characterizes the image quality of optical systems, which are commonly used in optical design. It measures the image performance by comparison with the diffraction-limited case. The Strehl ratio is defined as the peak value of the PSF divided by the value that corresponds to an aberration-free system with the same numerical aperture or equivalently the volume under the two-dimensional MTF. We use it to compute the Strehl ratio in this way from the MTF. Table I shows the relative lowering of the Strehl ratios at 1 deg of eccentricity with respect to the center of the fovea. The average relative decrease in the Strehl ratio at 1 deg with respect to the center of the fovea for all subjects and orientations is 0.94 (a 6% lowering in relation to the average value at the foveal center). These results should be understood in relation to the absolute percentage Strehl ratio values in the foveal center, which are 15.6% for PA, 14.4%

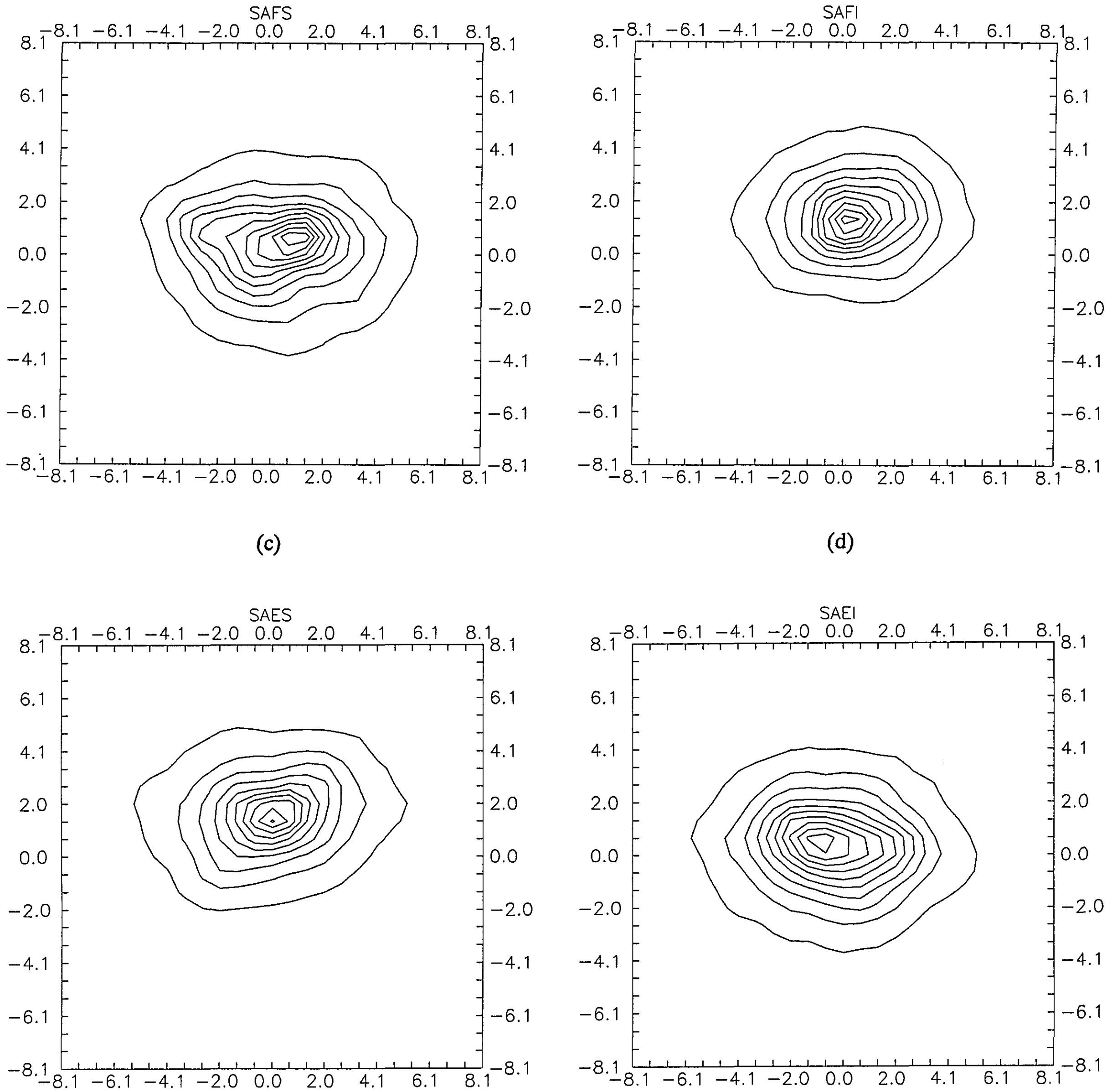


Fig 4. continued

for SA, and 11.3% for MA. Consequently the mean absolute Strehl ratio decrease is < 1%, and the maximum absolute decrease is 2.45% for subject SA (nasal). As a numerical reference an optical system is considered to maintain the diffraction-limited resolution after the Rayleigh criterion when the Strehl ratio is > 80%. This clearly indicates that the average degradation in image quality (1%) found for 1 deg of eccentricity has no real visual significance. Additional relative Strehl ratios corresponding to 5 deg of eccentricity in the nasal and temporal retina are also included in Fig. 8. These data were obtained by recording only the aerial retinal image of a single point by using an additional fixation test point at 5 deg from the laser beam.

From an analysis of the whole set of results we can conclude that differences within the aerial image couples (at the foveal center and at 1 deg) were found systematically. They were small in absolute terms and barely noticeable with the sensitivity of our system. In fact these differences are much smaller in relationship to the variability among the subjects. We were able to detect these differences only by using this specific experimental system with the twin-point test, which permitted us to maintain exactly the same experimental conditions by a simultaneous recording.

On the other hand, we generally found a low mean value of the background light in the foveal aerial images. The mean value of this background at the center of the fovea and at 1 deg of eccentricity was also computed. Small, barely measurable differences were found between these mean background levels; the difference was always smaller than 0.07% of the peak value in the aerial images. This means that the relative contribution to the ocular scattering of the extra retinal thickness at 1 deg is small in this setup.

These results also indicate that the effect of the scattering that is produced by the inner retina on these double-pass measurements of image quality has negligible importance. Moreover by using simple digital techniques we are able to remove the background and avoid any significant influence on the MTF measurements. In conclusion, with our system we have not found in red light the important effect of scattering that has been suggested by several authors.[15,16] Furthermore, since scattering is smaller for long wavelengths, we have repeated the background measurements in several aerial images of a couple of points in green light by using an Ar laser. The results of background values were basically the same as those that are obtained in red light.

Discussion: Effect of the Retinal Thickness on the Eye's Image Quality

Two main results have been obtained from the experiment that is presented above: on the one hand, a small but systematic degradation of image quality in the retinal images is obtained at 1 deg of eccentricity with respect to those corresponding to the center of the fovea; and, on the other hand, the mean value of the light background is practically the same for 0 and 1 deg. Since the two aerial images (at the foveal center and at 1 deg of eccentricity) were obtained simultaneously, the possible differences resulting from pupil size, accommodation, or eye position have been eliminated. Thus the variations found within a couple should be attributed to differences in retinal thickness and structure rather than to other factors. The differences in the MTF's are comparable with the estimated SEM, so that they are marginally statistically significant (see Fig. 6). The influence of the retinal orientation was found to be quite important, the differences being larger in the nasal and inferior part of the fovea, which could be attributed to differences in thickness at distinct parts of the inner retina. These points are discussed in detail in the following sections.

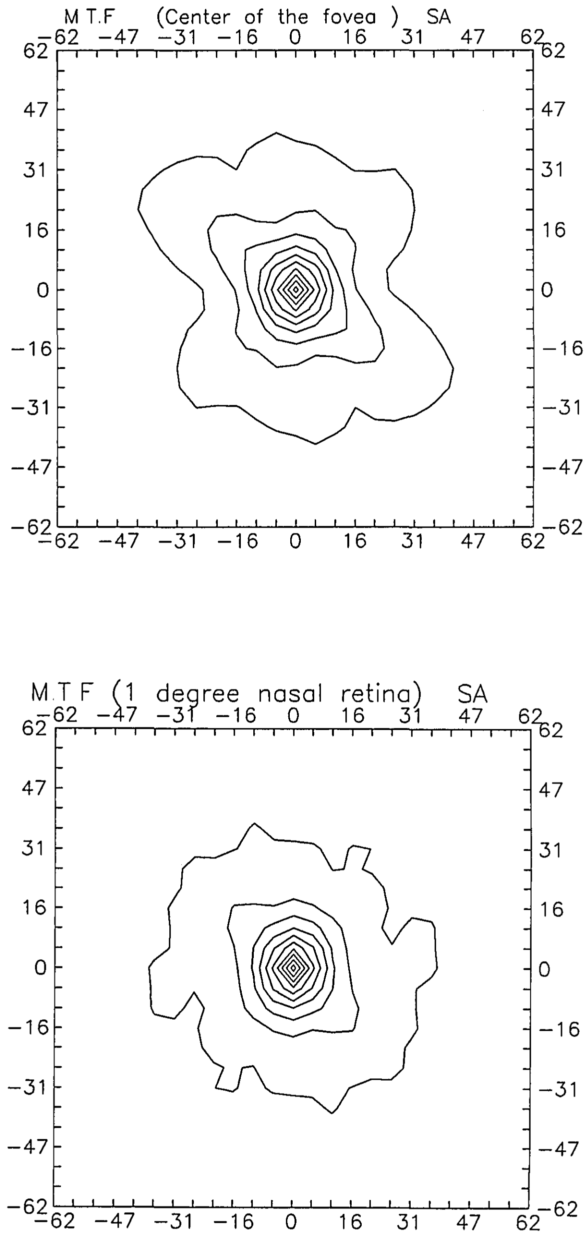
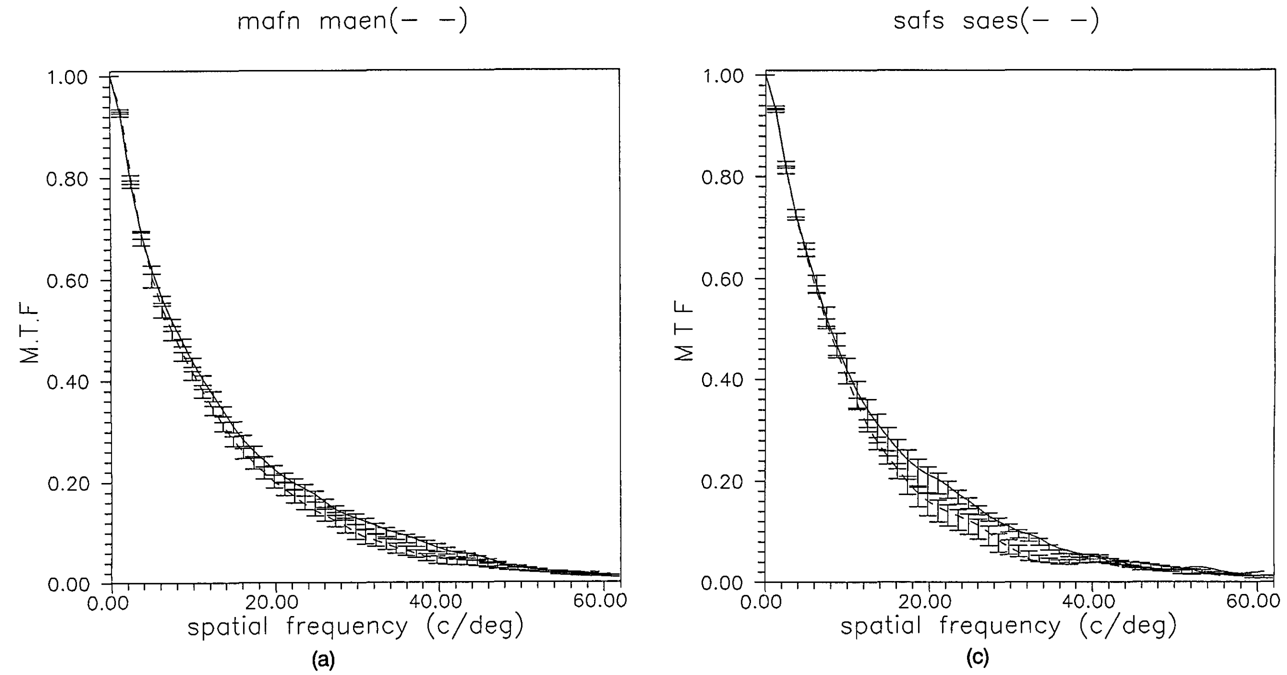


Fig 5. Two-dimensional MTF's for subject SA at the foveal center (upper plot) and at the 1-deg nasal retina (lower plot). Each plot has 10 contour curves from 95% to 5% of the maximum of the modulation. The scale represents the spatial frequency expressed in cycles per degree.

Contribution of the Retina to Optical Aberrations

As we mentioned above the small optical degradation that is observed at 1 deg of eccentricity is not attributable to the eye's optics but to the thickness of the retina. Let us consider the possible contribution of the retina, which is like a thick layer, to the aberrations of the eye. A plane-parallel plate with the same thickness as the retina would make a small contribution to the third-order aberrations. For example, the spherical aberration is ~ 0.1 μm assuming a 400-μm thickness and 1.36 refractive index.[17] However, the retina at 1 deg is far from being a plane-parallel plate because of the slope of the foveal pit. The skew incidence at these locations will introduce an extra amount of aberration. In fact a more detailed analysis using a realistic model of the retina probably accounts for the differences that are found between 0 and 1 deg of eccentricity. We do not believe that the origin of the extra amount of aberration is due to the cornea and lens working off-axis. The reason is that 1 deg is a really small eccentricity. Moreover the fovea is off-axis, and furthermore there is no real optical axis in the eye. Our results suggest that the retina as part of the eye's optical system contributes to the global aberrations of the retinal images. If this is true, the results obtained by use of the double-pass method include the contribution of the inner retina to the optical aberrations. In any case the contribution is extremely small, and, in fact, only by performing a particularly careful experiment, like the one that is presented here, is it possible to show the systematic degradation of image quality resulting from the reti-



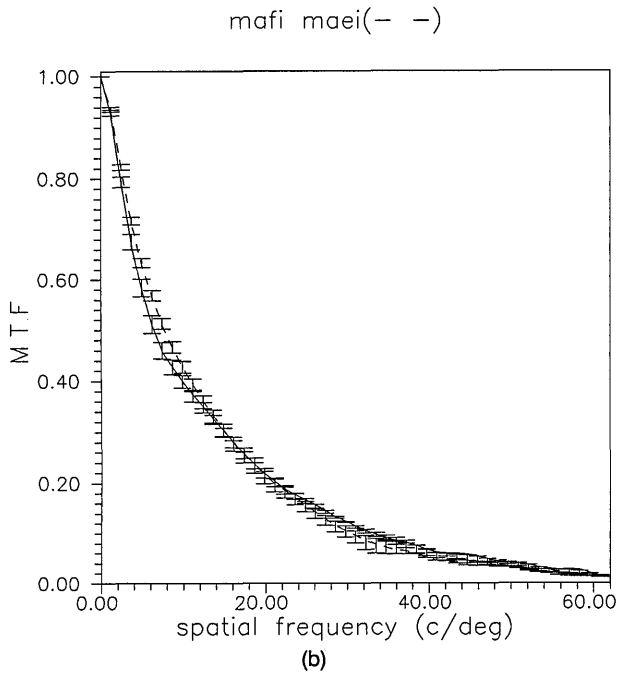


Fig 6. Sections of the two-dimensional MTF at the foveal center (solid curves) and at 1 deg of eccentricity (dashed curves). The error bars represent the SEM that was obtained as explained in the text: subject MA, (a) nasal and (b) inferior; (c) subject SA, superior.

nal thickness. The position of the optical axis of the eye (typically located 5 deg in the nasal direction) has no effect on our results. Moreover the greatest decreases in image quality were always found in that direction. This is further support for our previous claim. The image quality of the cornea and the lens must be kept fairly constant for that small eccentricity (with a retinal area up to 300 μm), while the decrease in image quality comes mainly from the increment in retinal thickness.

Nature of the Fundus Reflection

A particularly important aspect of the double-pass method is the location where the retinal reflection takes place. There is disagreement about this, and several contradictory and controversial hypotheses have been suggested. Several authors[18,19] found that light-maintaining polarization is reflected by the outer segments of the photoreceptors, and therefore that light should be highly correlated with the light that is absorbed in the visual process. This was the hypothesis in our previous double-pass work,[6] indicating that the double-pass measurements of image quality actually correspond to the visually significant retinal image. However, the actual retinal reflection is probably more complicated. In recent research van Blokland and van Norren[20] presented intensity and polarization measurements. They observed two components

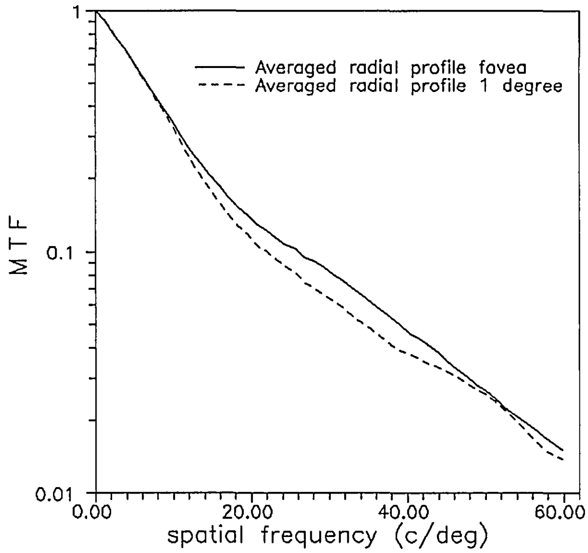


Fig 7. Radial profiles of the average of four MTF's that correspond to the SA subject for the central fovea (solid curve) and 1 deg of eccentricity in all orientations (dashed curve). The vertical axis is a logarithmic scale to permit a better comparison.

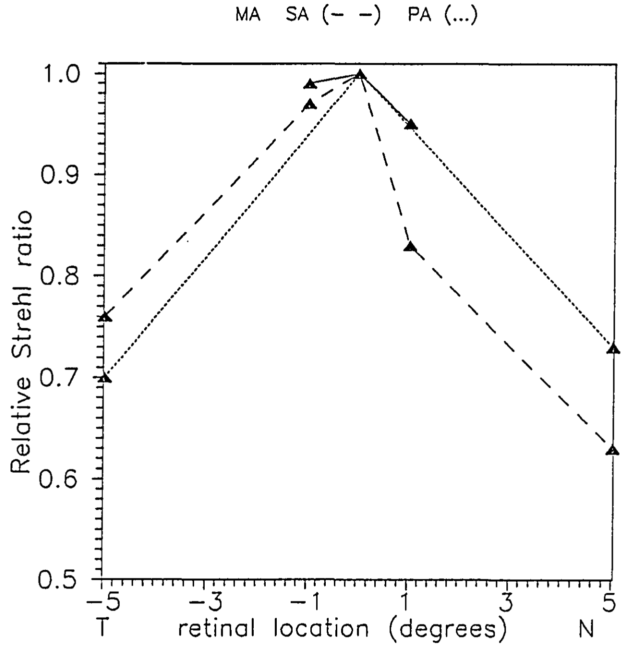


Fig 8. Relative Strehl ratio with respect to that of the center of the fovea in the horizontal meridian from 5 deg temporal (T) to 5 deg nasal (N). Solid curve, subject SA; dashed curve, subject MA; dotted curve, subject PA.

in the retinal reflection: a wide scattering halo and a specular component, which suggest that the reflection takes place mainly at the pigment epithelium. In addition the models that they propose to explain the results in spectral reflectance measurements[21,22] incorporate a multilayer contribution to the reflection including layers that are distant from such photoreceptors as the sclera. Snodderly and Weinhaus[23] suggested that retinal blood vessels contribute to the optical image quality, although this should not affect the fovea. Gorrand and Bacin[15,16] carried out a series of experiments to study the retinal reflection characteristics, particularly to evaluate the optical quality of the inner retina and the effect of retinal scattering on double-pass methods. From those experiments they concluded that the double-pass method in general underestimates the image quality of the eye.

At this point we must first consider one important characteristic of our experimental setup, i.e., the high magnification that implies a small depth of focus. Throughout this experiment we used a 200-mm focal length in the zoom (although 300 mm is a more typical value for single-point foveal experiments). This corresponds to a magnification of $\sim 12.5\times$, and then the depth of field is ~ 50 µm for the 4-mm pupil size, which is shorter than the length of the foveal cones [typically 70 µm (Ref. 24)]. This means that, in our double-pass system, light coming from a layer distant from the focusing plane should not contribute to the aerial image except with a diffuse background. This argument especially concerns the amount of light that could possibly be reflected by the sclera or blood vessels, which we could not detect in our measuring apparatus.

Table I. Strehl Ratio Relative Lowering at 1 Deg of Retinal Eccentricity with Respect to the Center of the Fovea

	Subjects		
Fovea Part	SA	MA	PA
Nasal	0.83	0.95	
Temporal	0.97	0.99	
Superior	0.94	1.00	0.98
Inferior	0.84	0.94	0.93

The results that are presented here are additional data to be added to the scattered set of evidence for understanding the nature of retinal reflection. In particular we mention briefly a recent experiment by Navarro and Williams[25] that consists of a comparison of subjective versus objective best focus positions in the fovea and near periphery. The focus differences were not statistically significant and never greater than the length of the outer segment of the foveal cones.

The model for the foveal reflection that fits with the results is as follows: the optical image is focused onto the plane of the photoreceptors, probably close to the outer segments, the light is waveguided and reflected by the pigment epithelium; it returns (initially guided also by the outer segments) and then becomes a diverging beam until it is refocused by the eye's optical system. Many previous experimental results,[20,21] the focusing experiment, and all the findings from this study are in agreement with this simple model, and in the next section we discuss more evidence for this.

Breaking the Coherence. Retinal Reflection: Diffuse or Specular?

We discuss at this point that which is crucial and sometimes misunderstood concerning the double-pass measurement. It is common to read in the literature that the second pass can be considered incoherent if the retina acts as a perfectly diffusing surface. This is not exactly correct, since to break the spatial coherence it is necessary to pass the coherent beam through a moving diffuser with the movement being faster than the measurement time. In our particular method the coherence is broken by averaging short-exposure images, which are equivalent to obtaining a long-exposure image. The coherence is in fact broken by the ocular movements, while the retina acts as a diffuser. That diffuser is far from perfect (Lambertian); it is composed of many small waveguides (cones) with high directionality. Campbell and Gubisch[2] investigated the reflection properties of the retina from the measurements that were made by using their particular setup with white light. They found a power of 4 dependence of the total reflected flux on the pupil diameter d^4. This corresponds to a completely diffuse component, while a power of 2 dependence d^2 indicates a specular reflection. Posterior researchers[18,26] did not find that d^4 dependence, but this question remains unclear because of a general understanding that diffuse reflection is a necessary and sufficient condition for obtaining the ocular MTF as the square root of the double-pass MTF. To continue on this point, we measured the aerial retinal image of a point using the same experimental setup as depicted in Fig. 1 but including different artificial pupils by using an additional afocal system consisting of two identical lenses. With the same incident irradiance the relative reflected total intensity of the aerial images was computed as a function of the pupil diameter. We repeated the measurements by placing an artificial eye consisting of a lens and a perfect diffuser in its focal plane. The results from studing one subject and the artificial eye are plotted in Fig. 9 along with the two theoretical curves d^2 (specular) and d^4 (diffuse). Our data, that were obtained with a monochromatic red light, are near but below the d^2 curve. The lower values that are found for large pupils are a clear consequence of the retinal waveguiding by the cones, which gives a highly directional beam, which can be interpreted as the effect of a smaller (apodizing) effective pupil size. These results along with other experimental clues lead us to believe that in our double-pass configuration the recorded aerial images correspond not only to a specular component but to a highly directional one. This is further support for the previously proposed model. The reflection in the retina produces a high-contrast speckle in the aerial images, but it appears that the retina is not a perfect diffuser at all. On the contrary one could think of an array of small and short optical fibers in front of a rough black screen. The speckle is produced by phase differences resulting from the distinct fiber length and position and also by the roughness of the black screen. The average of short-exposure images achieves speckle blurring, and then the second pass can be considered incoherent. It must be noted that even with a perfect diffuser the short-exposure images would be perfectly coherent, and only when the diffuser is moving is the speckle removed and the coherence broken.

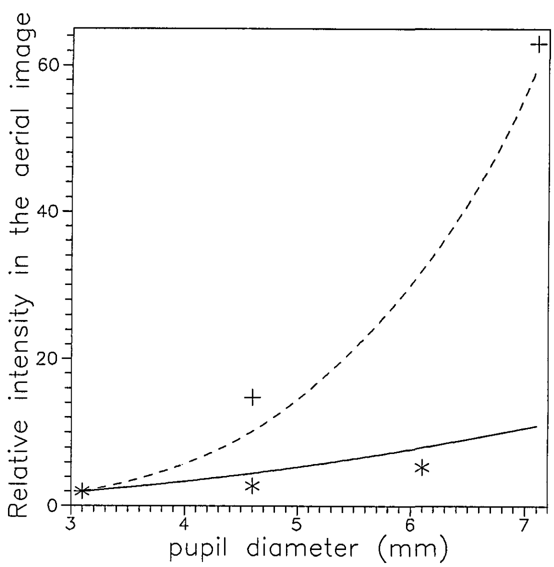


Fig 9. Experimental results of the relative reflected flux in the aerial image for subject PA (*) and for an artificial eye with a perfect diffuser (+) as a function of pupil diameter d. The solid curve shows the d^2 dependence and the dashed curve the d^4 dependence.

The effect of directionality on reflection is another related detail to be considered briefly, although it is the subject of a recent paper.[27] In that work the directionality of the retinal reflection was simulated by an apodizing pupil, and then the aerial images were recomputed from the wave aberration. The directionality of the retinal reflection causes the double-pass MTF to be slightly worse than the actual MTF. However, when the Stiles–Crawford effect is included in the calculation of the postreceptor MTF it tends to compensate finally for the effect of retinal directionality.

Conclusions

We have presented an experimental system based on one that was previously developed to measure the PSF of the eye, which allows the simultaneous recording of the double-pass aerial images of a couple of twin points, one placed at the foveal center and the second at 1 deg of eccentricity at different retinal orientations. With that system we performed an experiment in which we try to evaluate the contribution of retinal thickness to the optical aberrations of the eye and its influence on the image quality measurements that were obtained by the double-pass method. The small differences observed in the aerial images must arise exclusively from the thickness variations across the foveal pit, while other possible experimental variable factors have been avoided with this particular procedure. In this way we have been able to find a small but systematic degradation in 1-deg aerial images with respect to those that correspond to the foveal center, which is more marked in the nasal and inferior retina for all subjects that have been measured so far. These differences are marginally statistically significant, since they are comparable with the SEM of the MTF's. These differences can be explained by considering the inner retina as part of the optical system of the eye with a small contribution to the optical aberrations. In any case this contribution is so small that it cannot be considered relevant to vision. In addition we found no truly important contribution of the retinal scattering to our measurements. The nature of retinal reflection was also considered. We measured the reflected flux in the aerial images as a function of the pupil diameter and obtained a result near but below a d^2 dependence, which corresponds to a specular reflection in the retina. Our results fit those obtained in an array of waveguides with high directionality. The aerial images show a high-contrast speckled structure, but when averaging the frames the speckle is blurred, which leads to an effective break in the coherence. This allows the computation of the ocular MTF as the square root of the external MTF. A model of the foveal reflection fit with the data consists of considering first that the optical image is focused on a plane that is close to the cone's outer segments. The light is guided by the cones, and after reflection in the pigment epithelium it is guided back again through the photoreceptors.

As a final and indirect conclusion the results presented here are additional evidence supporting the reliability of the double-pass method for assessing the image quality of the human eye.

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