Visual performance after correcting the monochromatic and chromatic aberrations of the eye

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The development of technology to measure and correct the eye's higher-order aberrations, i.e., those beyond defocus and astigmatism, raises the issue of how much visual benefit can be obtained by providing such correction. We demonstrate improvements in contrast sensitivity and visual acuity in white light and in monochromatic light when adaptive optics corrects the eye's higher-order monochromatic aberrations. In white light, the contrast sensitivity and visual acuity when most monochromatic aberrations are corrected with a deformable mirror are somewhat higher than when defocus and astigmatism alone are corrected. Moreover, viewing conditions in which monochromatic aberrations are corrected and chromatic aberrations are avoided provides an even larger improvement in contrast sensitivity and visual acuity. These results are in reasonable agreement with the theoretical improvement calculated from the eye's optical modulation transfer function.

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1. INTRODUCTION

Though it has been known for some time that the human eye suffers from monochromatic aberrations in addition to defocus and astigmatism,[1] the visual benefit of correcting these aberrations has not been clear. In this paper we will refer to defocus and astigmatism, which conventional methods such as glasses and contact lenses correct, as second-order aberrations. We will refer to all other monochromatic aberrations as order as "higher-order aberrations," based on the orders (>2) they occupy in the Zernike expansion of the wave aberration. Many techniques[2–5] have been developed to measure the higher-order monochromatic aberrations. Liang and Williams[4] provided a complete description of the eye's aberrations up to tenth order corresponding to 63 different types of aberrations.

Liang and Williams[4] suggested that, to obtain optical performance limited only by diffraction, the eye's aberrations should be corrected up to third and eighth orders for a 3.4-mm and a 7.3-mm pupil, respectively. This quantifies the fact that the effect of higher-order aberrations on retinal image quality increases with pupil diameter. It may be possible to correct higher-order aberrations of the eye with contact lenses, intraocular lenses, or refractive surgery, and efforts are ongoing to achieve this.[6,7] The success of these efforts depends on the additional improvement in vision that can be obtained.

We can explore the visual benefit of correcting higher order aberrations in the laboratory with adaptive optics. Liang *et al.*[8] first successfully used adaptive optics to measure and correct the higher-order monochromatic wave aberrations of the eye. They found that correcting the higher-order monochromatic aberrations provided a six-fold improvement in contrast sensitivity when viewing a 27.5 cycles per degree (c/deg) monochromatic grating through a 6-mm pupil. They also found that a 55-c/deg grating could be resolved with adaptive correction of higher-order aberrations but not with a conventional best refraction. However, they measured contrast sensitivity only in monochromatic light and at two spatial frequencies.

This paper extends these monochromatic measurements to include viewing conditions that more closely approximate normal viewing. Specifically, we measured contrast sensitivity with and without adaptive optics in white light,[9] so that the residual uncorrected retinal image blur from longitudinal[10] and transverse ocular chromatic aberration[11,12] was included. These psychophysical measurements, supplemented with a theoretical analysis based on wave-aberration measurements, clarify the role of monochromatic and chromatic aberrations in limiting spatial vision and reveal the visual benefit of correcting higher-order aberrations in normal vision.

2. METHOD

A. Subjects

Measurements were made on the right eyes of two subjects, GYY and YY, whose ages were 32 and 33 years, respectively. They were slightly myopic (GYY, 0.35 D; YY, 1.2 D). Subject GYY had 0.5 D of astigmatism. The subject's head was stabilized with a bite bar. The stimuli, which were either gratings or letter targets, were viewed through either a 3-mm or a 6-mm artificial pupil inserted in a plane in the optical system that was conjugate with the eye's pupil. The subject's pupil was dilated with mydriacyl (1%) or cyclogyl (1%).

B. Wave-Front Sensing and Correction

An adaptive optics system described elsewhere[8] was used to measure and correct the eye's wave aberration. We

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measured the wave aberration with a Shack–Hartmann wave-front sensor that had a square array of 221 lenslets (lenslet spacing 0.4 mm and focal length 24 mm). The wave-aberration measurements were made at 790 nm. We measured the aberrations for a 6.8-mm pupil up to tenth radial order (63 Zernike coefficients except piston and x and y tilts). A deformable mirror with 37 PMN (lead magnesium niobate) actuators (Xinetics, Inc.) lay in a plane conjugate with the pupil and was used to correct the wave aberration.

Contrast sensitivity and acuity measurements were made either with or without the correction of monochromatic aberrations by using adaptive optics. In conditions with adaptive optical correction, the deformable mirror was reshaped from its normally flat surface to a shape that corrected most of the eye's higher-order monochromatic aberrations. This iterative procedure usually required approximately ten loops and took less than a second. Runs with and without adaptive correction were made in random sequence and without informing the subject of the experimental condition. However, subjects could tell when the higher-order aberrations were corrected because the sharpness of the edge of the field increased.

C. Measuring Contrast Sensitivity

Sinusoidal gratings were displayed on a color CRT, Mitsubishi Diamond Pro 710, which the subject viewed through the adaptive optics system. The grating, the spatial contrast of which was multiplied by a Gaussian envelope, subtended a visual angle of 1 deg measured from the full width at half-maximum on the Gaussian.

Because we were interested in obtaining the highest possible contrast sensitivity, especially at high spatial frequencies, care was taken to optimally refract each subject before the contrast sensitivity measurements. Astigmatism was first corrected with cylindrical trial lenses, and a Badal optometer provided fine and continuous control of focus. Subjects viewed a fixation target consisting of four concentric circles subtending 0.25, 0.5, 0.75, and 1.0 deg with spokes every 45 deg. Cylindrical power lenses in 0.25-D steps were inserted at the spectacle point and the subject adjusted defocus and cylinder axis to optimize image quality. This procedure was repeated until the subjects, who were both experienced observers, had selected the best cylinder and axis. Because the stimulus used in the contrast sensitivity measurements was a grating, it could be brought to best focus with the Badal optometer alone. However, we corrected astigmatism to minimize the excursion of the deformable mirror required to correct the eye's wave aberration, avoiding the stroke limits of the mirror. After the astigmatic correction was achieved, subjects adjusted the Badal optometer 4 times to optimize the contrast of a 16-c/deg grating. The Badal optometer was then set to the average of these measurements.

Contrast threshold was determined with the method of adjustment. Gratings were displayed within a Gaussian temporal envelope having a standard deviation of 100 ms. Four standard deviations of the Gaussian envelope were displayed with an interstimulus interval of 500 ms. We also checked some of the measurements on both subjects with a two-alternative forced-choice method, using the QUEST procedure,[13] and these results were very similar to those obtained with adjustment. One run consisted of one contrast threshold adjustment at each of six different spatial frequencies, 2, 4, 8, 16, 24, and 32 c/deg, presented in random order. A complete data set on a subject included five runs for each experimental condition. Each run took approximately 4 min, and there was 1-min rest period between runs.

D. Including Chromatic Aberrations

One of our goals was to measure the visual benefit of correcting higher-order aberrations in a situation that approximated normal viewing. Therefore we chose a broadband stimulus to be consistent with the broadband nature of the reflectance spectra of natural scenes. Though it appeared white, the CRT's emission spectrum was trimodal. This raised the issue of whether it accurately captured the effects of the eye's chromatic aberrations in normal viewing. To address this possibility, we calculated the effects of chromatic aberration on retinal image quality with the emission spectrum of the screen and with an equal energy spectrum. Figure 1 shows white-light modulation transfer functions[14] of the eye calculated with the spectrum of the CRT (dashed curve) and an equal energy spectrum (solid curve). Longitudinal chromatic aberration,[10] transverse chromatic aberration, and the measured monochromatic aberrations of subject GYY for a 6-mm pupil were included in this calculation (see below). The difference in modulation transfer functions was less than 5% on average across spatial frequencies up to 60 c/deg, suggesting that the CRT spectrum probably captures the important quantitative effects of chromatic aberration under normal viewing conditions.

E. Avoiding Chromatic Aberrations

Another purpose of the study was to compare contrast sensitivity under conditions in which chromatic aberra-

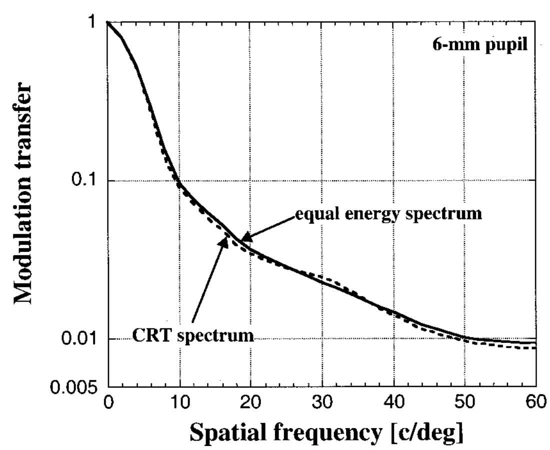

Fig. 1. Difference in retinal image quality when the actual CRT spectrum (dashed curve) and the equal-energy spectrum (solid curve) were used. The white-light modulation transfer functions shown were based on the measured wave aberration for a 6-mm pupil of subject GYY. The second-order aberrations, defocus and astigmatism, were removed. The CRT spectrum was the typical trimodal emission spectrum of a color monitor. The reference wavelength where chromatic aberration is zero was 555 nm, and the photopic spectral sensitivity function was used as a weighting function.

tion was present with conditions when it was absent. There are at least two methods to avoid chromatic aberration: to use an achromatizing lens and to use monochromatic light. We performed some preliminary experiments with an achromatizing lens designed by Bedford and Wyszecki[15] but found a smaller visual benefit than could be obtained with the use of monochromatic light. In theory, the visual benefit with a well-aligned achromatizing lens should be similar to that in monochromatic light. But in practice, achromatizing lenses are difficult to use because of transverse chromatic aberration[16] and/or the accuracy with which the lens can be aligned.[17] Instead, we chose to avoid both longitudinal and transverse chromatic aberration by viewing our broadband stimulus through a narrow-band interference filter (full width at half-maximum = $10\,nm$, peak transmittance at 550 nm). Although this method very effectively avoids the chromatic aberrations, it does require comparing the contrast sensitivities with stimuli that differ in color appearance, leading to the possibility that any difference we observed could be due to neural factors rather than to chromatic aberration. We think this is highly unlikely. Van Nes and Bouman[18] demonstrated that the photopic contrast sensitivity function does not depend on wavelength. Our monochromatic and white fields produce similar ratios of excitation of the long- and middle-wavelength-sensitive (L and M) cones and differ mainly in the excitation of short-wavelength-sensitive (S) cones. The S-cone system is known to have little or no influence on achromatic contrast sensitivity.[19]

The retinal illuminances of the white and the monochromatic fields were equated with neutral density filters. The space-averaged retinal illuminance was 14.3 trolands (Td) and 57 Td for 3-mm and 6-mm pupils, respectively. These low luminances were the highest available during viewing of the CRT in monochromatic light. They are appropriate for assessing the benefit of correcting higher-order aberrations because these benefits are expected to be largest in dim illumination, when the pupil is large.

F. Estimating Visual Benefit

We define the visual benefit of correcting various aberrations in two ways. The first way is based on our contrast sensitivity data: The visual benefit at each spatial frequency is defined as the ratio of the contrast sensitivity when various aberrations were corrected to that when only defocus and astigmatism were corrected as in a conventional refraction. A visual benefit of 1 at any spatial frequency corresponds to no effect on retinal image contrast of correcting aberrations, a value less than 1 signals a decrease, and a value greater than 1 signals an increase in retinal image contrast.

The second way to define visual benefit is based on the wave-aberration data obtained with our wave-front sensor. The modulation transfer function of the eye can be calculated from the wave aberration. On this basis the visual benefit is taken to be the ratio of the modulation transfer function when various aberrations were corrected to that when defocus and astigmatism alone were corrected. We computed the modulation transfer function as follows. First, the monochromatic point-spread function was computed by applying the Fourier transformation to the pupil function, defined as the product of input intensity distribution and the exponential function of the measured wave aberration. The Stiles–Crawford effect was not included in this calculation because the difference between retinal image quality with and without the Stiles–Crawford effect was small (<6%) in white light. We computed the monochromatic point-spread function every 10 nm from 405 to 695 nm assuming an equal-energy spectrum. Each monochromatic point-spread function had a different shape and position due to the longitudinal and transverse chromatic aberration of the eye. We used the longitudinal chromatic aberration data of Wald and Griffin[10] and estimates of the foveal transverse chromatic aberration from Thibos *et al.*[11] The latter 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 405 to 695 nm. Therefore the foveal transverse chromatic aberration that we assumed across this expanded range was 1.16 arc min. The monochromatic point-spread functions, thus altered by longitudinal and transverse chromatic aberration, were weighted by the photopic luminosity function and summed to yield the polychromatic point-spread function. The modulation transfer function was computed by Fourier transforming the polychromatic point-spread function.

When higher-order monochromatic aberrations in an optical system are relatively small, the retinal image quality depends on the variation of the total wave aberration rather than the characteristics of the individual aberrations.[20] In this case, the best image quality is achieved when the second-order aberrations, defocus and astigmatism, have values of zero. However, when the higher-order aberrations are large, nonzero defocus and/or astigmatism can provide better retinal image quality.

We optimized the amount of defocus by calculating the modulation transfer functions for different amounts of defocus. Figure 2 shows averaged white-light modulation

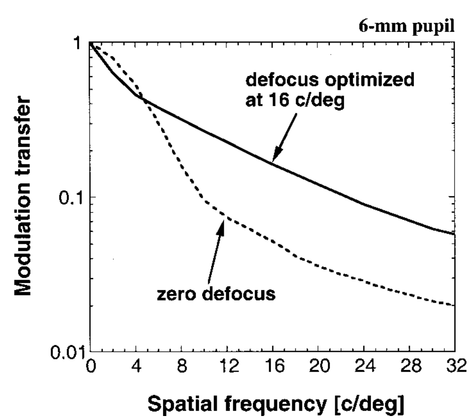

Fig. 2. White-light modulation transfer function when the amount of defocus is optimized (solid curve) and zero (dashed curve) for a 6-mm pupil. Both modulation transfer functions were the average of three subjects with no correction of aberration. Optimizing defocus provides better retinal image quality than that when defocus is zero.

transfer functions based on the uncorrected aberrations of the eyes of three subjects as measured with the Shack–Hartmann wave-front sensor. The solid curve corresponds to the case of optimizing the amount of defocus to achieve the best image quality for a 16-c/deg grating. The dashed curve is the case of zero defocus. Adding 0.55-D defocus on average provides better image quality in the spatial-frequency range higher than 4 c/deg. We found the same tendency, but with a different optimized amount of defocus, for the monochromatic modulation transfer function. Optimizing the amount of defocus, therefore, provides a more reliable estimate of the theoretical visual benefit of correcting higher-order monochromatic aberrations than setting defocus to zero. The image quality may be improved by optimizing astigmatism as well. For calculating visual benefit, we optimized only defocus, although in the contrast sensitivity measurements, both defocus and astigmatism were optimized with trial lenses. For all the modulation transfer function calculations, the wavelength that was selected to be in focus was that wavelength which maximized the modulation transfer at 16 c/deg. To facilitate comparison of the theoretical benefit with experiment, the same 16-c/deg spatial frequency was used by the subject for optimizing focus before contrast sensitivity was measured.

Although the two kinds of visual benefit described above are obtained from different measurements, contrast sensitivity in one case and wave-front sensing in the other, they should agree with each other because they both reflect increases in retinal image contrast caused by correcting aberrations. In each case, the denominator corresponds to the optimum performance or image quality that can be obtained with a conventional spectacle prescription, since that is the benchmark against which we wish to compare the effect of correcting additional higher-order aberrations.

G. Measuring Letter Acuity

Defocus and astigmatism were corrected as before. The illiterate letter E with one of four different orientations was displayed on the CRT at 100% contrast. From trial to trial, the orientation of the letter was varied randomly among four orientations: the normal orientation and rotations of 90, 180, and 270 deg. Subjects indicated the orientation of the letter by pressing one of four keys. The measurements of visual acuity with and without the correction of monochromatic aberrations were made in random order without the subject's knowledge of the state of correction. The psychometric function based on 40 trials was derived by using the QUEST procedure, and acuity was taken as the line thickness of the letter for which 82% (determined by the QUEST method) of responses were correct. The right eyes of seven subjects were measured. Measurements were made in monochromatic light with a lower retinal illuminance level, 57 Td, and in white light with a higher illuminance level, 575 Td. We made four measurements under each of five conditions: with and without correcting higher-order monochromatic aberrations in monochromatic light at 57 Td and the higher-illuminance white light, and without correcting higher-order monochromatic aberration in the lower-illuminance white light. The pupil size was 6 mm. Visual acuity in monochromatic light could not be measured at the high illuminance level owing to the limited luminance of the CRT.

3. RESULTS

A. Contrast Sensitivity

Figure 3 shows the contrast sensitivity functions for two subjects with only defocus and astigmatism corrected (× symbols), after avoiding chromatic aberration as well as defocus and astigmatism (open triangles), after correcting the higher-order monochromatic aberrations as well as defocus and astigmatism (open circles), and after correcting monochromatic aberrations and avoiding chromatic aberration, as well as correcting defocus and astigmatism (solid circles). The results are similar for the two subjects. Note that the absolute contrast sensitivity is low, owing to the low retinal illuminance, but that it is roughly consistent with other measurements in the literature.[18,21] The contrast sensitivity when most monochromatic aberrations are corrected with a deformable mirror is better than when only defocus and astigmatism are corrected. This illustrates that higher-order aberrations in normal eyes reduce visual performance. Moreover, correcting

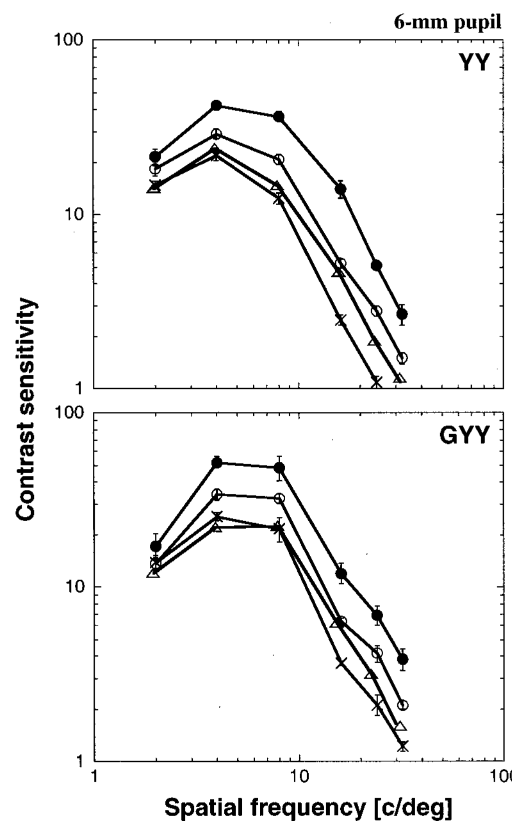

Fig. 3. Contrast sensitivity functions for a 6-mm pupil for subjects YY and GYY after correction of various aberrations: defocus and astigmatism only (× symbols), measured in white light; chromatic aberration, defocus and astigmatism (open triangles); monochromatic aberrations including defocus and astigmatism only (open circles), and both monochromatic and chromatic aberrations (solid circles), measured at 550 nm. The error bars represent ± one standard error.

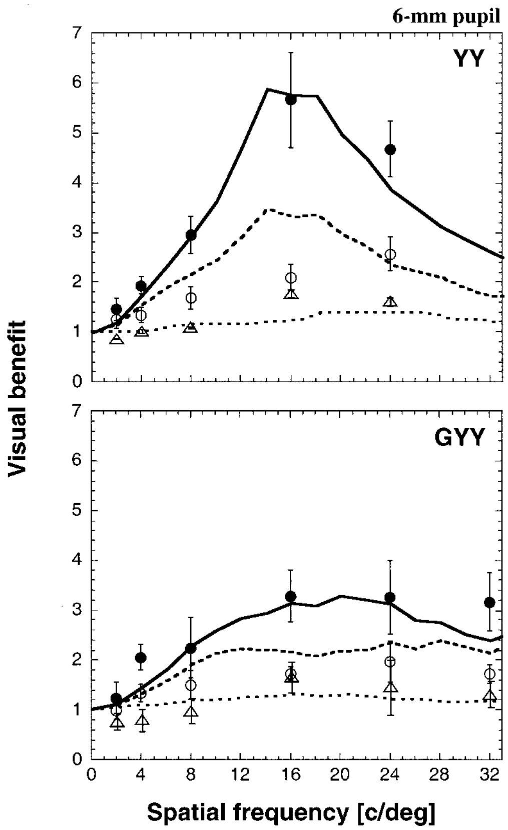

Fig. 4. Symbols show visual benefits for a 6-mm pupil as estimated from the contrast sensitivity functions in Fig. 3. The visual benefit is defined as the ratio of the contrast sensitivity function when various aberrations are corrected to that when defocus and astigmatism only are corrected. Open triangles, correspond to the visual benefit of correcting chromatic aberration (the ratio of open triangles to × symbols in Fig. 3). Open circles, visual benefit of correcting higher-order monochromatic aberrations (the ratio of open circles to × symbols in Fig. 3); solid circles, effect of correcting both higher-order monochromatic and chromatic aberrations (the ratio of filled circles to × symbols in Fig. 3), respectively. Continuous curves, theoretical visual benefit of correcting both higher-order monochromatic and chromatic aberrations (solid curve) and of correcting higher-order monochromatic aberrations only (dashed curve) and of correcting chromatic aberration only (dotted curve). The theoretical visual benefit was estimated by computing the modulation transfer function. To make the conditions of the theoretical computations as similar as possible to those of the contrast sensitivity measurements, the residual monochromatic aberrations due to the imperfection of the adaptive optics correction were taken into account in the calculations. The error bars represent ± one standard error.

chromatic aberrations as well as monochromatic aberrations provides an even larger improvement in contrast sensitivity. Avoiding chromatic aberration only, without correcting higher-order aberrations (open triangles), provides a smaller improvement than correcting higher-order monochromatic aberrations in white light. This implies that, for a larger pupil, the degrading effect of higher-order monochromatic aberrations on retinal image quality at the fovea is larger than that of chromatic aberration.

The symbols in Fig. 4 show the visual benefit of correcting various aberrations, defined as the ratio of contrast sensitivity with correction to that when only defocus and astigmatism are corrected. Open triangles show the improvement when chromatic aberration only is corrected, open circles the effect of correcting only monochromatic aberrations, and solid circles the improvement after correction of both monochromatic and chromatic aberrations. Contrast sensitivity when only monochromatic aberrations are corrected is improved by a factor of 2 on average at 16 and 24 c/deg. The maximum benefits for the two subjects are approximately a factor of 5 (YY) and 3.2 (GYY) on average at 16 and 24 c/deg when both monochromatic aberrations and chromatic aberration are corrected.

The solid, dashed and dotted curves in Fig. 4 represent the theoretical visual benefits as derived from the modulation transfer function calculations based on the measured wave aberrations. In the experimental measurements, the adaptive optics system does not perfectly correct all higher-order aberrations in the eye. Therefore we computed the modulation transfer function on the basis of the measured residual aberration with the Shack–Hartmann wave-front sensor after correcting the monochromatic aberrations. The calculations were based on the vertical modulation transfer function, since horizontal gratings were used in the contrast sensitivity measurements. For the various conditions, the theoretical expectation of the visual benefit is in reasonable, though by no means perfect, agreement with the experimental visual benefit from the contrast sensitivity measurements for

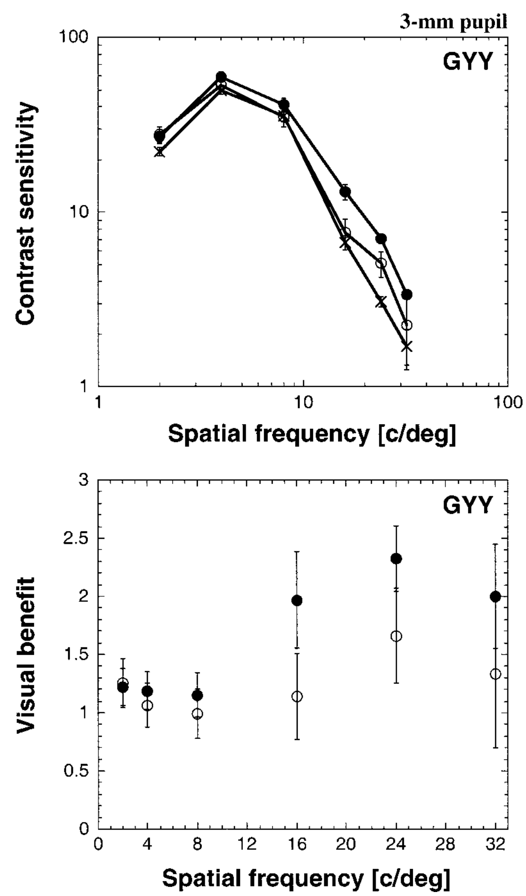

Fig. 5. Contrast sensitivity functions (upper) and the visual benefit (lower) for a 3-mm pupil under the same conditions as in Figs. 3 and 4. The error bars represent ± one standard error.

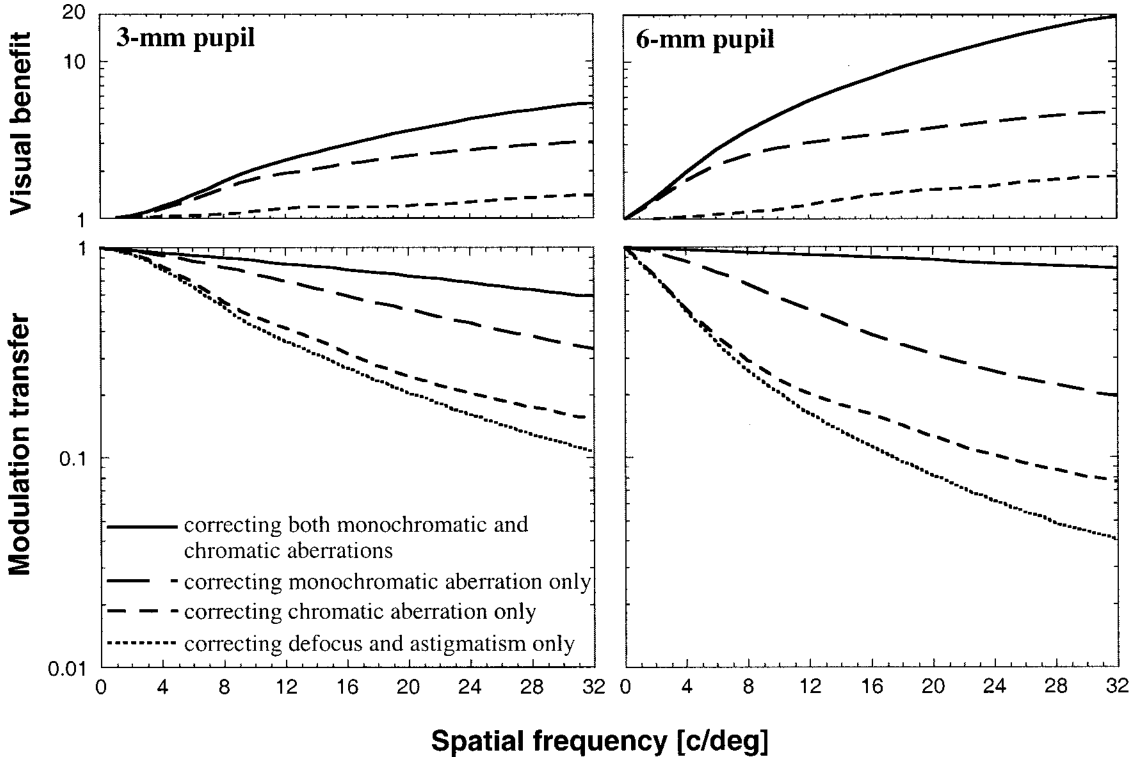

Fig. 6. Modulation transfer functions (lower) and the visual benefit (upper) of correcting various aberrations for a 3-mm (left) and a 6-mm (right) pupil when the correction of monochromatic and chromatic aberrations is perfect. This theoretical expectation is based on the measured wave aberrations of 17 normal human subjects. The amount of defocus was optimized for a 16-c/deg grating after setting astigmatism zero. A perfect correcting method was assumed for the calculation.

both subjects. One might anticipate that a better match might have been found if the wave-front sensor measurements had been taken concurrently with the contrast sensitivity measurements. Instead, they were collected before measuring contrast sensitivity, allowing time for changes in the wave aberration to play a role.

Contrast sensitivity was also measured for a 3-mm pupil, as shown in Fig. 5. A modest benefit of correcting higher-order aberrations and/or chromatic aberration can be seen at higher spatial frequencies, corresponding to a factor of 2 at 16 c/deg in monochromatic light. The visual benefit of either correcting the higher-order monochromatic aberrations only or correcting both chromatic and monochromatic aberrations is smaller than that for a 6-mm pupil. This is expected, because a smaller pupil includes less higher-order monochromatic aberration. In absolute terms, the contrast sensitivity for all conditions for a 3-mm pupil is comparable to that for the 6-mm pupil when adaptive optics are used. That is, although our adaptive optics system was capable of providing supernormal contrast sensitivity for a 6-mm pupil, it did not provide better contrast sensitivity than could be obtained with the pupil size of 3 mm that is optimal in normal viewing. The reasons for this require further investigation, especially since Liang *et al.*[8] obtained higher contrast sensitivity at 27.5 c/deg with adaptive optics and a 6-mm pupil than with any smaller pupil size. The present data were obtained with a generally longer time interval between adaptive correction and measurement. It is possible that changes in the wave aberration over time[22] make it difficult to maintain the benefit of the adaptive correction throughout lengthy contrast sensitivity measurements.

B. Theoretical Improvement in Contrast Sensitivity

Figure 6 shows the averaged modulation transfer functions and the maximum theoretical visual benefit computed from the measured wave aberrations of 17 subjects for a 3-mm and a 6-mm pupil. The modulation transfer functions were radially averaged. We assumed a perfect correction, i.e., no residual monochromatic aberrations or chromatic aberration after correction. There is little visual benefit (approximately 1.3 at 32 c/deg) in avoiding only chromatic aberration with a 3-mm pupil. A threefold improvement in contrast at 32 c/deg can be seen when only higher-order monochromatic aberrations were corrected.

For a 6-mm pupil, correcting monochromatic aberration provides a larger benefit by a factor of ~5 at middle and higher spatial frequencies. The theoretical benefit of correcting both chromatic and monochromatic aberration is substantially larger than that when only higher-order monochromatic aberrations are corrected. The theoretical benefits are larger than those measured empirically (Figs. 3 and 4). The lower experimental gain is due to the residual monochromatic aberrations, which were not corrected with our adaptive optics system. In theory, correcting both higher-order monochromatic and chromatic aberrations could improve contrast sensitivity by a factor of slightly less than 20 at 32 c/deg. When either the monochromatic aberration or the longitudinal chromatic aberration is corrected, the uncorrected aberration dilutes the benefit of correcting the other.[9,21] These results are similar to those reported by Guirao *et al.* on a larger population of eyes.[23]

C. Reducing the Effect of Chromatic Aberration

As the measured contrast sensitivity functions have illustrated in Figs. 3 and 4, chromatic aberration is a major factor that reduces the visual benefit of correcting higher-order monochromatic aberrations. Chromatic defocus can be avoided by using an achromatizing lens. However, such a lens consists of two or three different optical glasses, and each glass needs to have some thickness to produce proper divergence at each wavelength. The performance of the achromatizing lens is also very sensitive to alignment, making it impractical to use in everyday vision.

A second way of avoiding chromatic aberration in normal viewing is to narrow the spectral bandwidth transmitted by contact lenses or glasses. To examine the effect of reduced spectral bandwidth on retinal image quality, we computed the eye's modulation transfer function for different spectral bandwidths. Thibos *et al.*[24] calculated that the effect of longitudinal chromatic aberration on image contrast is roughly equivalent to ~0.2-D defocus in monochromatic light. The effect is relatively small because the eye is insensitive at the spectral extremes, where longitudinal chromatic aberration is largest. As a result, the visual benefit of correcting only chromatic aberration is small and monochromatic aberrations cause a larger reduction of retinal image quality in white light.[9] Our results also show, however, that the presence of monochromatic aberrations also greatly reduces the benefit of avoiding chromatic aberration.

We varied the spectral bandwidth of a hypothetical filter in ±10-nm-wavelength steps symmetrically with respect to the reference wavelength of 555 nm. The white-light modulation transfer function for a 6-mm pupil was calculated for different bandwidths from 20 to 290 nm.

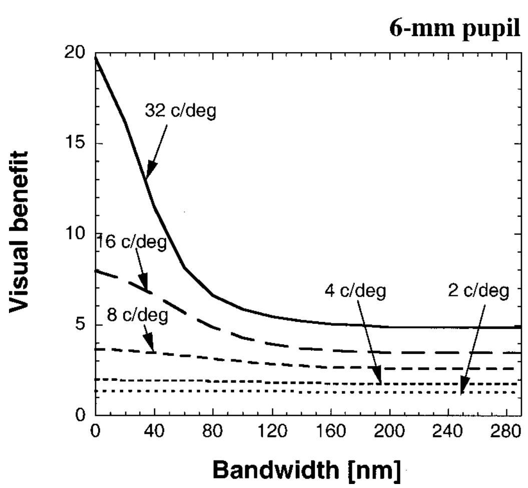

Fig. 7. Theoretical visual benefit for a 6-mm pupil produced by narrowing the spectral bandwidth of white light to reduce the effect of chromatic aberration. Perfect correction of monochromatic aberrations was assumed, and chromatic aberration remains but with an amount depending on spectral bandwidth. The bandwidth on the horizontal axis is chosen with ±10-nm wavelength steps around the reference wavelength of 555 nm.

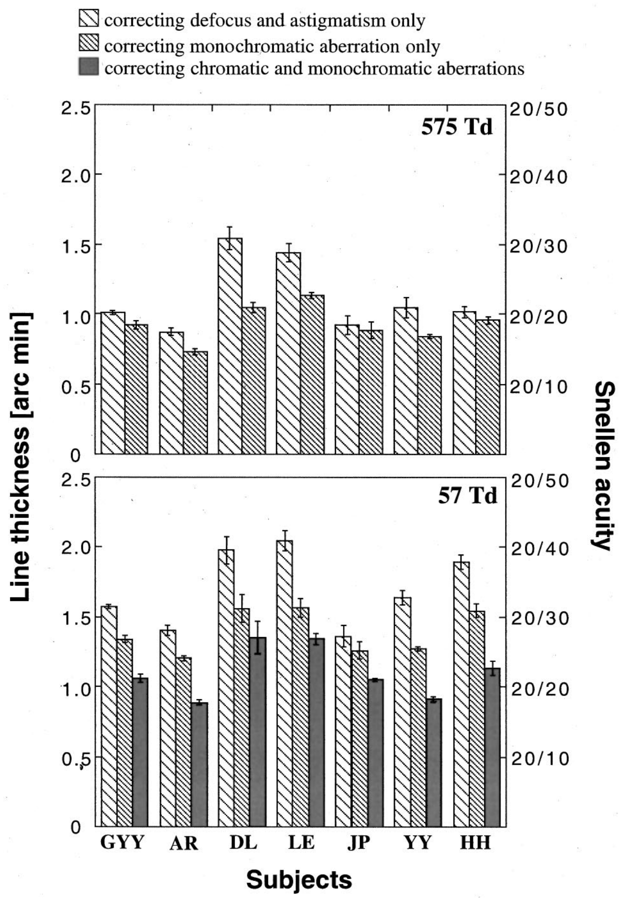

Fig. 8. Visual acuity (line thickness of the letter E target) measurements at two retinal illuminance levels, 575 and 57 Td when correcting various aberrations were corrected. The estimated Snellen acuity is also shown on the other vertical axis. The pupil size was 6-mm in diameter and the eyes were under cycloplegia. The error bars represent ± one standard error.

Visual benefit was computed from the modulation transfer functions for each spectral bandwidth, as shown in Fig. 7. In this calculation, we assumed that all monochromatic aberrations were perfectly corrected. The visual benefit is reduced as the bandwidth increases. For example, narrowing the bandwidth to 50 nm doubles the visual benefit at 32 c/deg compared with that with a full visible bandwidth, 290 nm. A faster initial reduction in visual benefit with bandwidth can be seen at higher spatial frequencies. Also, it can be seen that for lower spatial frequencies, 2 and 4 c/deg, there is no apparent difference in visual benefit of narrowing bandwidth.

D. Visual Acuity

Figure 8 shows visual acuity at a high (575 Td, upper) and a low (57 Td, lower) retinal illuminance with a 6-mm pupil. Correcting monochromatic aberrations improves visual acuity for the seven subjects by an average factor of 1.2 at 575 Td and 1.4 at 57 Td. Correcting both monochromatic and chromatic aberrations improves visual acuity by a factor of 1.6 at 57 Td. Therefore visual acuity as well as contrast sensitivity reveals the benefit of correcting higher-order monochromatic aberrations. As expected, the benefits for visual acuity are smaller than those for contrast sensitivity. This is a simple consequence of the steepness of the contrast sensitivity function at the high spatial frequencies relevant to the acuity task. A relatively large change in retinal image contrast produces a relatively small lateral shift in the steep contrast sensitivity function.[25] All subjects reported an obvious subjective improvement in image sharpness when higher-order aberrations were corrected.

The absolute values of visual acuity are not especially high compared with those reported elsewhere in the literature,[26] where the population mean is often ~20/18 at 100 cd/m^2 compared with a mean, 20/22.3 ± 20/5.2 (standard deviation), for our group at high light levels of 20.3 cd/m^2. One reason for this is that we used a high criterion of 82% correct to determine threshold. Had we used a lower criterion, such as 62.5% correct, which is more commonly used in four-alternative forced-choice procedures, the acuity values would be higher. The issue of the acuity criterion presumably has little or no effect on the visual benefit, because the underestimation of visual acuity occurs both before and after correction.

E. Theoretical Visual Benefit in Visual Acuity

Figure 9 shows the theoretical improvement in grating acuity, based on the modulation transfer functions for a 6-mm pupil shown in Fig. 6 and a neural contrast threshold curve measured by Williams.[27] Intersections of the modulation transfer functions and the neural contrast threshold curve predict grating acuity when higher-order monochromatic aberrations and/or chromatic aberration are corrected. The numbers in Fig. 9 correspond to the benefit in grating acuity that could be achieved by correcting various aberrations. Visual acuity is improved by a factor of 1.4 with correction of the higher-order monochromatic aberrations in white light. Correcting chromatic aberration alone provides a smaller improvement by a factor of 1.2. The measured improvement in illiterate E acuity from Fig. 8 is in qualitatively good agreement with this theoretical expectation, bearing in mind the complexity of comparing a theoretical expectation based on gratings with an empirical result based on letters.

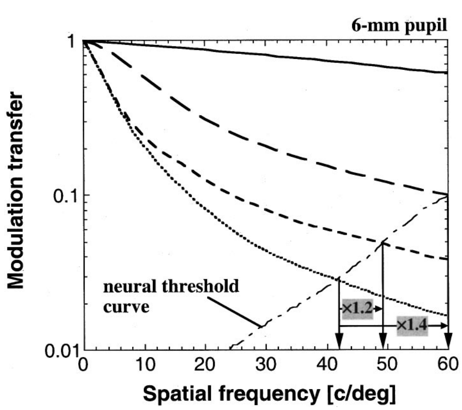

Fig. 9. Theoretical improvement in grating acuity when various aberrations were corrected. The same modulation transfer functions for a 6-mm pupil as those shown in Fig. 6 are used. Intersections between modulation transfer functions and the neural contrast threshold curve, from Williams,[27] provide cutoff spatial frequencies. Numbers in the figure correspond to theoretical visual benefit in visual acuity. Visual acuity is improved by factor of 1.2 and 1.4 by correcting chromatic aberration only and of correcting higher-order monochromatic aberrations only, respectively.

When both monochromatic and chromatic aberrations are corrected, the retinal image contrast is predicted to be high enough for aliasing by the foveal cone mosaic to be seen.[28,29] Based on cone spacing, the maximum spatial frequency the human can see without aliasing is approximately 60 c/deg for foveal vision. At lower spatial frequencies than this, the improvement in retinal image quality will enhance contrast sensitivity, but at higher spatial frequencies distortions in appearance should occur. We have not yet systematically explored this prediction, though one of our subjects reported seeing aliasing effects in foveal vision while viewing 90-c/deg gratings through adaptive optics.

4. DISCUSSION

There have been a number of studies describing the effect of chromatic aberration on retinal image quality. However, there has been relatively less work on the effect of higher-order monochromatic aberrations in addition to chromatic aberration. Thibos[30] computed the white-light modulation transfer functions using an eye model to evaluate the effect of transverse chromatic aberration on retinal image quality. Van Meeteren[14] also computed the white-light modulation transfer functions and compared them with experimental results. Marcos *et al.*[31] measured chromatic aberration as well as monochromatic aberrations and computed retinal image quality on the basis of the measured aberrations. Liang *et al.*[8] found that, for a 6-mm pupil, contrast sensitivity was improved by a factor of 6 at 27.5 c/deg by correcting monochromatic aberration in monochromatic light. This improvement is higher than that in this study. The discrepancy may be due to the fact that the visual benefit depends on the amount of higher-order monochromatic aberrations, which varies from subject to subject. Guirao *et al.*[23] estimated the visual benefit of correcting higher-order aberrations for a large population of eyes and found comparable individual differences. They showed that some people would benefit hardly at all from higher-order correction, while others with “normal” vision would see a significant benefit. If one has a relatively smaller amount of higher-order aberration, the benefit of customized correction would be small even with perfect correction.

The wave aberration of the eye is the main factor that limits spatial vision when the pupil is large. What, then, is the ultimate limit in visual acuity that could be achieved in an aberration-free eye? In the diffraction-limited eye, the ability of the brain to recover information from the discrete photoreceptor mosaic limits visual resolution. The photoreceptor spacing at the fovea ranges from 0.42 to 0.54 arc min (0.51 arc min on average).[29,28,32–36] This corresponds reasonably well with measurements of interference fringe acuity.[27,37] It is somewhat more difficult to predict letter acuity from cone spacing estimates because of the broad spatial-frequency spectra of the letters. Adopting the simplistic and probably incorrect assumption that a letter acuity of

20/20 corresponds to a grating acuity of 30 c/deg, letter acuity limits based on cone spacing would range from 20/8.4 to 20/10.8.

Williams *et al.*[38] and Charman[39] recently pointed out that even if correction methods completely removed the eye's monochromatic aberration, there could be a number of factors that might reduce the visual benefit. A smaller pupil in bright-light conditions is capable of a smaller potential improvement than is a larger pupil. Chromatic aberration is difficult to correct as we discussed above. However, as noted earlier in the paper, one possible method to correct chromatic aberration could be glasses or contact lenses tinted to reduce the bandwidth of the white-light spectrum, although this would produce a reduction in color information and luminance as well as in depth of field. Accommodative lag in dim light produces more error in focus and less visual benefit of correcting higher-order aberrations. Also, the short-term temporal instability of the monochromatic aberrations and their long-term changes with age could reduce the visual benefit.

Campbell and Gubisch[21] measured contrast sensitivity in monochromatic and white light and reached the important conclusion that, for a 4-mm pupil, there was no improvement in contrast sensitivity in monochromatic light. They attributed this in part to an effect of spherical aberration that increases with pupil diameter. Our results show that not only spherical aberration, but all higher-order aberrations, tends to obscure the effects of chromatic aberration on vision. This is subjectively obvious to subjects when they view targets in which monochromatic aberrations have been corrected. Our subjects found that chromatic fringes, which are normally masked by the achromatic blur caused by monochromatic aberrations, are more easily seen when the monochromatic aberrations have been corrected with adaptive optics. So while edges appear sharper, they also can have more obvious chromatic fringing produced by chromatic aberration.

5. CONCLUSION

We measured improvements in contrast sensitivity and visual acuity after correcting the higher-order monochromatic aberrations beyond defocus and astigmatism in monochromatic and white light. The results show reliable improvements in contrast sensitivity and visual acuity when higher-order aberrations are corrected. The measurements are in good agreement with theoretical expectations based on the measured wave-front aberrations and chromatic aberrations. It remains to be seen whether these same benefits can be achieved with contact lenses, intraocular lenses, or laser refractive surgery, but the results leave no doubt that improvement in normal vision over that provided by conventional correction is possible. Correcting both the monochromatic and the chromatic aberrations provides substantially larger benefit than simply correcting one or the other. When the monochromatic aberrations were corrected in white light, the visual benefit was reduced by chromatic aberration. A perfect method for correcting both monochromatic and chromatic aberration in an eye could conceivably provide a 20-fold improvement in contrast sensitivity at 32 c/deg in the perfect eye, though depth of field would be compromised. By narrowing the spectral bandwidth of white light, visual performance can be improved, although the color information and luminance information about the object are reduced. The challenge remains to come closer to the theoretical limit with methods that can improve vision in normal, everyday viewing conditions.

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