Calculated impact of higher-order monochromatic aberrations on retinal image quality in a population of human eyes: erratum

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Figure 5 was incorrectly printed when this paper was published [J. Opt. Soc. Am. A ***19****, 1–9 (2002)]. Because the authors believe that the appearance of the wrong figure severely compromised the continuity of their scientific presentation, we are republishing the paper in its entirety.*

We calculated the impact of higher-order aberrations on retinal image quality and the magnitude of the visual benefit expected from their correction in a large population of human eyes. Wave aberrations for both eyes of 109 normal subjects and 4 keratoconic patients were measured for 3-, 4-, and 5.7-mm pupils with a Shack–Hartmann sensor. Retinal image quality was estimated by means of the modulation transfer function (MTF) in white light. The visual benefit was calculated as the ratio of the MTF when the monochromatic higher-order aberrations are corrected to the MTF corresponding to the best correction of defocus and astigmatism. On average, the impact of the higher-order aberrations for a 5.7-mm pupil in normal eyes is similar to an equivalent defocus of ~0.3 D. The average visual benefit for normal eyes at 16 c/deg is ~2.5 for a 5.7-mm pupil and is negligible for small pupils (1.25 for a 3-mm pupil). The benefit varies greatly among eyes, with some normal eyes showing almost no benefit and others a benefit higher than 4 at 16 c/deg across a 5.7-mm pupil. The benefit for keratoconic eyes is much larger. The benefit at 16 c/deg is 12 and 3 for 5.7- and 3-mm pupils, respectively, averaged across four keratoconics. These theoretical benefits could be realized in normal viewing conditions but only under specific conditions.

OCIS codes: 330.7310, 330.5370.

1. INTRODUCTION

The correction of defocus and astigmatism with spectacles or contact lenses improves vision to an acceptable level in most subjects, mainly for small pupils. On the other hand, it is well established that the human eye suffers from higher-order monochromatic aberrations besides defocus and astigmatism.[1–12] A number of studies have shown the deleterious effect of higher-order aberrations on image quality by means of the ophthalmoscopic retinal image, the point-spread function (PSF), or the modulation transfer function (MTF).[3–5,8,13–21] These studies conclude that, except when the pupil is very small, the optical quality of even the best eyes is below the diffraction limit.

What is the impact of these higher-order aberrations on visual performance? Adaptive optics has demonstrated in a small number of subjects that correcting higher-order aberrations can increase contrast sensitivity and acuity.[22–24] Presently, the visual benefits observed with adaptive optics can be obtained only in the laboratory, but the success of the technique encourages the implementation of higher-order correction in everyday vision through customized contact lenses, intraocular lenses, or laser refractive surgery. Lathing technologies now exist that can create arbitrary surfaces on contact lenses, offering the possibility of customized contact lenses. There is an ongoing effort as well to refine laser surgery to correct other defects besides conventional refractive errors,[25,26] though at present these procedures increase higher-order aberrations rather than decreasing them.[26,27] Recently we used a Shack–Hartmann sensor to measure the aberrations in a large number of eyes, providing a description of the aberrations that are characteristic of a normal human population.[28] In this paper we calculate the visual benefit in white light expected by correcting higher-order aberrations in this larger population, which extends the ex-

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perimental measurements of this visual benefit made with adaptive optics on a small number of subjects.[24]

2. METHODS

A. Apparatus

Figure 1 shows a simplified schematic of the Shack–Hartmann wave-front sensor that we used. Details can be found in Refs. 8 and 14. The light source is an infrared superluminescent diode (SLD) emitting collimated linearly polarized light at 780 nm. The beam from the SLD focuses on the retina and acts as a point source. The light emerging from the pupil forms the aberrated wave front, which propagates back through the system and is focused by the lenslet array on a CCD. The lenslet array lies in a plane conjugate with the eye's pupil, and the CCD lies in a plane conjugate with the retina. We used a focus corrector to reduce the defocus present in the Shack–Hartmann images by placing the retina conjugate with the SLD and the CCD camera. The interlenslet spacing is 0.6 mm and the lenslet focal length is 40 mm. A total of 57 lenslets were used in the array, sampling a 5.7-mm-diameter pupil. The spot array pattern recorded by the CCD camera is sent to a personal computer. On the basis of the relative spot displacements, the local wave-front slope is determined and the wave aberration is reconstructed.

B. Subjects and Measurements

We measured the eye's wave aberration in a population of 109 normal subjects, for left and right eyes. Subjects had spherical refractive errors between +6 D (D is diopter) and −12 D (mean value −3 ± 3 D) and astigmatism lower than −3 D (mean value −0.5 ± 0.5 D). Age ranged between 21 and 65 years (mean age 41 years). Subjects had no known pathology. Four keratoconic subjects, as clinically prescribed, were also measured but not included within the normal population statistics.

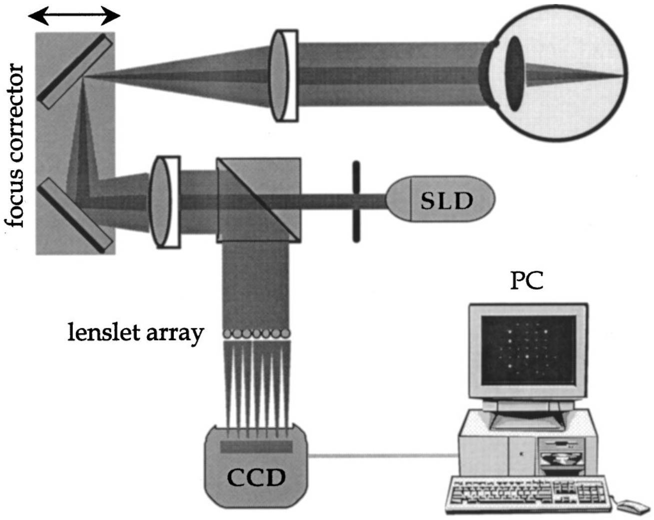

Fig. 1. Schematic of the apparatus of the Shack–Hartmann wave-front sensor used to measure the eye's aberrations. The light from the SLD serves as a beacon, forming a point source on the retina. Light reflected from the retina emerges through the eye's pupil as an aberrated wave front and is propagated through the system to the lenslet array, placed conjugate with the eye's pupil. The lenslet array forms the Shack–Hartmann image, which is sent to a personal computer, PC, for processing and calculation of the wave aberration.

Measurements were made under natural accommodation. The subject's pupil was aligned with a video camera while the head was fixed in space with a bite-bar mount or a head-and-chin-rest assembly. Subjects maintained fixation on a target placed at infinity. At least three Shack–Hartmann images, each with an exposure time of 500 ms, were collected in each eye. The total irradiance on the cornea was 6 μW, which is approximately 30 times below the American National Standards Institute maximum permissible exposure for continuous viewing at this wavelength.[29]

The wave aberration was calculated for 3-, 4.4-, and 5.7-mm diameter pupils and expressed as a fifth-order Zernike polynomial expansion.

To evaluate the effect of truncating the polynomial expansion, we also considered the wave aberrations of an additional population of ten normal eyes measured up through tenth order.

C. Image Quality and Visual Benefit

To estimate retinal image quality, we used the MTF in white light.[30,31] The white-light MTF was calculated from the polychromatic PSF, which was computed as the superposition of the monochromatic PSFs for each wavelength defocused by axial chromatic aberration[32] and shifted by lateral chromatic aberration.[33] Marcos *et al.*[33] found that the amount of the foveal transverse chromatic aberration in five subjects averaged to 0.756 arc min between 433 and 622 nm. We linearly extrapolated the amount of the transverse chromatic aberration over the spectral range from 400 to 700 nm. Therefore the foveal transverse chromatic aberration that we assumed across this expanded range was 1.2 arc min. The monochromatic PSFs were obtained between 400 and 700 nm at 10-nm intervals assuming an equal energy spectrum, weighted by the photopic spectral sensitivity curve for the CIE standard observer. The two-dimensional MTF was computed as the modulus of the Fourier transform of the polychromatic PSF. The one-dimensional MTF was obtained by averaging the two-dimensional MTF across all directions (radial average).

To quantify the improvement in image quality that can be achieved by correcting the higher-order monochromatic aberrations, we define the visual benefit as the ratio of the eye's polychromatic MTF when all the monochromatic aberrations are corrected to that corresponding to a conventional correction of only defocus and astigmatism. A visual benefit of 1 corresponds to no benefit of correcting higher-order aberrations. A value of 2 would indicate a twofold increase in retinal image contrast provided by correcting higher-order aberrations in addition to defocus and astigmatism. The visual benefit is directly applicable to visual performance as assessed with contrast-sensitivity measurements. That is, a visual benefit of 2 will lead to a twofold increase in contrast sensitivity as well as a twofold increase in retinal image contrast.

Our quantitative evaluation of the visual improvement over a second-order conventional correction rests on the calculation of the eye's MTF when only defocus and astigmatism are corrected. Due to the effect of the higher-order aberrations, nonzero values of defocus and astigmatism can improve subjective image quality.[34–36] We applied a computational method that would approximate the process of subjectively refracting a real eye. We searched a three-dimensional space of parameters corresponding to all three Zernike coefficients for defocus and astigmatism to optimize a metric defined as the volume of the contrast-sensitivity function (CSF). This CSF was calculated as the product of the MTF and the neural CSF. The neural CSF that we used was obtained from experimental data previously measured by interferometry.[37]

3. RESULTS

A. Population Statistics of the Wave Aberration

Figure 2 shows the distribution in the population of 218 normal eyes (mean value plus/minus one standard deviation) of the absolute value of each Zernike aberration in comparison with the mean values for the sample of eight keratoconic eyes. The pathology of keratoconus is revealed not only by abnormal astigmatism but also by the significantly larger magnitudes of the third-order aberrations (coma and triangular astigmatism) and some fourth-order aberrations (secondary astigmatism). The inset in Fig. 2 shows the distribution in the normal population of each Zernike aberration with its sign. The means of almost all aberrations are approximately zero, except for spherical aberration, which has a mean value of 0.13 ± 0.10 micrometers and is significantly different from zero. The magnitudes of the higher-order aberrations generally decline with order, except for spherical aberration, which is larger than any third-order aberration. The large dispersion of the Zernike coefficient z_2^{2} indicates a predominant with-the-rule astigmatism in the population. The coefficient z_2^{0} for defocus is not shown. It has a much larger dispersion than the other aberrations because the population was selected with a wide interval of spherical refractive errors. Second-order aberrations (defocus and astigmatism) have a much larger magnitude than the higher-order aberrations. They account for over 92% of the total variance of the wave aberration. However, the higher orders can still have a significant effect on image quality when the pupil is large.

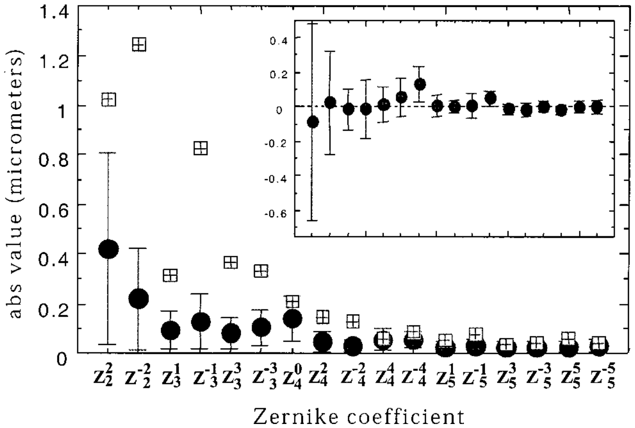

Fig. 2. Average across the population of the absolute values of each Zernike coefficient for a pupil of 5.7 mm. Circles, mean values (± standard deviation) for the population of 218 normal eyes; squares, mean values for the sample of eight keratoconic eyes. The inset shows the mean values (± standard deviation) in the normal population of each Zernike coefficient with its sign.

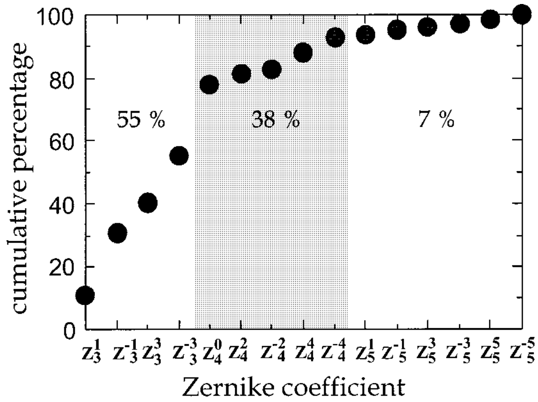

Fig. 3. Cumulative variance of the wave aberration after removal of the second-order aberrations. Results are averaged for the population of 218 normal eyes.

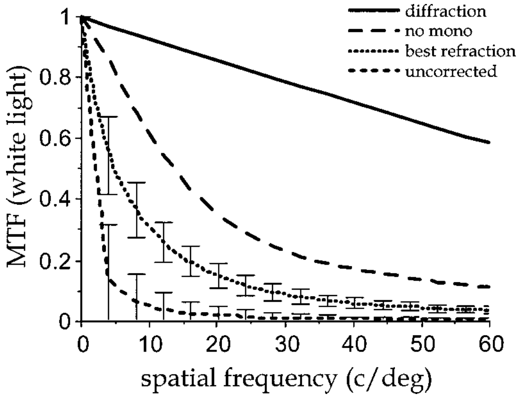

Fig. 4. White-light MTFs for different conditions in the normal population of 109 subjects, for a 5.7-mm pupil. The solid line, diffraction-limited MTF when the eye's monochromatic and chromatic aberrations have both been corrected; long-dashed curve, MTF with all the monochromatic aberrations corrected; dotted curve, mean MTF in the population for a conventional correction of defocus and astigmatism; short-dashed curve, mean MTF for the uncorrected eye. Error bars represent ± one standard deviation from the mean value.

Figure 3 shows the cumulative contribution to the wave-aberration variance in the normal population including only the higher-order Zernike aberrations. As we noted above, there is a tendency for the magnitude of the aberrations to decrease with increasing order. Third-order aberrations account for 55% of the variance of the higher-order wave aberration. Fourth-order aberrations account for 38%, and fifth order for 7%. The third order contributes the most to the higher-order aberrations as noted by Howland and Howland (Ref. 4). The total variance of the higher-order wave aberration is 0.12 ± 0.08 μm averaged across the population.

B. Impact of Monochromatic Aberrations on the Modulation Transfer Function

The distribution and magnitude of the monochromatic aberrations in the population shown above does not inform us directly about their impact on image quality and there-

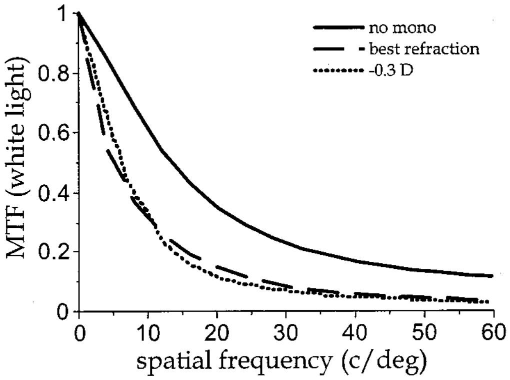

Fig. 5. Comparison of the effect on the white-light MTF (5.7-mm pupil) of the higher-order aberrations and an introduction of pure defocus. Solid curve, MTF with all the monochromatic aberrations corrected; dashed curve, average MTF in the normal population for the best correction of defocus and astigmatism, with the higher-order aberrations uncorrected; dotted curve, MTF for an eye with no higher-order aberrations and −0.3 D defocus.

fore about the visual improvement from correcting them. Figure 4 shows the MTF in white light when all the monochromatic aberrations have been corrected and only chromatic aberration remains. It also shows the MTFs, averaged in the normal population, for both the uncorrected eye and the best-refracted eye (correcting defocus and astigmatism). Although the higher orders make a small contribution (8%) to the total variance of the wave aberration, their correction raises the MTF substantially. The ratio between these two MTFs is the visual benefit that could be realized in theory by correcting the higher-order aberrations. The absolute improvement in MTF is similar to that reached from the uncorrected eye after a conventional correction.

In Fig. 5 we compare the effect of the eye's higher-order aberrations with the effect of introducing purely defocus. The average MTF in the normal population for the best correction of defocus and astigmatism (dashed curve) is similar to an MTF with no higher order aberrations and −0.3 D defocus (dotted curve). The variance of the wave aberration with introduction of −0.3 D of pure defocus is 0.12 μm for the 5.7-mm pupil, the same as the average variance of the higher-order wave aberration.

Figure 6 depicts the impact of the different orders by showing the MTF, averaged in the normal population, when additional aberration orders are progressively corrected in both white and monochromatic light. Although the wave-aberration variance for the fourth-order aberrations is ~1.4 times lower than that for the third-order aberrations (see Fig. 3), the improvement in the polychromatic MTF is larger when the fourth-order aberrations are corrected. This suggests that spherical aberration, which is the most important fourth-order aberration, could have a large effect on the MTF for this pupil size. The MTF corresponding to the correction up to third order plus the correction of spherical aberration is also shown. The relative importance of fourth-order aberrations over coma in the MTF does not necessarily imply that correcting fourth-order aberrations will produce a larger subjective improvement in image quality. For example, the asymmetric PSF that characterizes coma could increase its relative importance in subjective image quality. The curves shown in Fig. 6(b) indicate the improvement in the MTF in monochromatic light or for an eye free of chromatic aberration.

In our calculations we have included the measured aberrations only up to fifth order. Figure 7 shows the effect of changing the number of Zernike orders used to represent the wave aberration for a 6-mm pupil from an addi-

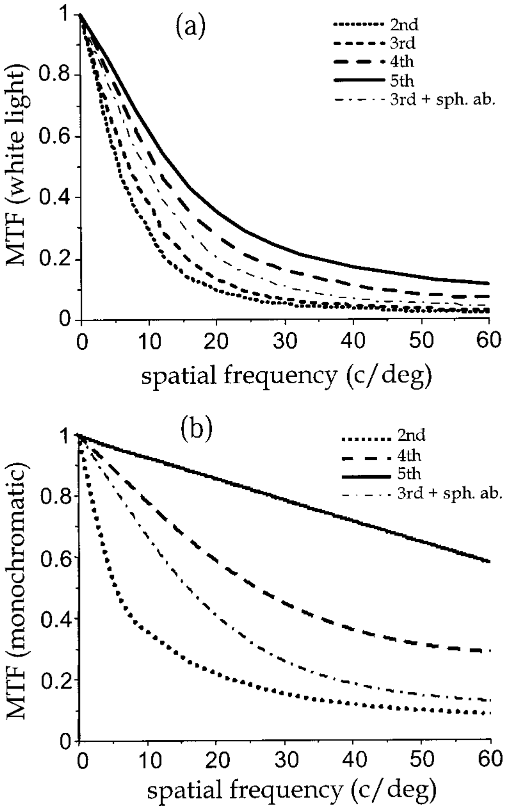

Fig. 6. MTFs averaged in the normal population of 109 subjects, for a 5.7-mm pupil, with only second-order aberrations corrected (dotted curves); second and third orders corrected (short-dashed curve); aberrations up through fourth order corrected (long-dashed curves); all orders corrected (solid curves); and aberrations up through third order plus spherical aberration corrected (dashed–dotted thin curves). (a) White light, (b) monochromatic light.

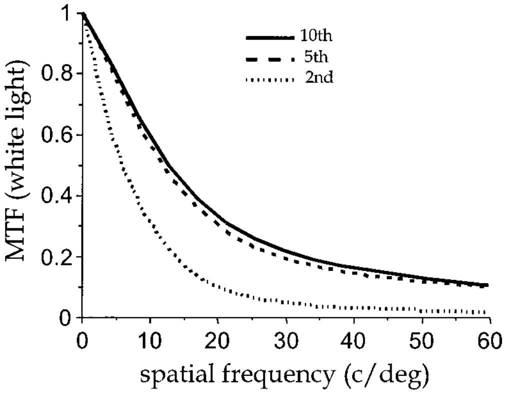

Fig. 7. Average MTFs, in white light, in a population of ten normal eyes and a 6-mm pupil, when the aberrations up through tenth order, up through fifth order, and up through second order are corrected. The wave aberrations for this population were measured up through tenth order.

tional population of ten eyes in which the aberrations were measured up through tenth order. In white light, the correction up through fifth order yields a MTF quite close to the MTF obtained when the aberrations are corrected up through tenth order. This indicates that our wave aberrations up through fifth order are an adequate representation of the eye's aberrations for the medium pupil size of 5.7 mm in white light.

C. Visual Benefit of Correcting Monochromatic Aberrations

Figure 8(a) shows the mean values of the visual benefit across the population of 109 normal subjects for three different pupil sizes as a function of spatial frequency. For the 3-mm pupil the visual benefit is modest. A small improvement might be realized at high spatial frequencies [~1.5 at 32 cycles per degree (c/deg)]. For small pupils, diffraction dominates, and aberrations beyond defocus and astigmatism are relatively unimportant. However, for medium and large pupils, a larger visual benefit can be obtained across all spatial frequencies by correcting the monochromatic higher-order aberrations. For example, with a 5.7-mm pupil the average visual benefit across the population is ~2.5 at 16 c/deg and ~3 at 32 c/deg. Figure 8(b) shows the average visual benefit in the sample of four keratoconic subjects, for the three pupil sizes. These patients could receive a large benefit at all pupil sizes.

The frequency histograms in Fig. 9 show, for a 5.7-mm pupil, how much the visual benefit varies among eyes in the normal population of 109 normal subjects and in the sample of four keratoconic patients. The distributions of visual benefit at spatial frequencies of 16 and 32 c/deg are shown because they correspond roughly to the highest frequencies that are detectable by normal subjects viewing natural scenes. Some normal eyes have a visual benefit close to 1, i.e., they show almost no benefit from the correction of higher-order aberrations. At the other extreme, some normal eyes show a benefit of more than a factor of 4. The mean value of visual benefit at 16 c/deg is 2.4 ± 0.5 and 3 ± 1 at 32 c/deg. The distribution becomes more symmetric and develops longer tails as the spatial frequency increases. The visual benefit in the keratoconic patients is much larger. One of the subjects of the sample, who is in the early stages of keratoconus, has a visual benefit similar to that for the normal population. The other three subjects show larger benefits than any subject does in the normal population (one of them as high as a factor of 25).

D. Simulated Retinal Images

Figure 10 shows simulated retinal images in white light of an object consisting of the last four lines of the Snellen chart corresponding to the 20/30, 20/20, 20/15, and 20/10 vision. The letters of the 20/20 line subtend an angle of 5 arc min. The retinal images were calculated as the convolution of the object with the polychromatic PSF obtained from the wave aberration for the 5.7-mm pupil. Four cases are shown. The upper images correspond to an eye with all the monochromatic aberrations corrected at the best focus [image (a)] and defocused -0.3 D [image (b)]. The lower images are for two real eyes for the best correction of defocus and astigmatism: image (c) eye with medium aberrations, image (d) eye with moderately high aberrations. In image (a) with monochromatic aberrations corrected, the 20/15 line can be easily read.

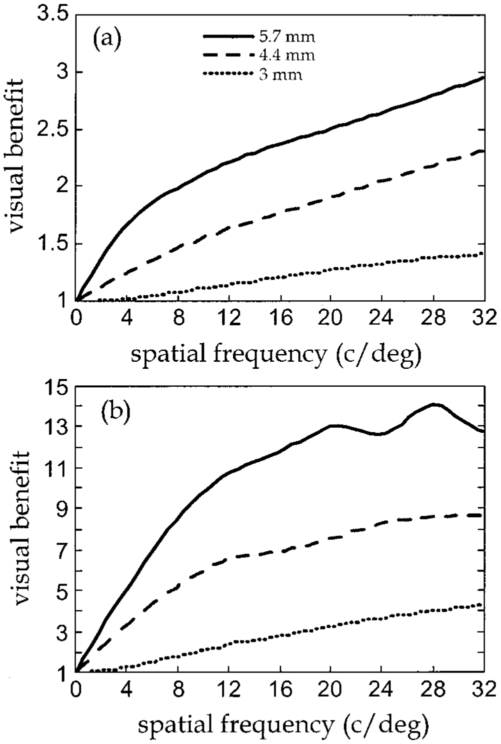

Fig. 8. Visual benefit for 5.7-, 4.4-, and 3-mm pupils. (a) Mean values for the 109 normal subjects. (b) Mean values for the four keratoconic subjects. Notice the scale change between (a) and (b).

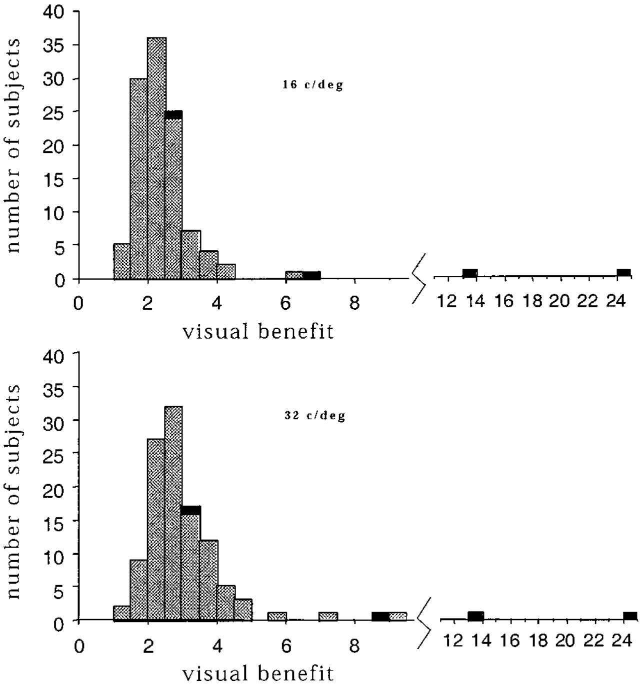

Fig. 9. Distribution of visual benefit for all normal subjects across a 5.7-mm pupil at 16 c/deg and 32 c/deg. The average across right and left eyes were considered in every subject. In black, the visual benefit for the four keratoconic subjects.

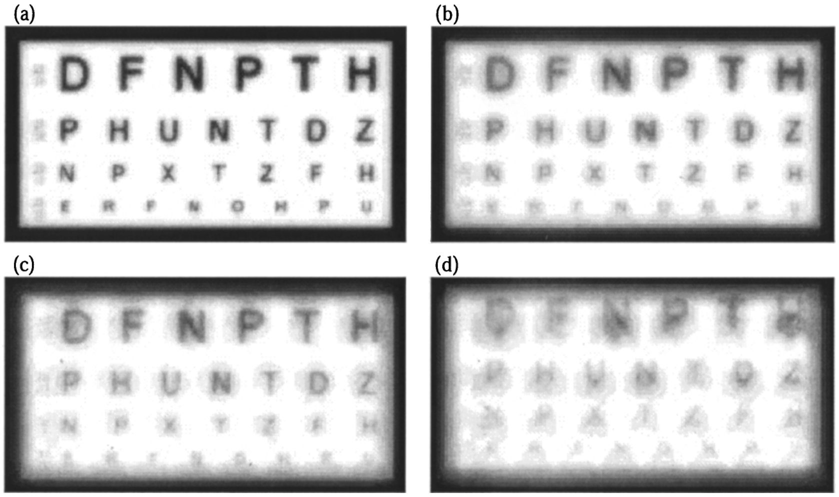

Fig. 10. Simulated retinal images in white light (5.7-mm pupil), of the last four lines of the Snellen chart corresponding to the 20/30, 20/20, 20/15, and 20/10 vision. 20/20 letters subtend 5 arc min. (a) Ideal aberration-free eye with only chromatic aberration uncorrected; (b) same as in (a), but defocused -0.3 D; (c) real eye with medium aberrations for the best correction of defocus and astigmatism eye, (d) same as in (c), for an eye with moderately high aberrations.

Even the 20/10 line presents enough contrast to be read as well, despite the eye's chromatic aberration. The case shown in image (c) represents the typical situation for an average eye and a medium pupil. This eye would clearly reach the 20/20 line and guess some letters from the 20/15 line. The theoretical visual benefit calculated for this eye was ~2.5 at 16 c/deg and ~3 at 32 c/deg. The increase in contrast from image (c) to image (a) indicates how these values of visual benefit would translate into retinal image quality. The second eye shown in image (d) with more aberrations would have some difficulty in reading even the 20/20 line. Its visual benefit was ~4 at 32 c/deg. The improvement in image quality from image (d) to image (a) indicates the benefit of correcting higher-order aberrations for more highly aberrated eyes.

The impact on image quality of a pure defocus of -0.3 D when the monochromatic aberrations are corrected is similar to the impact of higher-order aberrations when the eye is best refracted. One difference however, is that the blur in the letters in Fig. 10(c) is asymmetric compared with Fig. 10(b) owing to the effect of odd-order aberrations. These two images have roughly the same MTF averaged across all orientations, and the difference between them lies in the phase transfer function as well as variations in the MTF with orientation. This emphasizes a limitation in the MTF as an indicator of retinal image quality. In fact, the visual benefit defined here, which is based on the MTF, may underestimate the improvement in image quality, because correcting higher-order aberrations improves the phase transfer function as well as the MTF.

4. CONCLUSIONS

We have quantified the relative importance of the eye's monochromatic aberrations in a large population by using descriptors in the pupil plane, namely, the statistics of Zernike coefficients of the wave aberration. Also, we have used a metric related to the image plane, the MTF. The relationship between the wave-aberration variance in the pupil plane and the retinal image is not straightforward. The MTF more clearly quantifies retinal image quality, on which visual performance ultimately rests. One of the consequences of this is that although the higher-order aberrations make little contribution to the variance of the wave aberration in comparison with the second-order aberrations, they have a larger influence in reducing the MTF, as shown in Fig. 4. The relative importance of higher-order aberrations is better characterized by their effects on the MTF rather than from their absolute values defined in the pupil plane. We calculated the MTF for a conventional correction of defocus and astigmatism that would approximate the best MTF achievable by the process of subjectively refracting a real eye. This MTF is below the MTF that can be obtained by correcting the higher-order aberrations as well. We defined the ratio between these two MTFs as the visual benefit. This is a measure of the improvement in visual performance that could be realized by correcting monochromatic higher-order aberrations with methods such as customized contact lenses and intraocular lenses or customized laser surgery. In bright-light conditions, the natural pupil of most normal eyes is sufficiently small that the retinal image would not be greatly affected by aberrations, and therefore the visual benefit would be small. However, there are many illumination conditions for which subjects have medium and large pupils, in which cases they could experience significant increases in contrast if they had aberration-free eyes. There is a large variability in the eye's aberrations from person to person. Therefore some people will derive much more visual benefit from higher-order correction than others, even for small pupils. This is also the case for abnormal eyes such as keratoconics. Clearly, the development of technologies to correct the idiosyncratic higher-order aberrations of such patients would be especially valuable. The wave-front sensor coupled with calculations such as those shown here can efficiently screen the patients who stand to gain the largest benefit from customized correction.

An important problem is whether these theoretical estimates of visual benefit translate to subjective image quality. Improving the optics of the eye will improve the sharpness of the retinal image, and the visual system will have increased contrast sensitivity to gratings. Experimental measurements of CSF and Snellen visual acuity have recently been performed with adaptive optics.[22,24] Following the correction of the higher-order aberrations with adaptive optics, Yoon *et al.*[24] have shown an improvement in the white-light CSF by a factor 2 on average at 16 c/deg across a 6-mm pupil. We predicted a visual benefit of 2.5 at 16 c/deg for a 5.7-mm pupil. The experimental value is somewhat lower, perhaps owing to individual differences or because adaptive optics is incapable of perfectly correcting all the higher-order aberrations. Also, Yoon *et al.* found that visual acuity improved by a factor of 1.2 on average at high luminances. For instance, subjects improved from 20/20 vision to 20/15. We showed theoretically in Fig. 10 that normal subjects could experience those improvements. The simulated retinal images shown in Fig. 10 provide an idea of how the visual benefit translates into quality of retinal images.

Both our theoretical results and the experimental results under laboratory conditions point out the potential value of correcting the eye's higher-order aberrations. However, there are some important caveats about the visual benefit that can be realized by customized correction procedures in ordinary vision. First, the eye's higher-order aberrations change with accommodation.[38] This means that a correction tailored for distance vision would not be appropriate for near viewing, and vice versa. Calculations show that the customized correction of the higher-order aberrations for accommodation at infinity offers little or no visual benefit when the eye accommodates at 2 D (0.5 m). For some subjects, a higher-order correction designed for far vision could produce no benefit and even be detrimental at near distances, at least at spatial frequencies above 10 c/deg. This limitation does not apply to presbyopes. In younger people, a customized lens would still be valuable for distance vision. For many near tasks, such as reading, one has the option of decreasing the distance of the text, so that image blur is less troublesome. If the task for near vision is reading, for example, which involves spatial frequencies of ~10 c/deg, the subject could still wear the customized correction and achieve the same visual performance obtained with a standard correction. In any case, full aberration compensation is possible only for one level of accommodation.

Second, accurate accommodation is required for achieving the expected benefits of higher-order correction. We showed in Figs. 5 and 10 that a defocus of ~0.3 D will dilute the benefit of correcting the higher-order aberrations. The failure to focus correctly on the target is commonplace as a result of accommodative lag, which increases as the stimulus luminance is reduced.[39] Accommodative lag can easily produce a defocus of 0.3 D or more at low luminance. Thus the theoretical benefits through customized correction, which are highest for large pupils, will be diminished in dim light as a result of poor focus. Another effect of correcting higher-order aberrations may be the reduction of the eye's depth of focus. For objects that lie nearer or further than the plane of focus, image quality can actually be worse than it is when aberrations are left uncorrected. A complete analysis of this limitation has yet to be undertaken.

Third, although adaptive optics provides a dynamic correction of the eye's aberrations, a static correction with customized methods will not offer the expected outcome if the aberrations vary in time. Recent results[40] have shown that the wave aberration of the eye is sufficiently stable over short and long periods of time, indicating that a custom correction would be valuable. The largest source of temporal short-term instability is microfluctuations in accommodation. These fluctuations, on the order of 0.1 D, are less than the 0.3 D mentioned above, which is roughly equivalent to the net effect of higher-order aberrations. On the other hand, although the wave aberration is stable over relatively long time periods, it is known that ocular aberrations steadily increase with age.[41,42] Both changes in the crystalline lens[43] and changes in the cornea[44,45] are responsible. However, the cause of the degradation of the eye's optical quality is the loss of the aberration balance between cornea and lens that seems to be present in the younger eye.[46–48] These factors ultimately limit the longevity of an effective customized correction. Keratoconics, who stand to gain the most from higher-order correction, also unfortunately exhibit faster changes in the wave aberration as the condition progresses.

Another limitation is that the benefit from the correction of the higher-order aberrations will be reduced by decentrations of the correcting method. For example, a customized contact lens will translate and rotate to some extent with respect to the cornea. Calculations have shown that reasonable decentrations of contact lenses do not detract greatly from the potential benefit in white light.[49] Also, the eye is not completely static during a laser surgery procedure. The effect of decentration in this case may be more severe since the removal of corneal tissue may introduce large amounts of coma when the ablation is decentered.

Because customized correction with contact lenses, intraocular lenses, or laser refractive surgery would involve everyday viewing conditions in which the spectra of objects are broadband, we chose to calculate the visual benefit for white light. We are considering a customized correction that leaves chromatic aberration uncorrected. Although the eye's chromatic aberration does not have a significant impact when the higher-order monochromatic aberrations are uncorrected, it imposes an upper bound on the visual benefits that could be achieved by correcting monochromatic aberrations. The visual benefit of additionally correcting chromatic aberration would be substantially larger. In addition, there is evidence that chromatic aberration may be useful for some subjects in guiding their accommodation responses.[50,51] Also, the monochromatic aberrations may provide a cue to focus direction.[52] Thus an eye with both monochromatic and chromatic aberrations corrected might not accommodate properly. This is an interesting possibility that remains to be tested experimentally.

These caveats will unquestionably reduce the fraction of the population that could benefit from customized correction. The human eye is the product of millions of years of evolution, and it would be surprising if evolution created an optical system that, in the average eye, was grossly different in its performance from the neural visual system it serves. For this reason, many subjects already have optics of sufficient quality that correcting higher-order aberrations would provide no benefit in practice. However, the existence of variability in the amount of higher-order aberrations in the population leads inevitably to a segment of the population with large enough higher-order aberrations to warrant their correction. The fraction of the population that will benefit is difficult to predict because it depends not only on the caveats mentioned above but also on the finesse with which correction technology can be implemented. Ultimately, we will not know the true value of correcting higher-order aberrations until this technology has been implemented in everyday vision and visual performance can be assessed experimentally.

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