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The depth-of-field of the human eye from objective and subjective measurements

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Abstract

The depth-of-field (DOF) measured through psychophysical methods seems to depend on the target's characteristics. We use objective and subjective methods to determine the DOF of the eye for different pupil diameters and wavelengths in three subjects. Variation of image quality with focus is evaluated with a double-pass technique. Objective DOF is defined as the dioptric range for which the image quality does not change appreciably, based on optical criteria. Subjective DOF is based on the accuracy of focusing a point source. Additional DOFs are obtained by simulation from experimental wavefront aberration data from the same subjects. Objective and subjective measurements of DOF are only slightly affected by pupil size, wavelength and spectral composition. Comparison of DOF from double-pass and wavefront aberration data allows us to evaluate the role of ocular aberrations and Stiles–Crawford effect.

Keywords: Physiological optics; Optical quality; Depth-of-field; Ocular aberrations; Stiles–Crawford

1. Introduction

The human eye, as any other optical instrument has a limited sensitivity to optical blur. The depth-of-field (DOF) of the human eye (dioptric range for which the retinal image quality does not change appreciably) has both a clinical relevance, since it determines the precision of refractive compensation, as well as a more basic interest, for example in the study of factors affecting the accommodative process (Tucker & Charman, 1975; Atchison, Charman & Woods, 1997). The DOF of the human eye is basically a function of optical parameters (pupil size, optical aberrations, etc…) but is also affected by retinal, neural and more complex psychophysical factors (Green, Powers & Banks, 1980). There is a relatively large number of experimental investigations on the DOF of the human eye, mainly assessed through psychophysical experiments (see Atchison et al., 1997 for a recent review). These measurements of the overall, subjective DOF depend on the particular type of target, target detail size, and test conditions (Fry, 1955; Campbell, 1957; Ogle & Schwartz, 1959; Green & Campbell, 1965; Tucker & Charman, 1975; Charman & Whitefoot, 1977; Charman, 1979; Legge, Mullen, Woo & Campbell, 1987; Atchison et al., 1997). In most of these studies, the subjective results are compared to those theoretically derived from a diffraction-limited eye (Charman & Jennings, 1976). Most of these studies also addressed the influence of the pupil size on the DOF, and found that the DOF does not decrease with increasing pupil diameter as fast as in an aberration-free optical system. According to Campbell (1957), this effect is totally explained by a reduction in the effective size of the pupil produced by the Stiles–Crawford effect (Metcalf, 1965). For other authors, however, aberrations would also play an important role in increasing the DOF for large pupils (Charman & Whitefoot, 1977). For others, the influence of Stiles–Crawford effect would actually decrease DOF since it reduces the dominance of off-axis aberrations for large pupils (van Meeteren, 1974). In summary, the lack of objective measurements of the optical quality of the eye, and the limited knowledge of ocular aberrations led those authors to speculate about the reasons for the confirmed departure of DOF from ideal values for medium and large pupils.

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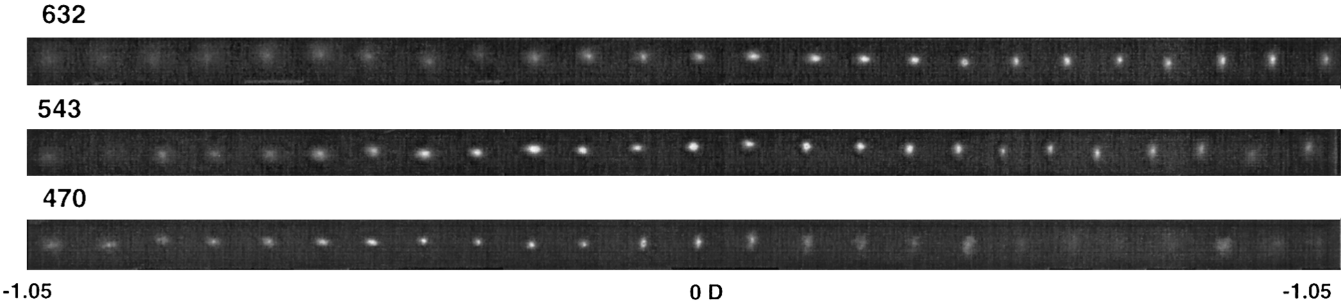

Fig. 1. Series of double-pass aerial images as a function of defocus, at steps of 0.086 D, for 632, 543 and 472 nm, respectively, (subject EM, 6-mm pupil).

Some of the mentioned DOF measurements were made with monochromatic light, while others were made with white light. Some works studied the variation of DOF with various wavelengths or compared the DOF for monochromatic with polychromatic light. The results are again controversial (Legge et al., 1987; Campbell, 1957). We believe that objective measurements of the DOF for different wavelengths would help in the understanding of the influence of wavelength on the DOF.

The variation of optical quality as a function of focus has been previously studied, in some cases through objective techniques (Charman & Jennings, 1976; Rynders, Navarro & Losada, 1998) or even applied to clinical conditions (Artal, Marcos, Navarro, Miranda & Ferro, 1995a; Woods, Atchison & Bradley, 1996). Bradley, Zhang, Ye and Thibos (1998), Burns, He and Marcos (1998) and Atchison, Joblin and Smith (1998) have recently reported the influence of wavefront aberrations and Stiles–Crawford effect in the variation of optical quality with focus. However, to our knowledge, none of these studies addressed the issue of the DOF of the human eye.

In this paper, we study the objective DOF of three cyclopeged normal eyes for various pupil sizes and wavelengths, using three different methods. The first method consists of double-pass measurements as a function of focus to determine the DOF objectively, using conventional optical criteria. We also calculated the variation of image quality with focus based on wavefront aberration data available from the same subjects (in green light) (He, Marcos, Webb & Burns, 1998; Navarro, Moreno & Dorronsoro, 1998) as well as realistic Stiles–Crawford functions. This computation allows us to evaluate the influence of aberrations and Stiles–Crawford effect (SCE) on the DOF, which was computed by applying the same criteria used in the analysis of double-pass measurements. The results obtained with these two objective methods are compared to the subjective DOF, measured on the same subjects in the same conditions as the double-pass experiment.

2. Methods

2.1. Subjects

Double-pass and psycophysical measurements were made on three subjects (two females and one male): EM, SM and RN, with ages 23, 26 and 39, respectively. All the subjects used their right eye. The three subjects had different amounts of negative refractive errors, that were compensated with the Badal focusing block within the apparatus. For subject SM an additional lens (−6 D) was inserted to compensate for her higher myopia. Unless otherwise noted, astigmatism was not corrected. Cycloplegia and mydriasis were achieved by instilling two drops of 1% cyclopentolate 0.5 h prior to the experiment. An additional drop was administered after every hour to assure continued complete cycloplegia. Both types of measurements were conducted in a single session for the three subjects. For control purposes, double pass measurements were conducted in one of the subjects (EM) in a second session separated several months from the first session, after a slight modification of the instrument.

2.2. Double-pass measurements

The apparatus used in this experiment is a modified version of the one used by Rynders et al. (1998) to measure the longitudinal chromatic aberration (LCA) across the human retina. It consisted of an extension of the basic double-pass apparatus (Santamaría, Artal & Bescós, 1987; Navarro, Artal & Williams, 1993), incorporating three laser sources of different wavelengths (see Fig. 1 in Rynders et al., 1998). The three beams shared the same optical path after being focused simultaneously by a microscope objective on a pinhole, which acts as spatial filter and is the point source projected onto the retina. The Badal focusing block was mounted on a platform controlled by a stepper motor that could be adjusted manually or automatically by the computer. Moving the first Badal lens back and forth varies the vergence of the incident beam, and of the light reflected off the retina. Our main modification consisted of using a high resolution, low scan CCD camera (SpectraSource Instruments, MCD600S). The data acquisition board controls the acquisition of images in the imaging system. The TTL output signals permit to synchronize the image capture, the internal and external electronic shutters and the stepper motor. The angular pixel size was 0.59 arc min for measurements in the first session and 0.31 arc min in the second session.

Measurements were obtained with three different wavelengths (543 nm for green light, 632 nm for red, and 472 or 458 nm for blue light). Three different artificial pupils were used: 2, 4 and 6 mm. They were projected onto the subject's natural pupil by means of the Badal pair of lenses. Despite steady stabilization of the subjects' head, control experiments revealed that the variability of optical quality in the best focus condition for a 2-mm pupil was of the same order of the variation of optical quality within the dioptric range measured, and therefore double-pass measurements for 2-mm pupils were not further considered. Centration is particularly critical for small pupils (Artal, Marcos, Iglesias & Green, 1996). The incorporation of a headrest (available in the second session) did not decrease the variability of the measurements for 2 mm. Control experiments also showed that the mentioned problem did not appear for 4-mm and bigger pupils.

All measurements were foveal. Fixation was achieved by opening the external shutter a few milliseconds before the image acquisition. Exposure time was 4 s. The irradiance at the pupil plane was in all cases lower than 0.25 μW for red and green and lower than 1.92 μW for blue light.

Prior to the experiment (for each pupil diameter, and in green light) the subject was asked to bring into subjective best focus the image of a point source by manually moving the Badal lens. This setting was repeated at least ten times and the average was taken as the best subjective focus (see Rynders et al., 1998, and next subsection for details). This position (for which the distance between the Badal lenses expressed in Diopters should correspond to the subject's refractive correction in green light) was taken as the 0 D position, and all the measurements are given relative to that value. The absolute value changed slightly for each pupil size due to spherical aberration.

A total of 26 aerial images were acquired for each condition (pupil diameter and wavelength) at steps of 0.0856 D in the first session, and 0.125 D in the second session: 12 with positive defocus and 12 with negative defocus about the best subjective focus for 543 nm, and two images for 0 D, scanning a total range of 2.1 and 3 D (in the first and second sessions, respectively). Recent objective measurements show that LCA takes a value close to 1 D at the foveal center, between the two most extreme wavelengths used in this experiment (Rynders et al., 1998). According to these measurements, we would expect best focus for blue and red to appear around −0.6 and +0.4 D, respectively.

Images were processed off-line using programs written in MATLAB (Mathworks, Inc., Nantick, MA). Single-pass two-dimensional modulation transfer functions (MTFs) were computed as the square root of the magnitude of the inverse Fourier transform of the aerial images (Santamaría et al., 1987; Navarro et al., 1993). Unlike the full-width at half maximum of the double-pass aerial image used by Charman and Jennings (1976), we have considered different parameters to characterize the single-pass image quality. Firstly, we examined the variation with focus of the modulation (from the radial profile of the MTF) at selected spatial frequencies. This parameter does not give a global description of the optical quality, but it is useful to predict differences in the tolerance to defocus for high or low frequencies (Legge et al., 1987). One possible refinement is to consider an average across a few frequencies, or alternatively the Strehl ratio (volume under the MTF normalized to the volume under the MTF of a diffraction-limited system for the same pupil diameter), which is a global parameter. However, the Strehl ratio has been shown not to be adequate to describe severely aberrated optical systems (Artal et al., 1995a), as may be the case for some human eyes with large pupils and defocus. Another alternative global quality parameter, that is especially well suited to analyze double-pass data, is the maximum intensity of the double pass aerial image normalized by the total intensity of the image (to avoid the effects of intensity fluctuations during measurements). This parameter (IMAX) has a double interpretation as a single-pass quality criterion. Firstly, it is related to encircled energy criteria, based on estimating the energy falling within circles of given radii. Since both the radius value and the fact of using circles instead of other window shape are arbitrary, one could use the PSF itself as the measuring window. This is equivalent to computing the peak of the autocorrelation function; i.e. the peak intensity of the aerial image. The second interpretation is as the global energy of the power spectrum of the single-pass PSF (one could even combine this parameter and the squared Strehl ratio to estimate the RMS value of the MTF). In what follows, we will be presenting either the modulation transfer for particular frequencies (averaged over orientations) or the IMAX as a more global value.

Given an optical quality parameter, the DOF can be determined as the dioptric range for which the image quality parameter does not fall below 0.8 times its optimal value. This definition has a physical interpretation for some parameters such as for the Strehl ratio (which corresponds to the Rayleigh criterion) and the modulation transfer (which corresponds to Hopkins criterion, Hopkins, 1955). However, since the variation of the optical quality with defocus will not necessarily be smooth (particularly for high spatial frequencies and IMAX) results based on the 0.8-criterion might be too noisy, since they rely only on the data just above or below the 0.8 limit. Some authors (Green & Campbell, 1965; Legge et al., 1987) overcome this problem by fitting straight lines through the data to the left and right of the best focus condition. In log linear coordinates, that would imply that optical quality decays exponentially with defocus. We avoided this assumption, which in principle is only true for an ideal lens, since asymmetries of the variation of optical quality with defocus are to be expected when aberrations are present. Instead, we interpolated the data versus focus with a spline method. We then computed a series of dioptric ranges for which the image quality parameter did not fall below x times its optimal value, with x ranging between 0.6 and 1 at 0.0167 steps. The DOF was finally calculated as the average of those dioptric ranges. This procedure allowed us to use a larger sample of the data, producing more robust estimates of the DOF. We tested for smooth simulated data, we obtained similar DOFs using this definition or using the 0.8-criterion.

2.3. Subjective settings

For subjective DOF measurements we used the illumination channel of the double-pass set-up described in the previous section. We reduced the laser intensities to low levels, so that the subjects could look into the beam comfortably during an extended period of time, and perceive adequately changes in their retinal PSF during the focusing setting. Luminance was modified independently for each wavelength, so that the subject judged the stimulus as white when the three wavelengths were viewed simultaneously. The subjects were instructed to adjust manually the Badal focusing block to the position best focus of the point source projected on his/her retina, looking for the image with the sharpest central peak. The point test was viewed on a dark background to preserve the conditions as close as in the objective experiment. The initial position was set randomly. The subjects typically scanned the focus several times to determine their best focus location. The best focus for each wavelength and pupil diameter was obtained as the average of 10–20 settings. Our three subjects were also experimenters and they were trained before collecting data. For subjective DOF, we have adopted a criterion based on the standard deviation (σ) of the settings. Charman and Whitefoot (1977), proposed, for their particular psychophysical experiment, the DOF to be equal to 4σ, and gave some conversion factors for other confidence levels (Woodworth & Schlosberg, 1966). Here we have adopted 2σ, instead, as a full-width ($\pm\sigma$) estimate, that will be compared to the objective full-width DOF values obtained.

2.4. Estimates from wavefront aberration data

Wavefront aberration data from the three subjects under dilated conditions and for a wavelength of 543 nm were available from previous published works (He et al., 1998; Navarro et al., 1998). The wavefront aberration function represented as a Zernike polynomial expansion had been obtained by an objective ray tracing technique (Navarro & Losada, 1997; Navarro et al., 1998) for RN and EM, and by a subjective spatially resolved refractometer (Webb, Penn & Thompson, 1992; He et al., 1998) for SM. In the ray tracing technique, a narrow laser beam enters the eye sequentially at 35 pupil locations (at 1-mm intervals) and projects a displaced spot onto the retina. Aerial images are obtained on a high-resolution CCD camera for the series of entry locations. The displacement of the centroid of the point image with respect to the principal ray represents the slope of the wavefront aberration. In the spatially resolved refractometer, an image of a point source is projected onto the subject's retina through a series of 35 1-mm sample apertures that sequentially tile the subject's pupil. A fixation channel projects a cross-hair target, through a centered small pupil. The subject aligns the point source to the center of the cross, by changing the angle of a gimballed mirror using a joystick. This angle represents the slope of the wavefront aberration. In both cases, aberrations are measured on the first-pass ingoing beam forming the retinal image. Wavefront aberration functions are obtained by a least square fitting to a Zernike polynomial expansion (Malacara, 1992). For this particular application, we only considered an expansion up to the 5th order (20 terms).

Double-pass aerial images and MTFs were derived from the pupil function for a series of defocus. Point-spread-functions (PSF) were computed as the squared modulus of the Fourier Transform of the pupil function, and the MTF as the modulus of the Fourier Transform of the PSF (Hopkins & Yzuel, 1970). Double-pass aerial images were obtained as the autocorrelation of the PSF (Artal, Marcos, Navarro & Williams, 1995b). We simulated the same amounts of defocus as in the double-pass experiment (by varying the defocus coefficient in the Zernike expansion, taking the 0 D condition as this for which $c(4) = 0$), for the same pupil diameters as in the experimental measurements (2, 4 and 6 mm). In the last Section, we discuss the effect of the Stiles–Crawford apodization (Metcalf, 1965) on the DOF. For these simulations, we introduce a Gaussian modulation of the modulus of the pupil function, representing a generic Stiles–Crawford effect (centered, and with directionality factor $\rho = 0.01$ mm^{-2}) (Burns et al., 1998). The variation of image quality with focus for the ideal lens was also computed, by setting all Zernike coefficients to 0, except for the defocus terms. We checked that we obtained the same results as the ones tabulated by Levi and Austing (1968). DOF was then computed by running the same programs that we used to process the double-pass experimental measurements.

3. Results

3.1. Variation of image quality with focus

Fig. 1 shows series of double-pass aerial images (subject EM) as a function of defocus (0.086 steps), for three wavelengths (632, top; 543, middle and 472 nm, bottom). Negative values stand for a negative spherical correction in the Badal focusing block (the correction that would be prescribed for myopic eye) and positive values for a positive spherical correction in the Badal focusing block (correction for a hyperopic eye). The illumination was kept constant within a session for each of the wavelengths. The images have been normalized by the maximum intensity in the entire series for each wavelength. Increasing defocus around the optimal condition (which lies close to 0 D for green, in the myopic region for blue and in the hyperopic region for red, due to the longitudinal chromatic aberration) results in a simultaneous decrease in the maximum intensity and a corresponding increase in the spatial spread of the image.

One optical image quality parameter upon which

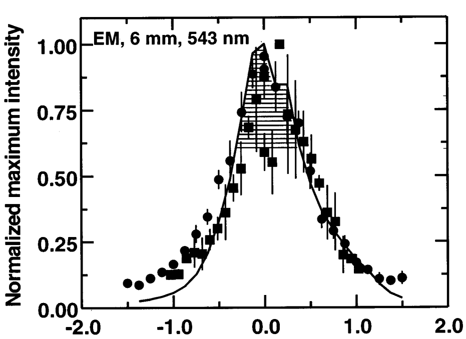

Fig. 2. Maximum intensity of the aerial image normalized by the total intensity of the aerial image (IMAX) as a function of defocus, for subject EM, with a 6-mm pupil diameter, and a 543-nm wavelength. Data from two different sessions are represented by squares and circles, respectively. Each symbol is the average of three different runs in a session, and the error bars are ± 1 SE. The solid line shows the normalized maximum intensity versus defocus based on wavefront aberration data for this subject, for a 6-mm pupil diameter and a 543-nm wavelength. The shaded area shows the range of data (0.6–1) used in our calculation of depth-of-field.

we based our estimates of DOF was the double-pass normalized maximum intensity (IMAX). Fig. 2 shows the normalized maximum intensity as a function of defocus for EM at 6 mm in green (543 nm) light. For the sake of clarity measurements in blue light (458 or 470 nm) or red light (632 nm) have not been included in the graph. The shape of the curves is similar for all wavelengths, but they are slightly shifted with respect to the curve for green light by an amount (0.316 and -0.43 D, respectively) consistent with the chromatic aberration of the eye between these wavelengths (Rynders et al., 1998). Each symbol is the average of three runs within a session, and the error bars represent ± 1 SEM, showing the typical variability of the normalized maximum intensity within a session. The two types of symbols represent results from two sessions separated by 12 months (squares are results from the first session and circles from the second session). There was a consistent notch in the curves from the first session (present in the three runs for all wavelengths) which was absent in the second session. The reason for the difference between the two sessions could either be due to the slightly sparser sample used in the second session (0.125 D instead of 0.086), to a slightly different refractive state, or to changes in the bleaching conditions. The solid curve represents the results from the simulation based on EM's wavefront aberration for the same conditions as in the double-pass experiment, which shows a close agreement with the double-pass data. The shaded area indicates the range of data (0.6–1) used for the computation of the DOF, as explained in the Section 2. Essentially, our estimation of DOF is the sum of the lengths of the horizontal segments in the shaded area divided by the number of segments.

We also estimated the DOF as a function of spatial frequency. Fig. 3 shows the variation of the modulation at different spatial frequencies as a function of defocus for the three subjects, from double-pass measurements (panels a–c), for a 4-mm pupil and a wavelength of 543 nm. Panel d shows estimates from the wavefront aberration for subject EM. There is significant intersubject variability for the modulation transfer values versus defocus from double pass measurements, even at best focus and the lowest frequency. The decrease in DOF as the spatial frequency increases (narrower curves for higher frequencies) is consistent for all subjects, except for subjects with very low modulation at the highest frequencies. In agreement with Charman and Jennings (1976) (Fig. 15), we find a shift in the optimal focus with spatial frequency (for EM, the peak moves clearly toward hyperopic corrections as the spatial frequency increases, for both the double-pass measurements and simulation from wavefront aberration data). The bet-

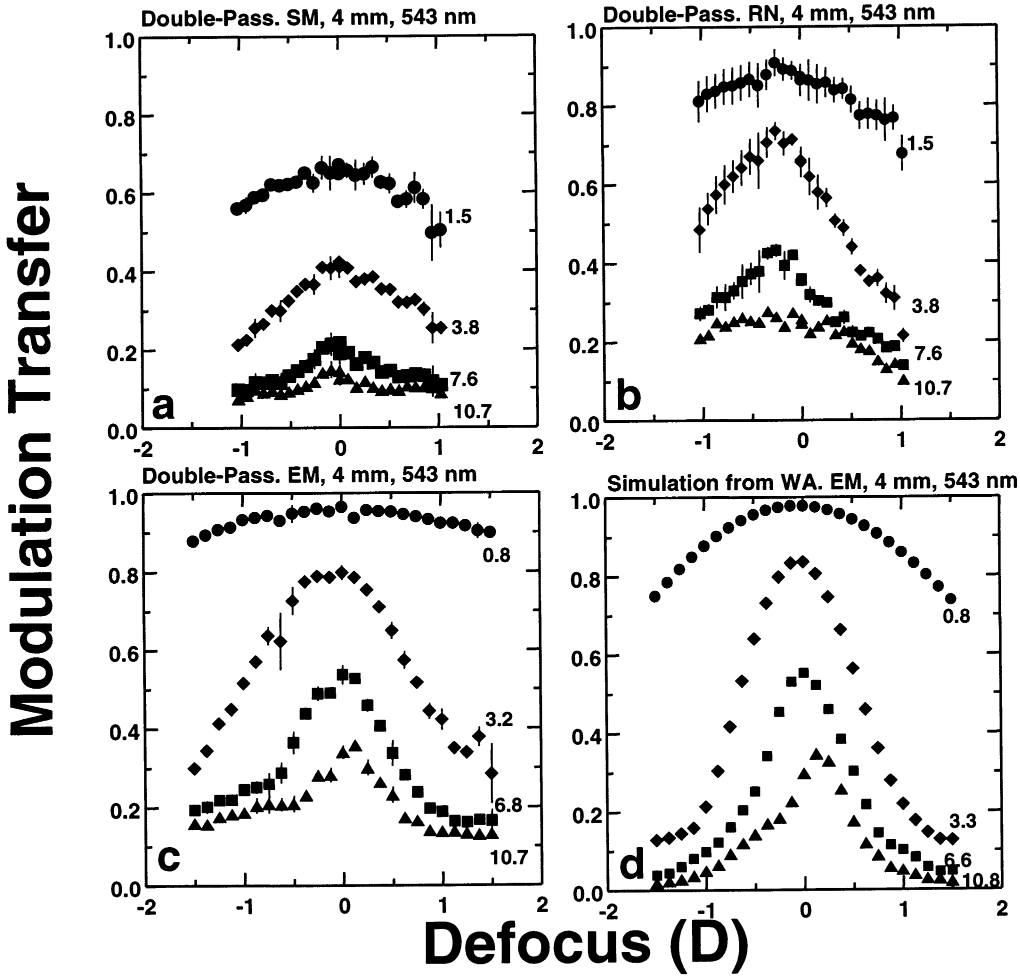

Fig. 3. Modulation at different spatial frequencies (in c deg^{-1}) as a function of defocus for the three subjects (SM, RN and EM), for a 4-mm pupil and 543 nm of illumination wavelength. Panels (a)–(c) show results from double pass measurements. Each symbol is the average of the three runs in a single session, and error bars represent ± 1 SEM. Panel (d) shows results obtained by simulation of the MTF based on wavefront aberration data for subject EM, measured by a ray-tracing technique.

ter agreement between experimental double-pass measurements and results from the simulation in our experiments, in comparison to Charman and Jennings', is possibly due to the fact, as suggested by the authors, that their results are affected by poor-signal to noise ratio and truncation errors (that underestimate their modulations) and the fact that they only considered spherical aberration in their simulation (whereas we use the subject's own aberrations up to the 5th order).

3.2. Depth-of-field as a function of spatial frequency

Fig. 4(a) shows the variation of the DOF with spatial frequencies in two different sessions for subject EM, along with the prediction based on the subject's wavefront aberration. As shown in Fig. 4(b), the DOF sharply decreases for all subjects when increasing the spatial frequency up to about 7.5 c deg^{-1}, and then unlike the ideal eye, remains virtually constant or even increases for the highest frequencies.

3.3. Depth-of-field as a function of pupil diameter

The variation of DOF with defocus (in terms of IMAX) is represented in Fig. 5 both for double-pass measurements (solid circles) and for estimates from wavefront aberration data (open diamonds, dashed line) along with subjective measurements (solid squares, solid lines). Panel (a) shows results from subject EM, and (b) averaged values across subjects. Squares and diamonds have been slightly displaced horizontally from the actual values to avoid overlapping of the error bars. Panel (b) also includes results for the ideal lens (dotted line). There is a clear decrease in the DOF between 2 and 4 mm in all cases, but our objective data show that for larger pupils DOF increases in some cases.

There is a good agreement between the DOF derived from double-pass measurements and the DOF derived from wavefront aberration data. The match is excellent for subject EM, and in general they both show the same trend in all subjects: the average DOF across subjects increases from 4 to 6 mm for both estimates from double-pass and wavefront aberration. The subjective values differ somewhat from the optical estimates. For EM, subjective DOF is shifted toward lower values, which might suggest that a simple redefinition of the subjective criterion could yield a closer match. On average, the agreement (values and/or trend) is good for the smaller pupil diameters, but markedly different (both values and trend) for the 6-mm pupil.

3.4. Depth-of-field as a function of wavelength

Fig. 6(a) shows results for subject EM, and (b) the average across subjects for a 4-mm pupil. As illustrated in Fig. 6, we do not find any systematic variation in the DOF with wavelength, for either the subjective nor the objective results. Fig. 6(a) shows results for subject EM, and (b) the average across subjects for a 4-mm pupil. For subject EM, we have calculated the DOF in white light from a weighted superposition of the monochromatic aerial images, shown in Fig. 6(a). To obtain a polychromatic image quality parameter (Bescós & Santamaría, 1981), we added the monochromatic aerial images, normalized to the total intensity and weighted by the photopic spectral sensitivity, $V(\lambda)$, and the daylight spectrum, $S(\lambda)$ (Wyszecki & Stiles, 1982). In principle, a coarser sampling of the white light spectrum should be used; however, since the image quality changes smoothly with wavelength, using only three monochromatic primaries (red, green and blue), appropriately weighted to produce a white stimulus, can be a reasonable approximation. The DOF in white light increases slightly with respect to the monochromatic case (see Fig. 6a).

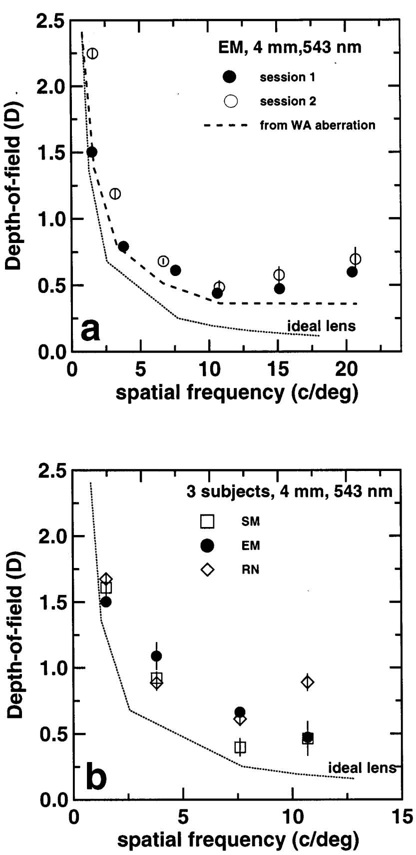

Fig. 4. Depth-of-field as a function of spatial frequency, for a 4-mm pupil and 543-nm wavelength, computed from the change in modulation transfer with defocus (see Fig. 3). (a) Subject EM; filled and open circles represents the first and second session, respectively (average of DOF from three runs in each session), and error bars are ± SE; the dashed line represents results from the simulation using EM's wavefront data; (b) for the three subjects; data are averages across runs and sessions and error bars are ± 1 SE. The dotted line indicates results for the ideal lens.

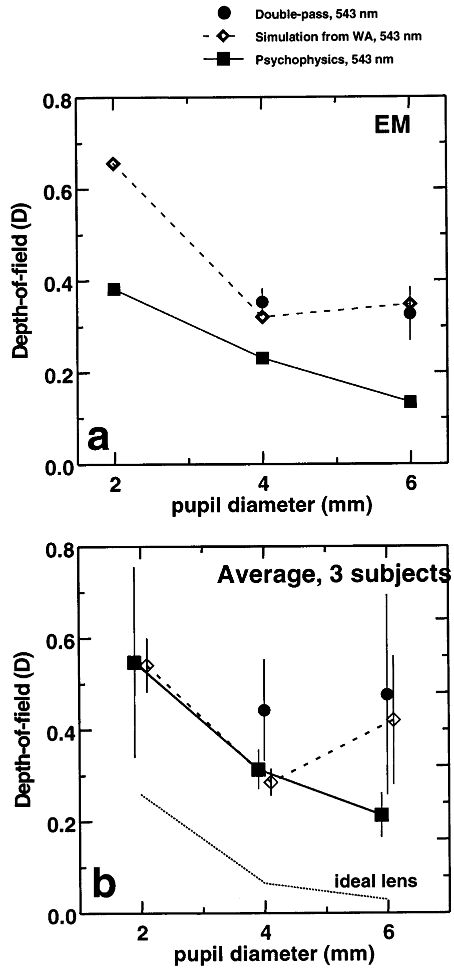

Fig. 5. Depth-of-field (for IMAX) as a function of pupil diameter, for a 543-nm wavelength. Filled circles represent data from double-pass measurements. Diamonds and dashed line are results from the simulation based on wavefront aberration data, and solid line and squares represent subjective DOF. Panel (a) shows results for subject EM; double-pass data are averaged across runs and sessions, and the error bars are ± SE. Panel (b) shows results averaged across subjects; symbols have been displaced horizontally to avoid overlapping of the error bars (± 1 SE). The variation of DOF with pupil diameter, for IMAX, for the ideal lens is plotted on dotted line.

4. Discussion

We have shown that the DOF of the eye decreases with increasing spatial frequency, at a slower rate than in an aberration-free lens, and decreases with pupil diameter for medium pupil sizes, although it tends to increase in some cases for 6-mm pupils. Unlike other measurements in the literature (Campbell, 1957), we have found no clear systematic variation of DOF with wavelength, and calculated only a slight increase of the DOF with white light with respect to monochromatic light. While the agreement between results from the double-pass measurements and the estimates from wavefront aberrations in the same subjects is reasonably good, subjective estimates based on the ability to focus a point source are lower, particularly at the largest pupil diameter. Our results are consistent with reported data in that the DOF is not ideal, especially at larger pupils. However, there was no general agreement for the causes of this discrepancy. Aberrations and Stiles–Crawford effect were evaluated as potential reasons, but except for some simulations using generic data (Charman & Whitefoot, 1977), discussions were based more on speculations than on actual measurements (Campbell, 1957; Legge et al., 1987). We have gathered for the first time two types of objective measurements, as well as subjective data in the same subjects, to address these issues.

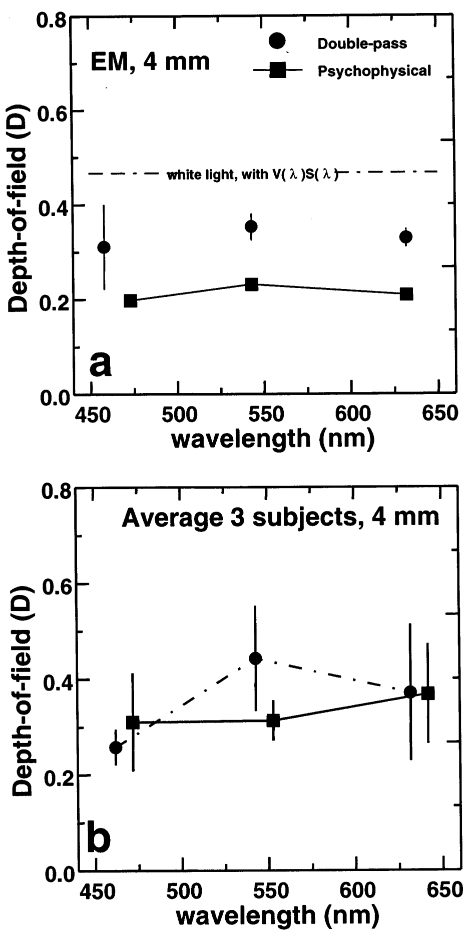

Fig. 6. Variation of the depth-of-field with wavelength, for IMAX, for a 4-mm pupil diameter. Filled circles represent data from double-pass measurements, and squares subjective estimates. (a) For EM, double-pass data are the averaged across runs and sessions; error bars are ± 1 SE. (b) Average across subjects; symbols have been displaced horizontally to avoid overlapping of the error bars (± 1 SE). Panel (a) also shows DOF for white light calculated by averaging measurements for the three wavelengths and weighting by $V(\lambda)$ and the daylight spectrum $S(\lambda)$.

4.1. Depth-of-field from double-pass and wavefront aberration measurements

DOF from double-pass or wavefront aberration measurements both give the same trend for the change in DOF with pupil diameter, and they also give comparable absolute values. The difference between the two pairs of measurements for subject EM is not significant (see Fig. 5a). In general, estimates of DOF from double-pass measurements are higher than from wavefront data (1.6 times higher for 4 mm and 1.1 times for 6 mm). There could be three potential reasons for the difference. Firstly, we have considered only terms up to 5th order in the Zernike coefficients of the polynomial expansion. If there are additional aberrations not considered in the expansion their effect would be to decrease optical quality and consequently to increase the DOF (we will present below an example of the effect in the DOF of incorporating additional aberrations). Secondly, double-pass measurements tend to underestimate slightly the MTF (Williams, Brainard, McMahon & Navarro, 1994), which would imply an overestimation of the real DOF. Finally, the presence of a double peak in double-pass measurements when defocus was varied in small steps (see Fig. 2) could suggest that a double reflection might be taking place at two different planes within the retina, or even along the outer segment of the cones (the peaks are separated by 0.258 D, or equivalently 71 μm within the retina). This result is not conclusive, since it only occurred in one of the sessions for one subject (although very repetitively). The peaks are so close that they would not be resolved except for special sampling conditions, and very good optical quality (as could happen for subject EM, in the first experimental session). If such a double reflection was present, in general the effect would be to broaden slightly the curves of double-pass optical quality versus defocus.

4.2. Objective and subjective depth-of-field

It has been shown that the subjective DOF varies significantly with the target used. We designed our subjective task so that the criterion was as similar as possible to the one we used objectively: perceptible blur of a point source. In addition, the point test provides maximum bandwidth which guarantees its use as a global criterion, not restricted to any particular frequency band. We chose the DOF to be twice the standard deviation (2σ) of a set of best focus settings as judged by the subject, and obtained, on average, values of 0.54 D for a 2-mm pupil, 0.31 D for 4-mm, and 0.21 D for a 6-mm pupil. Most of the DOF measurements in the literature with complex targets use a 4σ criterion (Charman & Whitefoot, 1977) or the whole range for which the target appears unchanged (Campbell, 1957; Atchison et al., 1997), which is closer to the 4σ criterion. Therefore, we can divide these published results by two to compare them with our results. After this conversion, Campbell (1957) found 0.215 D for a 3-mm pupil using a target with 10 min arc black circles, Charman and Whitefoot (1977), found a DOF of $\sim$ 0.15 D for pupil diameters higher than 5 mm, and Atchison et al. (1997): 0.43, 0.295 and 0.275 D for 2-, 4-, and 6-mm pupils, respectively; all values are comparable to ours.

With our definitions the subjective DOF is in most cases smaller than the objective DOF. Differences in absolute values are expected, due to the lack of an absolute criterion; thus only the variation in shape can be compared. Fig. 5 shows that objective and subjective DOF are not simply translated: subjective DOF decreases with increasing pupil size from 4 to 6 mm, whereas objective DOF increases on average with this increase in pupil size (see Fig. 5b). This discrepancy suggests that cues other than perceptible blur are being used to make the best focus setting, for instance the shape of the point spread function on the retina. Aberrated PSFs for different amounts of defocus might fall within the criterion established as non-defocused for the optics, but having different shapes, they are easily differentiated by the subject.

4.3. Depth-of-field for different spatial frequencies. Comparison to contrast sensitivity data

As with previous studies based on contrast sensitivity (Charman, 1979; Legge et al., 1987) we found that the DOF decreases with increasing spatial frequency, but beyond 3 c deg^{-1} the decrease is less pronounced than what would be expected from the ideal behavior (Fig. 4b). There is good agreement between DOF estimated from contrast sensitivity measurements at particular spatial frequencies, and our objective estimates based on double-pass or wavefront aberration data. For example, Legge et al. (1987) found a DOF of 1.4 D at 3.5 c deg^{-1} and a pupil size of 6.5 mm (scaling their data by 0.3187, since they used a half-amplitude criterion), comparable to our 0.91 D for similar conditions.

4.4. Influence of the Stiles–Crawford effect on the depth-of-field

There are controversial hypotheses in the literature concerning the influence of the SCE on the DOF of the human eye. Campbell (1957) proposed that the SCE would be responsible for the fact that DOF does not decrease with pupil size for big pupils, as predicted for ideal optics. According to Campbell, the eye has a smaller effective pupil due to the SCE apodization and consequently a larger DOF. van Meeteren (1974), however argued that SCE will reduce the effect of aberrations (whose effect is to increase the DOF) and consequently the SCE effect may actually decrease DOF. Charman and Whitefoot (1977), simulated the DOF for an eye with a typical amount of spherical aberration and SCE. Bradley et al. (1998), Burns et al. (1998), and Atchison et al. (1998), have recently reported that asymmetries in the variation of optical quality with focus are caused by the combined effect of ocular aberrations (particularly spherical) and the SCE. We have calculated the DOF based on the actual wavefront aberration data of our subjects (as described before) and introduced a centered Gaussian mask into the modulus of the pupil function (equivalent to an SCE effect function of $\rho = 0.1$ mm^{-2}). Simulations have been performed for subjects EM and RN, which are known to have an almost centered SCE, not for subject SM, whose SCE is rather eccentric. Our conclusion is that for an average aberrated eye the SCE slightly decreases the DOF, but the effect is very small. Although the effect is larger for bigger pupils and high spatial frequencies, the differences between DOF obtained with and without SCE are small. For example, for EM the DOF is 1.04 times greater (1.07 times for RN), when SCE is not considered than when it is present, for a 6-mm pupil using the IMAX criterion; and 1.09 times greater for a 6-mm pupil with a spatial frequency of 20.71 c deg^{-1}. Fig. 7 shows ratios of DOF with SCE to DOF without SCE, for the IMAX criterion for subjects EM and RN. Whereas for the real eye, the effect of apodization slightly reduces the DOF, for the ideal eye the effect is just the opposite.

4.5. Influence of ocular aberrations on the depth-of-field

Since the SCE does not seem to play the most significant role in the DOF, even for large pupils, the good agreement between double-pass DOF measurements and estimates based exclusively in wavefront aberration data from the subjects in Fig. 5 confirms, as suggested by van Meeteren (1974) and Charman and Whitefoot (1977) that aberrations are responsible for the increase of DOF at large pupils. We found a good correlation between RMS wavefront distortion (that

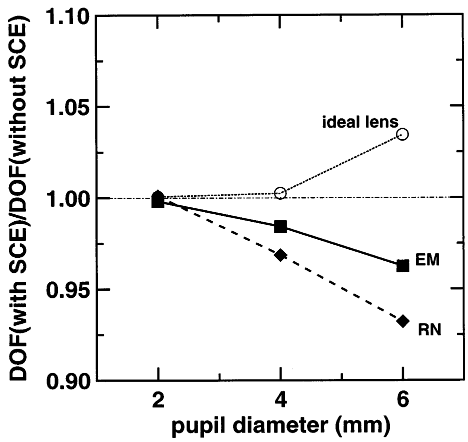

Fig. 7. Influence of the SCE on the depth-of-field, as a function of pupil diameter, for IMAX. Open symbols represent the ideal lens, and filled symbols real eyes with aberrations (EM, squares; RN, diamonds). For the ideal lens, the DOF increases when the SCE is included. However, the DOF decreases slightly for the aberrated eye. The effect is larger for bigger pupils.

describes globally the amount of aberrations present in the eye) and the DOF. For example, for 6 mm and 543 nm, the RMS wavefront distortion was 1.31 μm for SM, 0.58 μm for EM, and 0.434 μm for RN, and their DOFs for the same conditions were 0.90, 0.32 and 0.20 D, respectively. These measurements are significantly correlated ($r^2 = 0.99$).

We performed an additional experiment in order to estimate the influence of a low (second) order aberration (astigmatism) on the DOF. Three series of double-pass aerial images were obtained for subject EM, using a 6-mm pupil and a 543-nm wavelength, as in the experiments described above. One series with the subjects uncorrected eye, another correcting for the subjects astigmatism ($+0.5$ D) with a cylindrical trial lens, and a third one increasing the astigmatism with a cylindrical lens of opposite sign (-0.5 D). The DOF, at spatial frequency of 10.7 c deg^{-1}, decreased by a factor of 1.16 when the astigmatism was corrected, and increased by a factor of 2.29 when astigmatism was added. Simulations based on the same subject's aberrations for the same conditions predict a factor of 2.32 (differences probably caused by residual errors in the astigmatism axis chosen for the trial lenses).

4.6. Depth-of-field for different wavelengths

Our estimates of DOF from double-pass measurements show no systematic variation with wavelength (Fig. 6). This result should be expected based on the results of the variation of DOF with pupil diameter. The two main chromatic aberrations should not produce any effect on the value of the DOF. Longitudinal chromatic aberration only displaces the position of the optimal focus, and lateral chromatic aberration would induce only a shift in the position (which is actually cancelled in the double-pass aerial image), but not in the shape of the retinal image. If, except for tilt and defocus, the rest of the terms in the wavefront aberration are not affected by wavelength (van Meeteren, 1974), an increase in the wavelength from 458 to 632 nm would be equivalent to a decrease in the pupil diameter from 6 to 4.27 nm. We have observed a non-systematic variation of the DOF in this range of pupil sizes (an increase with pupil diameter on average, although highly dependent on the subject). Charman and Jennings (1976) observed changes in the double-pass MTFs as a function of wavelength (more degraded in blue and red than in green light), that they attributed entirely to light scattering in the eye media and the retina, and poor signal-to-noise ratio in their measurements. Recent comparison of double-pass and interferometric estimates of the MTF show that our measurements (at least in green and red light) are not likely to be affected by these problems (Williams et al., 1994). It is strange, however that Campbell (1957), using a psychophysical technique found significantly smaller DOF for green light than for red and blue, especially for bigger pupils. He attributed such a difference to the SCE, what we believe to be unlikely. His argument was that, since the SCE is higher for red and blue light than for green light, the effective pupil should be larger for green light and consequently the DOF smaller. However, we have shown that, in presence of aberrations, the effect of the SCE on the DOF is just the opposite. In addition, we have shown very small variation of the DOF between $\rho = 0$ mm^{-2} (no SCE) and $\rho = 0.1$ mm^{-2}. Variations in the DOF with wavelength from changes in ρ values between 0.06 and 0.075 mm^{-2} (for the most extreme wavelengths, according to Campbell) should be negligible.

4.7. Depth-of-field for monochromatic/white light

We have computed the DOF in white light by combining normalized measurements at three different wavelengths, weighted by the photopic spectral sensitivity and the white light spectrum (daylight). We found that the DOF in white light is 1.4 times higher than the DOF in green light (543 nm), for the IMAX criterion. This result is comparable to Campbell's experimental estimates (DOF 13% larger with white light than for 550 nm), and to results from Campbell and Gubisch (1966) (ratio white light/578 nm = 1.4). Part of the small differences between studies is probably due to differences in the spectral composition of the different white sources. We found slightly different results weighting the monochromatic stimuli by different functions $S(\lambda)$ that would equally produce a white image. Except for Legge et al.'s 1987 data, which show a slight increase in DOF for yellow light with respect to white light, there is a general agreement that the effect of chromatic aberration should be to increase the DOF, although its impact is largely attenuated by the spectral sensitivity of the cones.

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References

Artal, P., Marcos, S., Iglesias, I., & Green, D. G. (1996). Optical modulation transfer function and contrast sensitivity with decentered small pupils. *Vision Research*, *6*, 3575–3586.

Artal, P., Marcos, S., Navarro, R., Miranda, I., & Ferro, M. (1995). Through-focus image quality of eyes implanted with monofocal and multifocal intraocular lenses. *Optical Engineering*, *34*, 772–779.

Artal, P., Marcos, S., Navarro, R., & Williams, D. R. (1995). Odd aberrations and double-pass measurements of the retinal image quality. *Journal of the Optical Society of America A*, *12*, 195–201.

Atchison, D. A., Charman, W. N., & Woods, R. L. (1997). Subjective depth-of-focus of the human eye. *Optometry and Visual Science*, *74*, 511–520.

Atchison, D. A., Joblin, A, & Smith, G. (1998). Influence of Stiles–Crawford apodization on spatial visual performance. *Journal of the Optical Society of America A*, *15*, 2545–2551.

Bescós, J., & Santamaría, J. (1981). Colour based quality parameters for white light imagery. *Optica Acta*, *28*, 43–45.

Bradley, A., Zhang, X., Ye, M., & Thibos, L. (1998). Moderating the influence of Stiles–Crawford effect apodization and spherical aberration on defocused retinal images. *Investigative Opthalmology and Visual Science* (*Supplement*), *39*, 203.

Burns, S. A., He, J. C., & Marcos, S. (1998). The influence of cone directionality on optical image quality. *Investigative Opthalmology and Visual Science* (*Supplement*), *39*, 203.

Campbell, F. W. (1957). The depth of field of the human eye. *Optica Acta*, *4*, 157–164.

Campbell, F. W., & Gubisch, R. W. (1966). Optical quality of the human eye. *Journal of Physiology* (*London*), *186*, 558–578.

Charman, W. N., & Jennings, J. A. M. (1976). The optical quality of the monochromatic retinal image as a function of focus. *British Journal of Physiological Optics*, *31*, 119–134.

Charman, W. N., & Whitefoot, H. (1977). Pupil diameter and the depth of field of the human eye as measured by laser speckle. *Optica Acta*, *24*, 1211–1216.

Charman, W. N. (1979). Effect of refractive error in visual tests with sinusoidal gratings. *British Journal of Physiological Optics*, *33*, 10–20.

Fry, G. A. (1955). Blur of the retinal image. *British Journal of Physiological Optics*, *12*, 130–152.

Green, D. G., Powers, M. K., & Banks, M. S. (1980). Depth of focus, eye size and visual acuity. *Vision Research*, *20*, 827–835.

Green, D. G., & Campbell, F. W. (1965). Effect of focus on the visual response to a sinusoidally modulated spatial stimulus. *Journal of the Optical Society of America*, *55*, 1154–1157.

He, J. C., Marcos, S., Webb, R. H., & Burns, S. B. (1998). Measurement of the wave-front aberration using a fast psychophysical procedure. *Journal of the Optical Society of America A*, *15*, 2449–2456.

Hopkins, H. H., & Yzuel, M. J. (1970). The computation of diffraction patterns in the presence of aberrations. *Optica Acta*, *17*, 157–182.

Hopkins, H. H. (1955). The frequency response of a defocused optical system. *Proceedings of the Royal Society* (*A*), *231*, 91–103.

Legge, G. E., Mullen, K. T., Woo, G. C., & Campbell, F. W. (1987). Tolerance to visual defocus. *Journal of the Optical Society of America A*, *5*, 851–863.

Levi, L., & Austing, R. H. (1968). Tables of the modulation transfer function of a defocused perfect lens. *Applied Optics*, *7*, 967–974.

Malacara, D. (1992). *Optical shop testing*. New York: Wiley.

Metcalf, H. (1965). Stiles–Crawford apodization. *Journal of the Optical Society of America*, *55*, 72–74.

Navarro, R., Moreno, E., & Dorronsoro, C. (1998). Monochromatic aberrations and point-spread functions of the human eye across visual field. *Journal of the Optical Society of America A*, *15*, 2522–2529.

Navarro, R., & Losada, M. A. (1997). Aberrations and relative efficiency of light pencils in the living human eye. *Optometry and Visual Science*, *74*, 540–547.

Navarro, R., Artal, P., & Williams, D. R. (1993). Modulation transfer function of the human eye as a function of retinal eccentricity. *Journal of the Optical Society of America A*, *10*, 201–212.

Ogle, K. N., & Schwartz, J. T. (1959). Depth of focus of the human eye. *Journal of the Optical Society of America*, *49*, 273–280.

Rynders, M. C., Navarro, R., & Losada, M. A. (1998). Objective measurement of the off-axis chromatic aberration in the human eye. *Vision Research*, *38*, 513–522.

Santamaría, J., Artal, P., & Bescós, J. (1987). Determination of the point-spread function of human eyes using hybrid optical-digital method. *Journal of the Optical Society of America A*, *4*, 1109–1114.

Tucker, J., & Charman, W. N. (1975). The depth of focus of the human eye for Snellen letters. *American Journal of Optometry and Physiological Optics*, *52*, 3–21.

van Meeteren, A. (1974). Calculations of the optical modulation transfer function of the human eye for white light. *Optica Acta*, *21*, 395–412.

Webb, R. H., Penn, C. M., & Thompson, K. P. (1992). Measurement of ocular local wave distortion with a spatially resolved refractometer. *Applied Optics*, *31*, 3678–3686.

Williams, D. R., Brainard, D., McMahon, M., & Navarro, R. (1994). Double pass and interferometric measures of the optical quality of the eye. *Journal of the Optical Society of America A*, *11*, 3123–3135.

Woods, R. L., Atchison, D. A., & Bradley, A. (1996). Monocular diplopia caused by ocular aberrations and hyperopic defocus. *Vision Research*, *36*, 3597–3606.

Woodworth, R. S., & Schlosberg, M. (1966). *Experimental psychology*. London: Menthuen.

Wyszecki, G., & Stiles, W. S. (1982). *Color science—concepts and methods, quantitative data and formulae*. New York: Wiley.