Pergamon

PII: S0042-6989(96)00107-1

Vision Res., Vol. 36, No. 22, pp. 3575–3586, 1996

Printed in Great Britain
0042-6989/96 $15.00 + 0.00

Optical Modulation Transfer and Contrast Sensitivity with Decentered Small Pupils in the Human Eye

PABLO ARTAL,*§ SUSANA MARCOS,† IGNACIO IGLESIAS,* DANIEL G. GREEN‡

Received 11 January 1996; in revised form 15 April 1996

Human observers experience a large decrement in visual acuity when a small artificial pupil is displaced from the center to the edge of the dilated natural pupil. This decrement in visual resolution, called the Campbell effect, has been attributed to the retina, the ocular optics, or a combination of the two. Given the uncertainty about the relative magnitudes of these two components over the range of spatial frequencies used in normal vision, we have obtained objective measurements of the retinal image quality and psychophysical measurements of visual performance, with decentered pupils. The contributions of monochromatic aberrations were determined by using double pass measurements of the modulus of the optical transfer function (MTF). For all of the observers, there was a substantial decrement in the MTF with decentering, showing that even when using a 1.5 mm pupil and appropriate spherical/cylindrical refractive corrections, there is a considerable contribution of monochromatic aberrations to the effect. We have compared these optical MTFs with the psychophysical contrast sensitivity functions (CSFs) measured under exactly the same conditions using green gratings generated on the screen of a color monitor. At the low and intermediate spatial frequencies considered (2–16 c/deg), we find the fall in the CSF is much greater than the fall in the monochromatic MTF, with the difference becoming greater as the spatial frequency increases. We show that this discrepancy can be mostly attributed to the effect of transverse chromatic aberration due to the bandwidth of the green stimulus used for the CSF measurements. In conclusion, the combination of the ocular transverse chromatic aberration and monochromatic aberrations accounts for the loss in visual sensitivity found with a decentered small pupil at low and intermediate spatial frequencies. Copyright © 1996 Elsevier Science Ltd.

Optical transfer function   Contrast sensitivity   Human eye   Decentered pupils

INTRODUCTION

In his original report of a retinal directional acuity effect, Campbell (1958) reported there was a factor of 8 loss in visual acuity for grating patterns when a 1 mm diameter pupil was displaced by 4 mm from the center of the dilated pupil. Since this acuity loss through the decentered small pupil could not be corrected with combinations of spherical and cylindrical lenses, he suggested the effect was retinal in origin and due to the oblique incidence of rays on the photoreceptors. He reasoned that a ray that was oblique to the long foveal cones could leak from one receptor to the next and thus cause a bundle of receptors to be stimulated by each point in visual space. Campbell & Gregory (1960) later found there was a much smaller fall in acuity for Fraunhofer diffraction patterns viewed through a decentered pupil. Since these diffraction patterns are formed on the retina as a result of the wave properties of light, they bypass ocular aberrations. Consequently, this finding showed that a significant portion of the off-axis loss that Campbell had described earlier was due to off-axis optical aberrations. There still was, however, a substantial retinal directional acuity effect. For example in Campbell's eye, using Fraunhofer diffraction patterns, acuity fell from center to the edge of the pupil by a factor of 2.9.

However, when Green (1967) used coherent light from a laser to form interference fringes directly on the retina and measured acuity under similar conditions of decentering, he could find no evidence for a retinal

---

*Laboratorio de Optica, Departamento de Física, Universidad de Murcia, Campus de Espinardo (Edificio C), 30071 Murcia, Spain.
†Instituto de Optica, Serrano 121, 28006 Madrid, Spain.
‡Neuroscience Laboratory, Department of Ophthalmology, University of Michigan, 1103 E. Huron St., Ann Arbor, MI 48104, U.S.A.
§To whom all correspondence should be addressed [*Fax* +34-68-363528/364148; *Email* pablo@fcu.um.es].

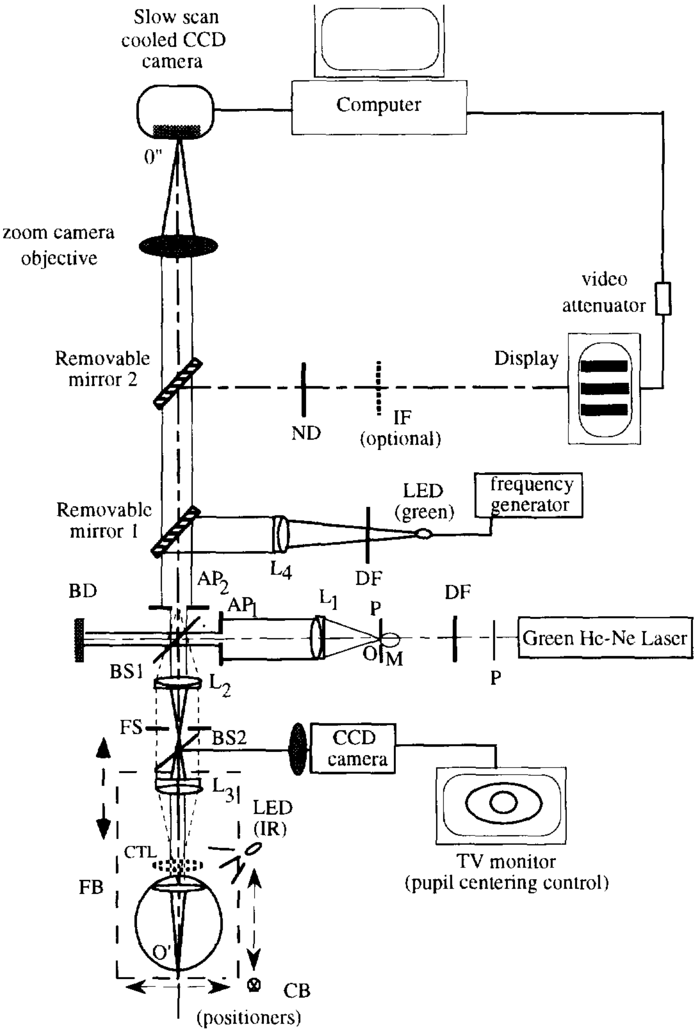


FIGURE 1. Schematic diagram of the apparatus used in this study. P, polarizer; DF, variable neutral density filters (ND = 0.5–2.5); AP_1, AP_2, 1.5 mm diameter artificial entrance and exit pupil; BS1, BS2, pellicle beam splitters; L1, L2, L3, L4, achromatic lenses; ND, 0.5 density filter; CTL, cylindrical trial lenses; FS, field stop; BD, light trapping; FB, focusing block; IF, optional interference filter. (See the text for additional details.)

directional acuity effect. On the other hand, Green's measurements of the contrast sensitivity function through a decentered artificial pupil showed substantial losses. There was a factor of 3 loss in acuity when a 2 mm pupil was decentered by 3 mm perpendicular to the grating. Thus, Green argued that all of the Campbell effect was optical. Green thought this off-axis loss was primarily caused by off-axis monochromatic aberrations, but others have pointed out that with the broadband green phosphor he used, lateral or transverse chromatic aberration (TCA) is likely to play an important role (Van Meeteren & Dunnewold, 1983; Thibos, 1987; Thibos *et al.*, 1991; Bradley & Thibos, 1995).

Van Meeteren & Dunnewold (1983) used a 0.8 mm pupil and monochromatic illumination and reported a loss of acuity with decentering which they argued must be retinal because their calculations showed that the eye should be diffraction-limited with a 0.8 mm pupil and monochromatic illumination for all positions of pupil entry. They reported that visual acuity fell by a factor of 1.5 at 500 nm when a 0.8 mm pupil was displaced by 3 mm. To reconcile their findings with those of Green, they suggested that since the interference fringes result from coherent waves interacting with the antenna-like properties of the receptors, under these conditions there might be less cross-talk between neighboring cones in the case of oblique incidence. Further supporting evidence for the existence of a retinal effect comes from the experiments of Walsh & Charman (1988) who calculated the quality of the retinal image from wave-front aberration data for individual eyes using an objective aberroscope technique (Walsh *et al.*, 1984). They found only small differences in the optical quality for up to 2 mm of decentration of a 1 mm pupil, supporting Van Meeteren and Dunnewold's claim that retinal images with small pupils are diffraction-limited, although they also showed substantial optical degradation with larger eccentric pupils.

More recently, Chen & Makous (1989) have repeated Green's experiments with interference fringes and confirmed and extended his findings. Their interesting new finding, in this regard, is that at spatial frequencies higher than those Green originally used, there is a loss in visual acuity for interference fringes that are oblique with respect to the axis of the foveal cones. Thus, they have found what appears to be a genuine retinal directional acuity effect. However, the frequencies at which these losses occurred were sufficiently high that retinal directional acuity would be expected to be of little importance in normal vision through natural pupils, and should not have been present at the spatial frequencies used in the Van Meeteren and Dunnewold experiments.

In view of the lack of agreement in the literature, we have tried to determine the relative contributions of the eye's optics and the retina to the Campbell effect. We measured the contribution of monochromatic aberrations to off-axis imagery and compared this with the Campbell effect measured using psychophysical measurements. That is, we have carried out simultaneous measurements of both contrast sensitivity and ocular MTF using an artificial pupil (1.5 mm diameter), centered and 3 mm horizontally displaced, with appropriate refractive correction. The effect of the transverse chromatic aberration (TCA) due to the bandwidth of the monitor green channel used has also been examined experimentally and theoretically. Our measurements show that there is a loss in visual performance at low and middle spatial frequencies (up to 16 c/deg) with small decentered pupils that is due to a combination of monochromatic aberrations and the TCA. These two factors account for the bulk of the Campbell effect and thus we conclude that there is no significant retinal contribution in the spatial frequency range we have tested.

METHODS

A schematic view of the apparatus used for these experiments is shown in Fig. 1. It is based on the double pass system for measuring the ocular MTF described in detail elsewhere (Santamaría *et al.*, 1987; Artal & Navarro, 1992; Artal *et al.*, 1995a). In addition, we incorporated three other subsystems to the apparatus allowing: (i) the real-time monitoring of the relative position of the artificial pupil with respect to the dilated natural pupil; (ii) the measurement of flicker thresholds with centered and decentered pupils to estimate the magnitude of the Stiles–Crawford brightness effect (Stiles & Crawford, 1933) at 3 mm decentration for each subject; and (iii) the measurement of the contrast sensitivity function for centered and decentered pupils under the same conditions used for the optical measurements.

To measure the optical MTF, we recorded 4 sec exposure aerial images of a monochromatic green point object ($\lambda = 543$ nm) after double passage through the eye. [In some of the preliminary measurements red light ($\lambda = 632.8$ nm) was used.] A high resolution cooled CCD camera (SpectraSource MCD1000) integrates the light coming back from the retina. The exposure time is long enough to break the coherence and blur the speckle and short enough to prevent eye blinks or subject's discomfort. All the measurements were obtained with a 1.5 mm diameter entrance and exit artificial pupil located at different positions in the eye pupil. The artificial pupils were produced by an afocal system, which formed a 1.5 mm diameter image of an aperture in the observer's pupil: The aperture AP_1 in Fig. 1, acts as an artificial entrance pupil and AP_2 as an exit pupil. The subject's head is stabilized by a bite bar mounted on a three-dimensional micropositioner (CB). Centration was achieved by moving the subject's head horizontally and vertically, and noting the positions where the image of the fixation point disappeared to the left and right, and on the top and bottom, that is, the positions for which the beam entering the eye was blocked by the iris. The point midway between these values was then taken as the geometrical center of the pupil. Decentered pupils were achieved by displacing the subject's head using the micropositioner. To assure correct centration of the pupils during the measurements, the position of the artificial pupil with respect to the natural pupil is monitored by using a second CCD camera being the eye illuminated with an infrared LED. The best refractive state was objectively determined for the centered and decentered pupils by moving the focusing block (FB), including the lens L_3 of the afocal system and the eye, with respect to the lens L_2 and placing appropriate cylindrical trial lenses in front of the eye to maximize the peak intensity of the double pass aerial image. Four seconds exposure—256 × 256—16 bits-pixel retinal and four background images were recorded for each situation. To obtain the two-dimensional single pass ocular MTF, the root square of the Fourier transform of the averaged aerial retinal image was calculated (Artal *et al.*, 1995a). The peak that typically appears at zero frequency in the modulus of the Fourier transform of the retinal images due to the background in the double pass images was removed in every image by using the procedure in the Fourier domain described in Artal *et al.* (1995a).

Contrast sensitivity was measured for centered and 3 mm temporally decentered pupils using exactly the same experimental conditions that were used to obtain the MTFs, including spherical and cylindrical correction. Vertical sinusoidal patterns were generated by computer using a MATROX–Magic image processing board and presented using the green gun of a 20 in high resolution RGB monitor (Sony GDM-2036S) placed 3.5 m away from the Badal system. The image processing board can only produce gray levels on the screen that are accurate to 8-bits. To increase this number, we combined the signals from the three color channels to produce images with more than 12-bits of gray level using a video attenuator and software, similar to that described by Pelli & Zhang (1991). By means of removable mirror 2, shown in Fig. 1, a 3.5 deg patch of vertical green fringes ($\lambda_{\max}$ of 530 nm and an approximate half-width at half-height of 35 nm) was seen through the same optical set-up that was used for the MTF measurements.

The Stiles–Crawford brightness effect was compen-

FIGURE 2. Aerial retinal images of a point source obtained in subject PA with a 1.5 mm pupil diameter with different decentering from 4 mm nasal (top left corner image) to 4 mm temporal (bottom right image) along the horizontal meridian. The intensity of each image was normalized to allow a better comparison.

sated by reducing the luminance of the gratings for the centered situation with a neutral density filter of 0.5 density. The correction factor was determined in each subject by measuring the reduction in the flicker threshold for a green LED when this is seen by the observer through the centered and decentered artificial pupils by placing the removable mirror "1" in the set-up. We measured the intensities required to produce the same critical flicker fusion frequency with centered and decentered pupils. That is, curves of flicker thresholds vs intensity were obtained on each subject using central and 3 mm displaced 1.5 mm pupils. The lateral shift of these two curves along the log intensity axis established the Stiles–Crawford brightness correction factors for each individual. The magnitude of the Stiles–Crawford correction for the four subjects with 3 mm pupil decentration was around 0.3. These values were sufficiently close to each other, that the same 0.5 neutral density was used for every subject to attenuate the monitor's brightness when making CSF measurements through a centered pupil.

The mean luminance level of the display was 22.5 cd/m^2 so with 1.5 mm diameter pupils, the retinal illuminance was 39.7 td for the eccentric and 12.3 td for the centered pupil. Contrast thresholds were estimated for several spatial frequencies from 4 to 24 c/deg using the method of adjustment. Five contrast settings were averaged to define the threshold at each spatial frequency.

The measurements were taken in four normal subjects. A 25-year-old 6 D myopic female, (subject SM) (right eye) and three males: 34 years old 1.5 D myopic (subject PA), 31 years old 1 D myopic (left eye) (subject II) and 28 years old 4 D myopic (subject NL). In a standard ophthalmological test, all the subjects had a best corrected decimal visual acuity of 1, or better. During the experiments, the accommodation was paralyzed and the pupil dilated by instilling two drops of tropicamide

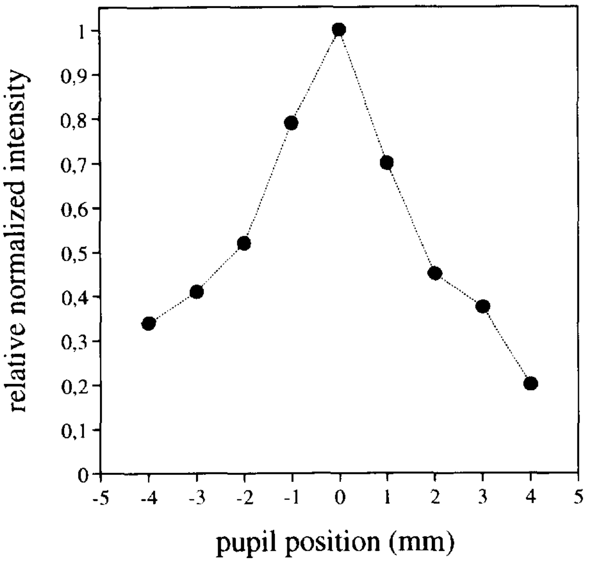


FIGURE 3. Relative normalized intensity in the double pass images as a function of decentration in the pupil along the horizontal meridian.

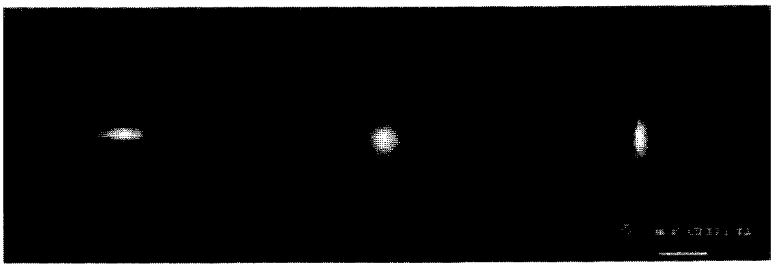


FIGURE 4. Effect of changing focus on decentered double pass images (P.A.).

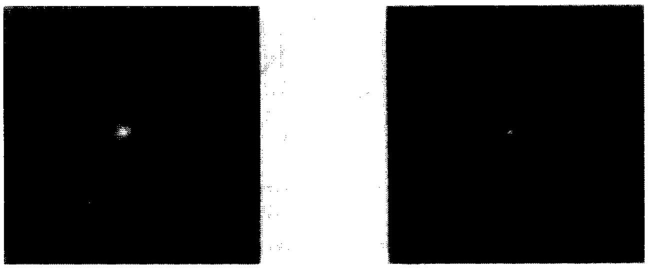


FIGURE 5. Best corrected 3 mm decentered double pass image (left) and centered aerial image (right). The scale is the same as in Fig. 4.

1% in the eye's subjects, with 5 min between drops, and a 15 min interval before taking measurements.

RESULTS

Double pass retinal images

The main objective of this study was establishing the extent to which the fall-off in visual acuity that occurs when an artificial pupil is decentered is optical. We began with measurements of the quality of the retinal image when a 1.5 mm pupil was systematically displaced along the horizontal meridian of the pupil. Figure 2 shows sample double pass aerial retinal images obtained on one observer (PA) in monochromatic ($\lambda = 632.8$ nm) for decentration from one edge of the pupil to the other in 1 mm steps. All of the images were obtained with a fixed -1.5 D spectacle lens, i.e., the correction which produced the sharpest image in the centered position was used in all positions. As the figure shows, retinal image quality systematically deteriorates as the pupil is decentered. The decentered double pass images have a structure which provides clues to the nature of the optical defects. It is difficult, however, to attribute the degradation to a specific class of aberrations, although the lack of radial symmetry suggests that oblique astigmatism may play a role. The problem is that in the double pass imagery, asymmetric aberrations, such as coma, become right–left symmetrical in the aerial image (Artal *et al.*,

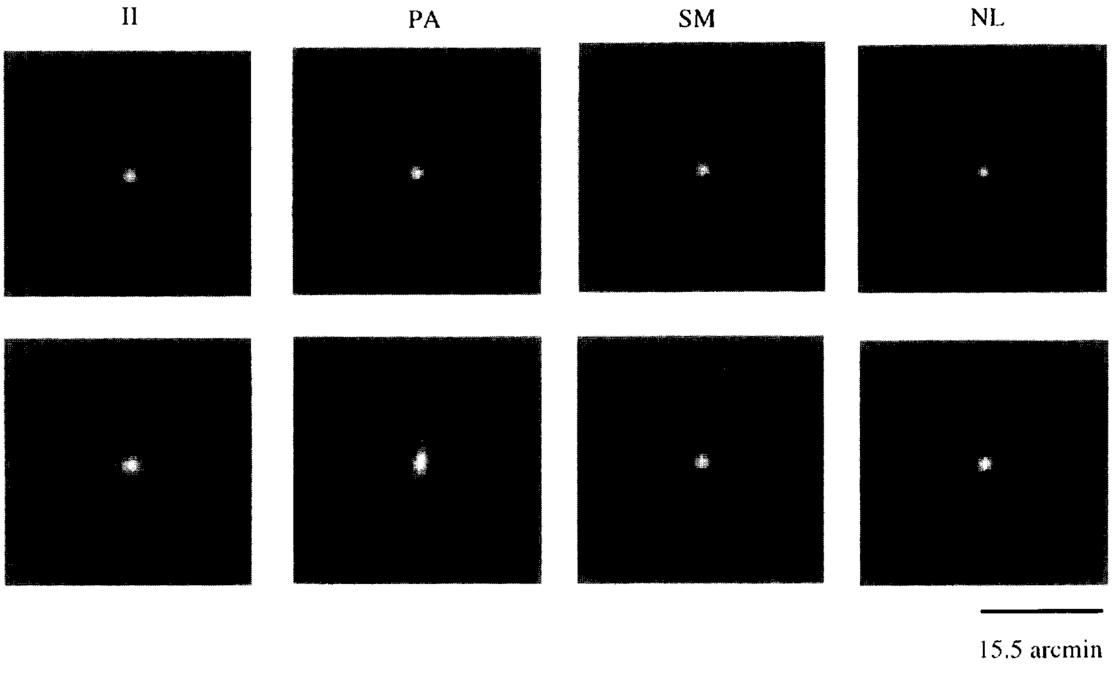


FIGURE 6. Centered and 3 mm decentered after correction double pass images for the four subjects.

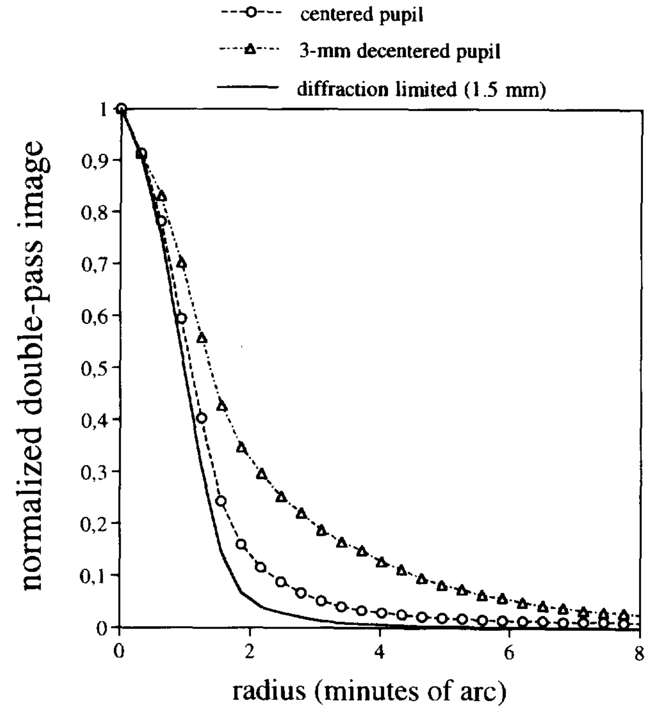


FIGURE 7. Average one-dimensional radial profile of the double pass images for the centered and 3 mm decentered pupil. The solid line represents the autoconvolution of the diffraction-limited point spread function for 1.5 mm diameter.

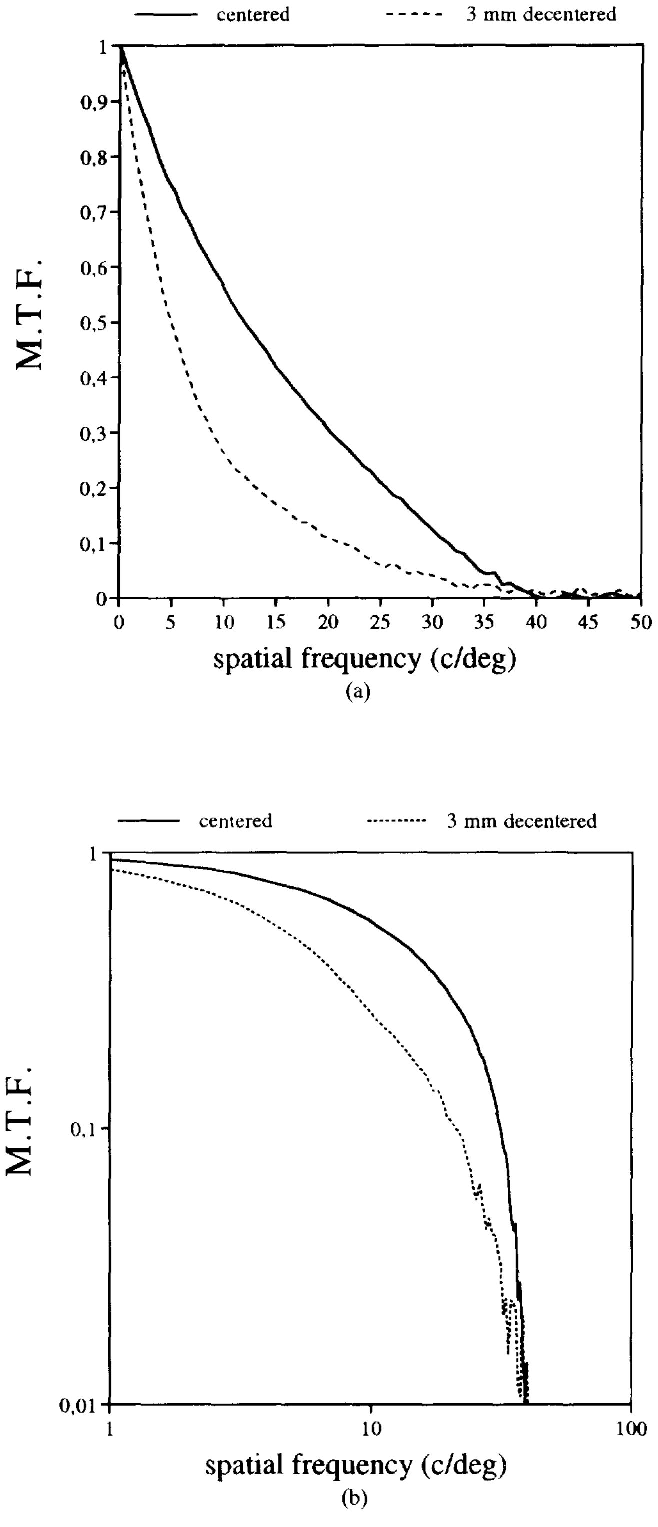
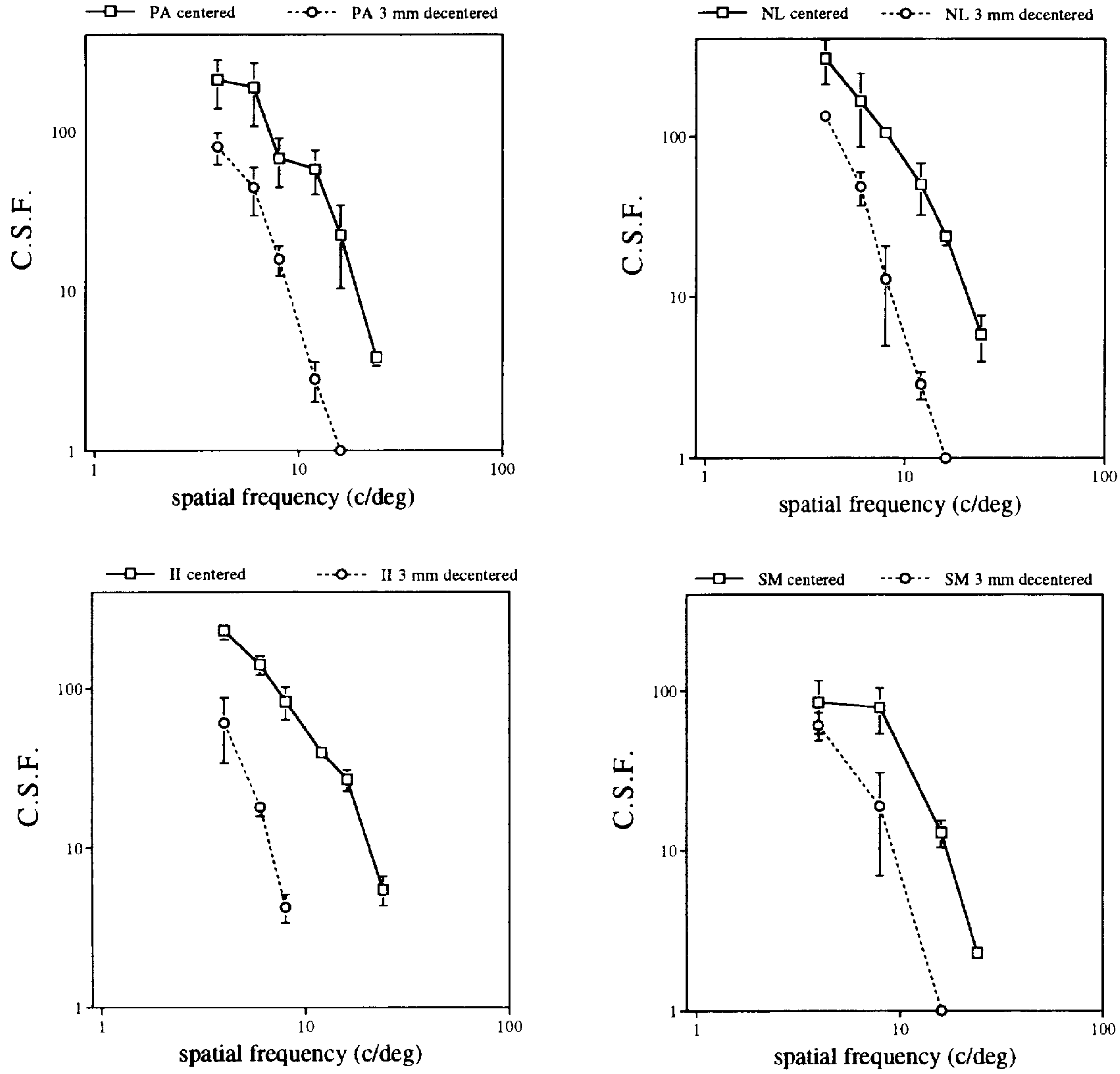


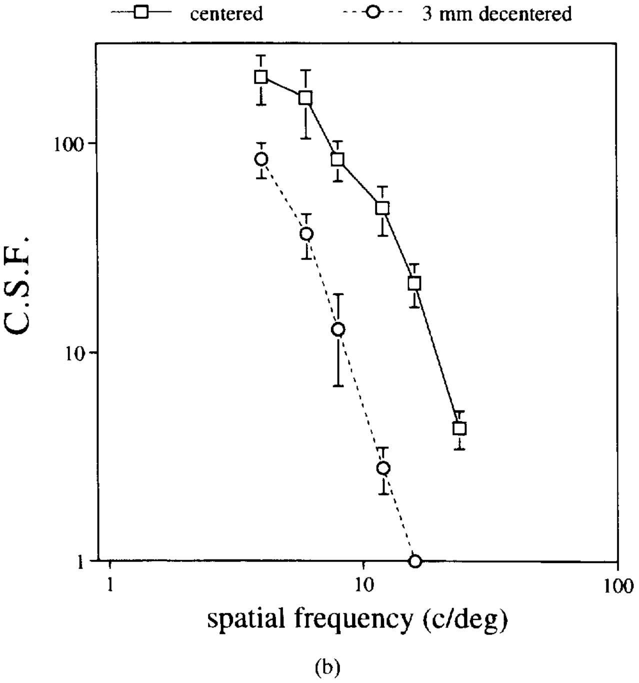
FIGURE 8. (a) Average MTFs for the four subjects computed from the double pass images obtained with the 1.5 mm diameter centered pupil (solid line) and 3 mm decentered (dashed line). (b) Represents the MTF in a log–log representation to allow a direct comparison with the CSF results.

1995b). This means that the elongated appearance of the aerial image does not reveal whether or not the main aberration is coma or astigmatism. The retinal images spread more with greater decentration, but they are also dimmer. That is, the total integrated flux in the double pass image is smaller. Figure 3 shows the relative intensity for each double pass image for different decentrations. Since the incident irradiance on the eye was kept constant during the whole experiment, the finding is that the amount of light collected back from the retina decreases with decentration. This is likely to be an indication that the light which forms the aerial image is affected by the retinal reflection directionally (van Blockland, 1986; Burns *et al.*, 1995). If this interpretation is correct, when decentered pupils are used, the fraction of stray light from structures other than the photoreceptors, which is likely not dependent on the position of the pupil, would be expected to increase relative to the light reflected back from the photoreceptors.

In order to establish the extent to which the image degradation at 3 mm decentration was due to astigmatism, we varied the sagittal astigmatic plane of focus, using spherical lenses. That is, with decentration of 3 mm, the refractive state (subject PA) was changed systematically over a range of 0 to −6 D. The resulting double pass images are shown in Fig. 4. Halfway between the tangential (−1.5 D) and sagittal foci (−7.5 D), a circle of least confusion was found (at −4.5 D). Once, we identified the amount of astigmatism for the 3 mm decentered pupil, we compensated it and recorded the corresponding double pass image. Figure 5 shows the double pass images for the best correction (sphere and cylindrical) at 3 mm decentration (left image) and to the centered pupil. Comparing the images in Fig. 5 one can see that the aerial images for centered and off-axis pupils, even with best correction, are quite different. In other



(a)



(b)

FIGURE 9. (a) Centered CSFs for the four subjects (solid line) compared with decentered CSFs (dashed lines). (b) Average for the centered (solid with squares) and decentered (dashed with circles) CSFs for the four subjects.

words, decentering a small pupil causes an optical degradation in the retinal image which is not correctable with combinations of cylinders and spheres, because it results from higher order ocular aberrations.

Figure 6 shows the aerial images for centered and 3 mm decentered pupils (after spherical and cylindrical correction) for the four subjects. Figure 7 shows the one-dimensional average radial profile for the four subjects of the centered and 3 mm decentered pupils double pass images. The image quality of the centered pupil image is close to being diffraction-limited, as others have predicted. Yet there is a substantial degradation in optical quality that cannot be corrected when the pupil is eccentrically displaced.

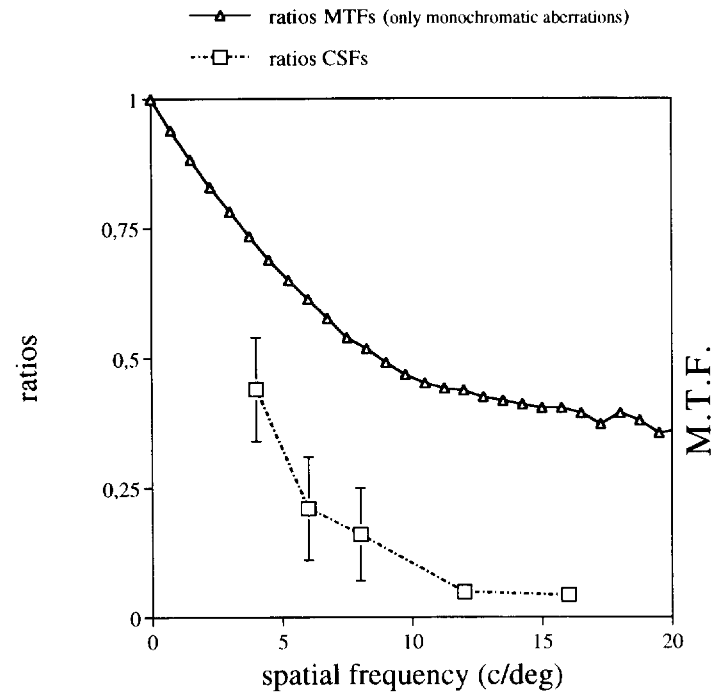


FIGURE 10. Average ratios of the CSFs (open squares) compared with the average ratios of the monochromatic MTFs (solid line with open triangles).

Modulation transfer functions

To quantify these double pass images results in a way that allowed comparison with the contrast sensitivity, single pass MTFs were computed from the double pass aerial images as described in Artal *et al.* (1995a). The average MTFs at centered and 3 mm decentered pupils for the four subjects are presented in Fig. 8. Figure 8(b) shows the same MTFs plotted in a log–log axis representation to allow a direct comparison with the CSF results. Since the MTF for the centered 1.5 mm pupil (solid line) is lower, but comparable to that of a diffraction-limited system, the MTFs with eccentric pupils are definitely not diffraction-limited.

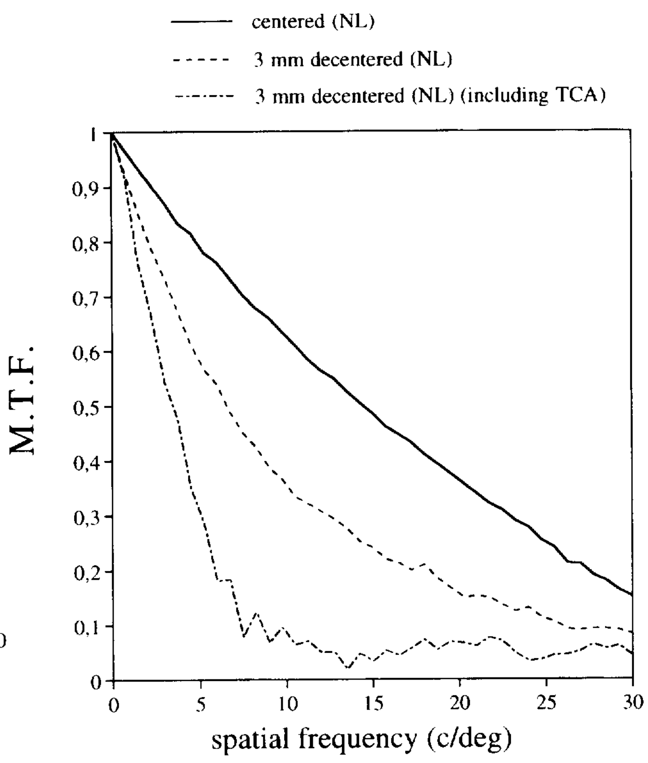


FIGURE 12. MTFs for subject NL. Centered pupil (solid line), decentered pupil (dashed line) and considering the TCA (short dashed line).

Contrast sensitivity measurements for centered and decentered pupils

Psychophysical contrast sensitivity functions (CSFs) were obtained on our four observers using a small pupil (1.5 mm) that was either centered in the dilated pupil or displaced horizontally by 3 mm. The optical conditions for measuring the CSFs were exactly the same as those used for the double pass measurements. Figure 9 shows both the centered and decentered contrast sensitivity functions for vertical gratings obtained for the four observers (a) and the averages of the four observer (b). In every subject, moving the small pupil eccentrically

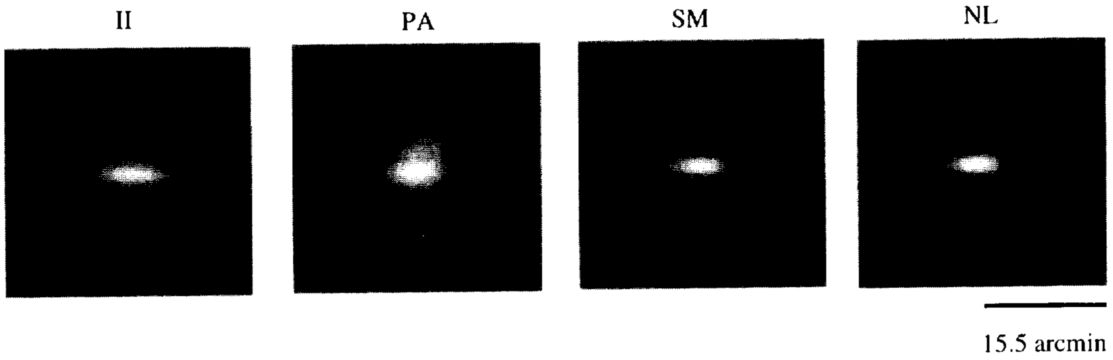


FIGURE 11. Calculated double pass images including the effect of the TCA for the four subjects. These images should be directly compared with the measured double pass images of Fig. 6.

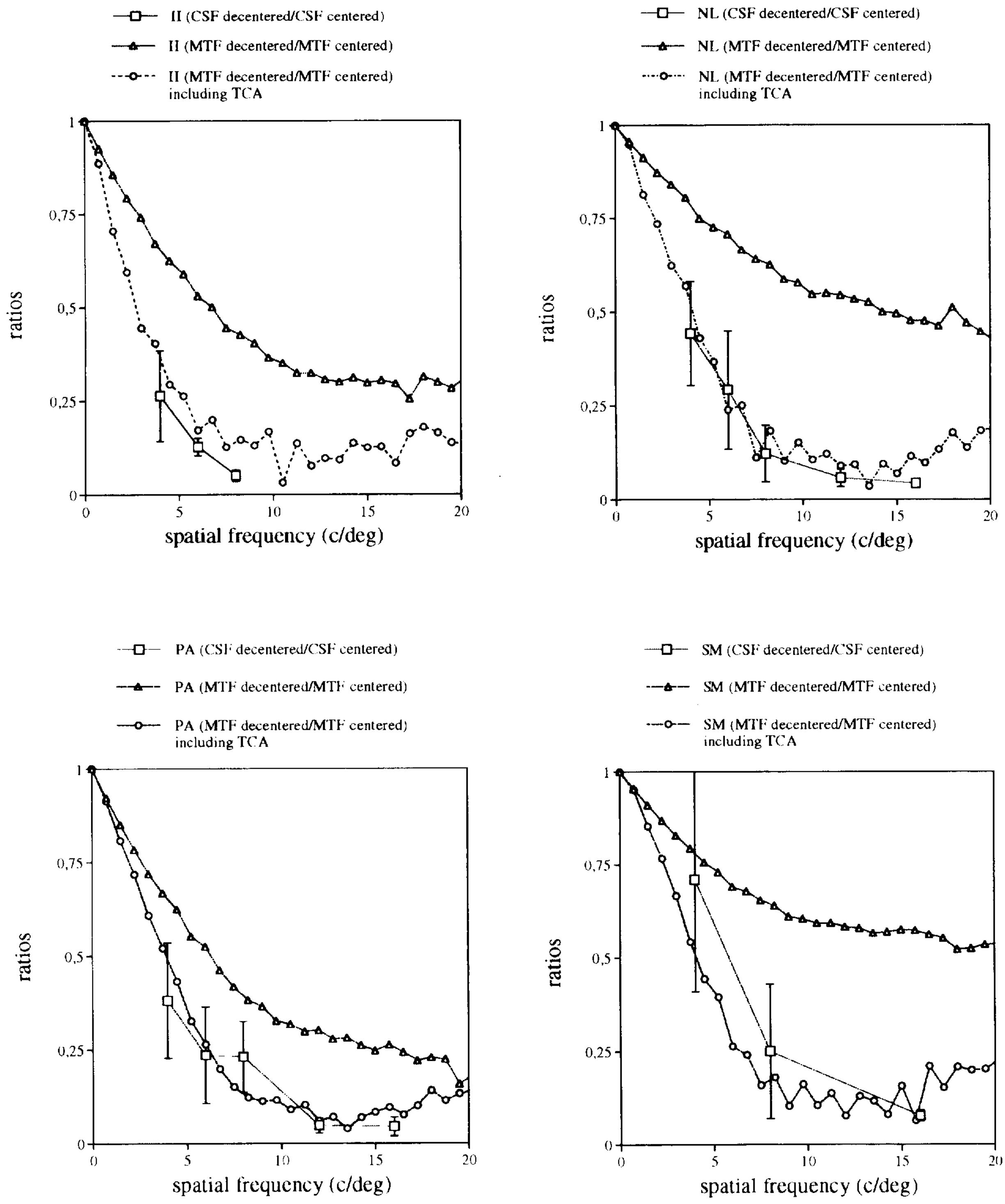


FIGURE 13. Ratios of the CSFs (open squares) compared with the average ratios of the MTFs (open triangles) and MTFs computed, including TCA (open circles). The four panels present the results for the four subjects.

caused a substantial loss in contrast sensitivity. Over the range of frequencies used, the results of displacing the artificial pupil can be summarized as producing a shift along the spatial frequency axis of about 0.3 log units. In other words, the high spatial frequency limit is reduced from 32 to 16 c/deg, a factor of 2 loss in visual acuity.

Are the effects shown in Fig. 9 primarily due to optical or retinal effects? The objective measurements of the monochromatic double pass point spread function provide a means for answering this question. Those measurements were made under exactly the same experimental conditions and at the same time as the MTF measurements, except for the fact that the output from the green phosphor of the monitor is not monochromatic. As we have already seen, for all of the observers there was a substantial decrement in the monochromatic MTF with decentering, showing that there is a contribution of optics to the Campbell effect, even when using a 1.5 mm pupil. A convenient way to present these data is to calculate the ratio of the MTF decentered to the MTF centered. Comparing the ratio of the decrement in CSF to the ratio of the decrement in MTF provides a direct measure of the magnitude of the retinal component relative to the monochromatic optical effect. This comparison is shown in Fig. 10, where the average monochromatic MTF ratio is represented with triangles and the average CSF ratio with squares. We find that at all spatial frequencies, even at relatively low spatial frequencies, (2–16 c/deg) the fall in the CSF is considerably greater than the fall in the monochromatic MTF, with the difference becoming greater as the spatial frequency increases. This figure shows that the monochromatic aberrations cannot account for the fall in contrast sensitivity. This does not necessarily mean there is a retinal component to the Campbell effect. The monitor screen is not monochromatic and the effect of TCA must be considered. In the next section, we discuss in greater detail the effect of TCA on images through decentered pupils.

Effect of the transverse chromatic aberration

To compare the optical and CSF measurements, it is very important to include the effect of the TCA on the decentered retinal image. While the phosphor on the monitor produces a vivid green color, the energy distribution from the green phosphor is centered at 530 nm and has a half-width at half-height of about 35 nm. Figure 11 shows the calculated effects of TCA on the decentered double pass image for the four subjects. These images should be compared with those presented in Fig. 6. In the calculations, we used the spectral distribution of the green phosphor and the published measurements of the chromatic aberration of the eye (Wald & Griffin, 1947; Howarth & Bradley, 1986). We computed the geometrical displacement of the retinal image for each wavelength by relating the longitudinal chromatic aberration and the pupil decentering with the TCA (Thibos *et al.*, 1990). We added, weighted with the emission value of the monitor, all these retinal images to obtain the chromatic double pass images. From these images we computed the corresponding polychromatic MTF. Figure 12 presents the MTF computed including TCA for subject NL in comparison with the monochromatic MTFs for centered and decentered pupils. Figure 13 summarizes the results for the four subjects. It shows the ratio of the decrement in the monochromatic MTFs (represented by solid circles) and the ratio of the decrement in MTF calculated, including the effect of the TCA (open circles), in comparison with the ratio of the decrement in CSF (open squares). The error bars in the CSF ratios represent the calculated standard deviation in the psychophysical measurements. The observed fall in the CSF with decentration is mostly explained at these spatial frequencies by the contributions of both monochromatic aberrations and transverse chromatic aberration.

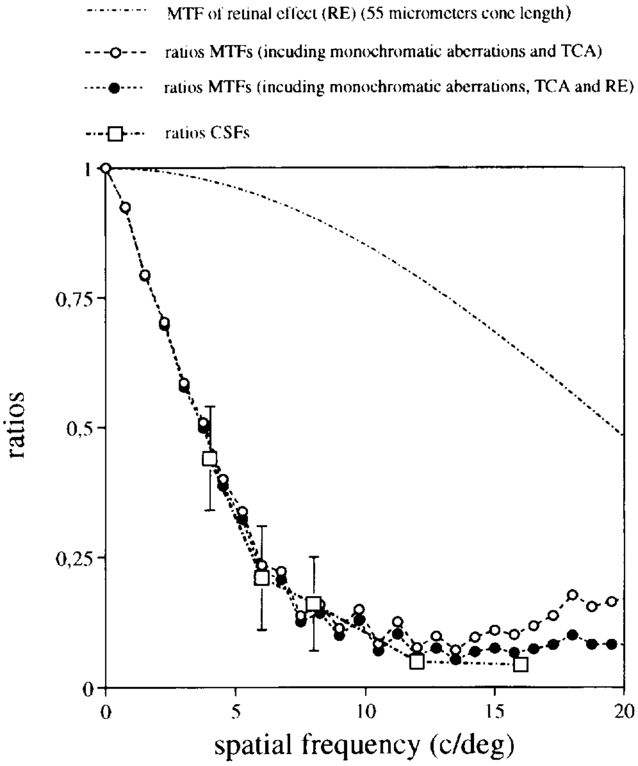


FIGURE 14. Average ratios of the CSFs (open squares) with the error bars showing the standard error, compared with the average ratios of the MTFs computed including TCA (solid circles) and both TCA and the calculated retinal effect (open circles). The dashed curve shows the calculated MTF for the retinal effect assuming the cone outer segments are 55 μm long, and that the oblique ray is equally effective in stimulating all the outer segments that it passes through.

Effect of the retinal directionality

We examined the possibility that a small contribution by the retinal directionality effect contributed to the reduced contrast sensitivity for the spatial frequencies considered. Our calculations, however, indicate that this contribution could not be detected by our experiments because it would be smaller than our error in determining the CSFs. We computed the MTF for the retinal directional effect using a simple geometrical model (Bradley & Thibos, 1995) for a 55 μm photoreceptor length and 3 mm of pupil decentering. This model assumes that obliquely incident rays pass through multiple photoreceptors and produce an effective point spread with an associated retinal effect MTF. We use this model to show the approximate amount of the retinal effect, although it must be pointed out that Chen & Makous (1989) showed its inadequacy. In Fig. 14, we compared the retinal MTF (dashed line) with the average ratio of optical monochromatic and chromatic MTFs (open circles) and the average ratio including the retinal effect (solid circles) in comparison to the CSF ratios (open squares).

DISCUSSION

Since the original report of Campbell (1958) suggesting a retinal directional acuity effect, the magnitude of the effect has been a matter of controversy. Over the years, the magnitude of the postulated retinal component due to the passage of an oblique ray through multiple photoreceptors has been steadily decreasing. The factor of 8 reduction in acuity initially reported dropped to 2.9 with interference fringes formed on the retina (Campbell & Gregory, 1960). This was the first indication that in spite of the fact the loss of acuity for rays oblique to the axis of the photoreceptors was not correctable with combinations of spherical and cylindrical lenses, a significant portion of the off-axis loss that Campbell found was due to off-axis optical aberrations. The most extreme position has been that of Green (1967) who argued there was no retinal directional acuity effect. His conclusions were based on the finding that there is, after correction for the Stiles–Crawford brightness effect, virtually no loss in sensitivity for interference fringes formed with light that passes through the margins of the pupil. More recently Chen & Makous (1989) have confirmed and extended these and have shown that Green's conclusions need to be qualified with the statement that there is no Campbell effect for interference fringes at spatial frequencies lower than 20 c/deg. There is still the suggestion of Van Meeteren & Dunnewold (1983) that there is something different about interference fringes, since with ordinary targets there is a fall in acuity from 20 to 15 c/deg with 3 mm of decentering, when as they argue, the eye must be diffraction limited (0.8 mm pupil and monochromatic illumination).

In the present paper, we carried out simultaneous measurements of both contrast sensitivity and the ocular MTF under exactly the same conditions. The only difference was in the spectral content of the green light used to measure the CSF. Rather than being monochromatic, the green phosphor had a bandwidth of ±35 nm. Our measurements of the MTF show that even with small 1.5 mm pupils and monochromatic light, decentering a pupil causes a degradation in the quality of the retinal image. We have attributed this loss to monochromatic aberrations in the peripheral parts of the eye's optical system. Of course if the light returning from the retina comes from multiple layers in the retina itself, this could lead to lateral smearing of the retinal image when the rays are obliquely incident. If these kind of effects were important one would expect a significant loss of image quality when images are formed out of the center of the fovea and this does not occur (Artal & Navarro, 1992). There should also be systematic differences between double pass and interferometric measurements of the image quality with large pupils, and this is not found. There is no evidence that the light returning from multiple retinal layers contributes to the double pass image (Williams *et al.*, 1994). Thus, even when the images formed through a 1.5 mm centered pupil seem to be more or less diffraction-limited, the monochromatic aberrations in the peripheral parts of the eye's optical system can be a significant factor.

To assure ourselves further that the monochromatic aberrations make sense, we have used earlier determinations on the wave aberrations (Artal *et al.*, 1988) to make calculations. The wavefront aberrations had been estimated on the eye of one of our subjects and this allowed us to use these aberrations to calculate a decentered MTF. However, this is an approximate estimate of the wavefront aberration because it was computed from equal pupil size double pass images, losing the information on odd aberration lost (Artal *et al.*, 1995b). The wavefront data did not extend far enough in the pupil for us to calculate the MTF for 3 mm decentration. Nonetheless, the monochromatic MTF we have measured at 2 mm of decentering quantitatively agrees well with what the wave aberrations predict.

Spectral differences between the laser light used for the optical MTF measurements and the monitor phosphor used for the CSF measurements are very important. Figure 11 shows the effect of TCA on the aerial images calculated using this spectral distribution. From these calculations and the CSF measurements with an interference filter placed in front of the screen, it is clear that significant degradation occurs in the decentered pupil images, because the output from the monitor is not monochromatic. Even different wavelengths are imaged in front of or behind the retina; with the small pupil and centered pupils the depth of focus is sufficiently great to mitigate the effects. However, when the pupil is decentered, TCA causes the image at each wavelength to be translated laterally by varying amounts. For example, the longitudinal chromatic aberration for a wavelength of 500 relative to 530 nm is 0.21 D. When the pupil is centered, this moves the image plane by about 75 μm, without translating the image (except for the small effect due to the eccentric location of the fovea). However, when the entrance pupil is decentered by 3 mm there will be a lateral shift of about 12 μm of the center of the image. Thus, the chromatic dispersion of the stimulus causes the light entering the pupil to be laterally dispersed over the retina. In the end, this results in the same sort of effect Campbell postulated to occur with oblique incidence (a bundle of receptors are stimulated) but the cause is optical, not retinal. Thus, an important contribution to the Campbell effect shown in Fig. 10 comes from the transverse chromatic aberration, as was predicted by Van Meeteren & Dunnewold (1983) and by Thibos *et al.* (1991). To test the correctness of this conclusion we have carried out measurements with a narrow band interference filter in front of the eye. The dimness of the display reduces the precision of the measurements and the range of spatial frequencies over which it is possible to make measurements. Also the bandwidth of the interference filter is still about 10 nm and then we still have some effect of the TCA. Nonetheless, reducing the chromatic bandwidth of the light from the phosphor brings the eccentric loss in the

CSF measurements closer to what would be expected from the monochromatic aberrations.

We have also calculated the magnitude of the retinal MTF for the spatial frequency range. Even assuming long outer segments (55 mm) and neglecting losses as the ray passes from one receptor to another, the calculated loss in contrast sensitivity at 16 c/deg is only 35% reduction. The effect of the retinal MTF for a 3 mm decentered pupil at 4–16 c/deg is so small it would be difficult to be detected with our experimental methods. However, for higher spatial frequencies, the retinal effect should become more important and could be detected. This is in agreement with the study of Chen & Makous (1989) who reported a retinal effect for medium and high spatial frequencies. In conclusion, we have shown that for low and intermediate spatial frequencies the main contributions to the decay in visual performance with pupil decentration are monochromatic aberrations and the transverse chromatic aberration, even when not very broadband stimuli are used.

REFERENCES

Artal, P., Iglesias, I., López-Gil, N. & Green, D. G. (1995a). Double pass measurements of the retinal image quality with unequal entrance and exit pupil sizes and the reversibility of the eye's optical system. *Journal of the Optical Society of America A, 12*, 2358–2366.

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

Artal, P. & Navarro, R. (1992). Simultaneous measurement of two-point-spread functions at different locations across the human fovea. *Applied Optics, 31*, 3646–3656.

Artal, P., Santamaría, J. & Bescós, J. (1988). Retrieval of the wave aberration of human eyes from actual point-spread function data. *Journal of the Optical Society of America A, 5*, 1201–1206.

Bradley, A. & Thibos, L. N. (1995). Modeling off axis vision I: the optical effect of decentering visual targets or the eye's entrance pupil. In Peli, E. (Ed.), *Vision models for target detection and recognition*. In memory of Arthur Menendez. Singapore: World Scientific.

Burns, S. A., Wu, S., Delori, F. & Elsner, A. E. (1995). Direct measurements human cone-photoreceptor alignment. *Journal of the Optical Society of America A, 12*, 2329–2338.

Campbell, F. W. (1958). A retinal acuity direction effect. *Journal of Physiology (London), 144*, 25–26P.

Campbell, F. W. & Gregory, A. H. (1960). The spatial resolving power of the human retina with oblique incidence. *Journal of the Optical Society of America A, 50*, 831.

Chen, B. & Makous, W. (1989). Light capture by human cones. *Journal of Physiology (London), 414*, 89–109.

Green, D. G. (1967). Visual resolution when light enters the eye through different parts of the pupil. *Journal of Physiology (London), 190*, 583–593.

Howarth, P. A. & Bradley, A. (1986). The longitudinal chromatic aberration of the human eye & its correction. *Vision Research, 26*, 261–366.

Pelli, D. G. & Zhang, L. (1991). Accurate control of contrast on microcomputer displays. *Vision Research, 31*, 1337–1350.

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

Stiles, W. S. & Crawford, B. H. (1933). Luminous efficiency of rays entering the eye at different points. *Proceedings of the Royal Society of London B, 112*, 44–58.

Thibos, L. N. (1987). Calculation of the influence of lateral chromatic aberration on image quality across the visual field. *Journal of the Optical Society of America A, 4*, 1673–1680.

Thibos, L. N., Bradley, A., Still, D. L., Zhang, X. & Howarth, P. A. (1990). Theory and measurement of ocular chromatic aberration. *Vision Research, 30*, 33–49.

Thibos, L. N., Bradley, A. & Still, D. L. (1991). Interferometric measurement of visual acuity and the effect of ocular chromatic aberration. *Applied Optics, 30*, 2079–2087.

van Blockland, G. J. (1986). Directionality and alignment of the foveal receptors, assessed with light scattered from the human fundus *in vivo*. *Vision Research, 26*, 495–500.

Van Meeteren, A. & Dunnewold, C. J. W. (1983). Image quality of the human for eccentric entrance pupils. *Vision Research, 23*, 573–579.

Wald, G. & Griffin, D. R. (1947). The change in refractive power of the human eye in dim and bright light. *Journal of the Optical Society of America, 37*, 321–336.

Walsh, G. & Charman, W. N. (1988). The effect of pupil centration and diameter on ocular performance. *Vision Research, 28*, 659–665.

Walsh, G., Charman, W. N. & Howland, H. C. (1984). Objective technique for the determination of monochromatic aberration of the eye. *Journal of the Optical Society of America A, 1*, 321–328.

Williams, D. R., Brainard, D., MacHahon, 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.

Acknowledgements—This research was supported by a DGICYT grant No. PB94-1138-C02-01, Spain and a collaborative research grant from NATO (CG940081). We thank Fernando Vargas for help with the CSF software development, Norberto López-Gil for serving as a subject, José María Artigas who provided us with the emission spectrum of the monitor's green phosphor, and Arthur Bradley, Walt Makous and David Williams for their comments and suggestions on the manuscript.