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Role of high-order aberrations in senescent changes in spatial vision

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Abstract

The contributions of optical and neural factors to age-related losses in spatial vision are not fully understood. We used closed-loop adaptive optics to test the visual benefit of correcting monochromatic high-order aberrations (HOAs) on spatial vision for observers ranging in age from 18 to 81 years. Contrast sensitivity was measured monocularly using a two-alternative forced-choice (2AFC) procedure for sinusoidal gratings over 6 mm and 3 mm pupil diameters. Visual acuity was measured using a spatial 4AFC procedure. Over a 6 mm pupil, young observers showed a large benefit of AO at high spatial frequencies, whereas older observers exhibited the greatest benefit at middle spatial frequencies, plus a significantly larger increase in visual acuity. When age-related miosis is controlled, young and old observers exhibited a similar benefit of AO for spatial vision. An increase in HOAs cannot account for the complete senescent decline in spatial vision. These results may indicate a larger role of additional optical factors when the impact of HOAs is removed, but also lend support for the importance of neural factors in age-related changes in spatial vision.

Keywords

aging; contrast sensitivity; spatial vision; adaptive optics; high-order aberration

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Introduction

Contrast sensitivity has been widely used to characterize the integrity of visual mechanisms sensitive to luminance variations in a scene. Research indicates that despite the absence of ocular and neurological disease, contrast sensitivity is compromised with normal aging. At photopic levels, senescent losses are typically greatest at middle to high spatial frequencies (Derefeldt, Lennerstrand, & Lundh, 1979; Elliott, 1987; Owsley, Sekuler, & Siemsen, 1983; Tulunay-Keesey, Ver Hoeve, & Terkla-McGrane, 1988), and become more pronounced as illumination decreases (Sloane, Owsley, & Alvarez, 1988a; Sloane, Owsley, & Jackson, 1988b). The mechanisms responsible for the reduction in contrast sensitivity are not fully understood, with evidence for the importance of both optical (Burton, Owsley, & Sloane, 1993; Owsley et al., 1983), and neural origins (Elliott, 1987; Elliott, Whitaker, & MacVeigh, 1990; Morrison & McGrath, 1985).

Senescent changes in the optics of the eye that reduce the retinal illuminance include a reduction in pupil size (Winn, Whitaker, Elliott, & Phillips, 1994) and increased ocular media density (Weale, 1988; Werner, 1982). These changes are accompanied by increased light scatter (Hennelly, Barbur, Edgar, & Woodward, 1998) and will have deleterious effects on retinal image quality. However, the degree of contrast sensitivity decline attributable to optical factors is not clear. Optical contributions to senescent changes in spatial vision have been explored with young observers by simulating the reduced retinal illumination present in older eyes. Using this method, it has been shown that young observers maintain superior contrast sensitivity when pupil size is controlled (Elliott et al., 1990; Sloane et al., 1988a), when retinal illumination is decreased through a neutral density filter (Elliott et al., 1990; Owsley et al., 1983), and when additional intraocular scatter is introduced (Whitaker & Elliott, 1992). These findings point to the presence of additional factors which serve to limit spatial vision with increased age.

A further reduction in retinal image quality is produced by a decline in the modulation transfer function (MTF) across the life span (Artal, Ferro, Miranda, & Navarro, 1993; Calver, Cox, & Elliott, 1999; Guirao et al., 1999; McLellan, Marcos, & Burns, 2001), most of which is thought to be a product of an increase in the 3rd and 4th-order wave aberrations, corresponding to coma-like and spherical aberration (Applegate, Donnelly, Marsack, Koenig, & Pesudovs, 2007; Calver et al., 1999). Some reports indicate that changes in the 5th through 7th-order, corresponding to irregular aberrations, also contribute to age-related declines in spatial vision (Brunette, Bueno, Parent, Hamam, & Simonet, 2003; McLellan et al., 2001). The cornea may account for the increase in coma-like aberrations due to a loss of symmetry (Oshika, Klyce, Applegate, & Howland, 1999), while the lens may account for changes in spherical aberration (Glasser & Campbell, 1998). However, these individual changes are too small to explain the overall reduction in the MTF. Instead, an increasing imbalance in the aberrations of the cornea and lens may be responsible for the majority of the decline (Alió, Schimchak, Negri, & Montés-Micó, 2005; Artal, Berrio, Guirao, & Piers, 2002).

The relative contribution of age-related increases in HOAs to losses in contrast sensitivity has not been measured directly. Several investigations have attempted to link senescent contrast sensitivity loss to increased HOAs, but the results have not been conclusive. Artal et al. (1993) found the decrease in MTF for older observers corresponded well to the loss of contrast sensitivity reported by Owsley et al. (1983), but only at spatial frequencies below 5 c/deg. A more recent study has correlated reduced contrast sensitivity directly to the degree of coma-like aberrations irrespective of age (Oshika, Okamoto, Samejima, Tokunaga, & Miyata, 2006), but this study used a small number of older adults (all under the age of 60) and reported their results in terms of the area under the log contrast sensitivity function, obscuring any spatial-frequency dependent effects.

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With adaptive optics (AO), it is possible to not only measure, but also correct HOAs in the eye. One of the first studies illustrating the benefit of AO reported a 6-fold increase in contrast sensitivity at 27.5 c/deg (Liang, Williams, & Miller, 1997). The two observers in this study were also able to resolve a 55 c/deg square-wave grating with AO compensation, which is normally undetectable with only a sphere and cylinder correction. These results have been replicated in two other observers (Yoon & Williams, 2002), both showing at least a 2-fold increase in contrast sensitivity at 24 c/deg, indicating that HOAs reduce the MTF of the eye, and, in turn, limit spatial vision to a large degree in young, healthy eyes.

AO holds promise as a useful tool to separate optical and neural limits on spatial vision as they change across the life span. If underlying neural structures are compromised in senescence, correcting HOAs in an older eye may not produce a significant increase in spatial vision. For example, an age-related reduction in ganglion cell number (Curcio & Drucker, 1993; Gao & Hollyfield, 1992) will reduce the sampling efficiency at the retina and may place a hard limit on visual perception at high-spatial frequencies. The aim of this study was therefore to evaluate the benefit of correcting HOAs on the spatial vision performance in a group of older observers. Contrast sensitivity functions were collected with and without AO compensation for both young and older observers with a dilated pupil. To evaluate the role of HOAs under more natural viewing conditions when pupil diameter is reduced for older observers, additional contrast sensitivity measures were collected over a 3 mm pupil. The contribution of HOAs on the reduced visual acuity typically present in older eyes (Elliott, Yang, & Whitaker, 1995; Owsley et al., 1983) was also evaluated.

Methods

Observers

Ten younger (mean age of 23.4 years, range 18–29 years, 6 male) and 10 older (mean age of 75.9 years, range 65–82 years, 5 male) phakic observers participated in the experiment. Observers were tested monocularily using their preferred eye (i.e., the eye with superior visual acuity and health, or by individual preference). Refractive errors did not exceed ±4 diopters (D) sphere or ±2.25 D cylinder for any observer (average of −0.8 D sphere and 0.3 D cylinder for young observers; 0.16 D sphere and 0.9 D cylinder for older observers). Corrected Snellen acuity was better than 20/25 in the tested eye. The presence of abnormal ocular media and retinal disease was ruled out for each observer by conventional eye exam, including a slit lamp examination and ophthalmoscopy. It should be noted that the conventional eye exam does not rule out subtle effects of intraocular light scatter. Color fundus photographs of the macula and optic disc were evaluated by a retinal specialist. All but one participant had no more drusen than is considered normal for their age and no abnormal vascular, retinal, choriodal or optic nerve findings. One young observer had a few hard drusen near the fovea, but no other signs of abnormal structure or function. All observers had intraocular pressure of ≤22 mm Hg, and all had normal color vision as measured with the Farnsworth D15 Color Vision Test. Written informed consent was obtained following the Tenets of Helsinki and with approval of the Institutional Review Board of the University of California, Davis, School of Medicine.

Wavefront sensing and correction

Our AO system has been described in detail by Choi et al. (2006). The psychophysics path of this system is illustrated in Figure 1. Wavefront aberrations were measured using a Shack-Hartmann wave-front sensor (WFS), with a 20 × 20 lenslet array (24-mm focal length) over a 7 mm pupil. A superluminescent diode (SLD) operating at 835 ± 20 nm was used to form a WFS beacon on the retina. Aberrations were corrected over a 7 mm pupil with a 68 mm diameter, 109 actuator, continuous surface deformable mirror (DM, Litton ITEK), at a plane conjugate to the observer's pupil. The DM has an approximate mirror stroke of ±2 μm and was

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operated using direct slope control. The wavefront was sampled at 20 Hz, allowing a closed-loop bandwidth of ~0.9 Hz for a gain of 30%. There is a possible source of error in the non-common path (which has not been quantified), but this error should be minimal. Observer's pupil position was monitored continuously during testing through the WFS centroid display, and all AO compensation measures were carried out using closed-loop dynamic correction.

Contrast sensitivity

Stimuli were viewed through a 6 mm aperture in a plane conjugate with the eye's pupil (pupil plane in Figure 1) and were presented on a gamma corrected, custom built, 25 cm monochrome CRT display (peak λ = 550 nm, Moraine Displays), driven by a Macintosh G4 computer with a video card providing 10-bit resolution. Prior to the experiment, each observer adapted to a uniform field of 50 cd/m^2 (luminance measured at the observer's pupil plane) for 5 min. Contrast sensitivity was measured using Gabor patches (sinusoidally modulated gratings windowed by a Gaussian envelope with a standard deviation of 0.375°) and subtending 1.5° (144 pixels per degree). Mean luminance was the same as the adaptation field. Contrast thresholds were measured for vertical Gabor patches of 0.55, 1.125, 2.25, 4.5, 9 and 18 c/deg. It was necessary to use a fixed size to confine the stimuli to the isoplanatic patch of retina. As a result, spatial frequencies of 0.55 and 1.125 did have a broader spatial frequency spectrum due to fewer cycles (in fact, the lowest spatial frequency was presented with less than 1 full cycle). A 2AFC psychophysical method was combined with a QUEST procedure and 2 interleaved staircases (Watson & Pelli, 1983). The QUEST procedure terminated when the standard deviation of the threshold estimate dropped below 0.05 log units of contrast after a minimum of 45 trials (per staircase). Stimuli were presented for 1 sec with a sine-wave modulation at 1 Hz, providing a single temporal contrast cycle. Thresholds for each spatial frequency were measured with and without AO compensation in a random order. Experimental software was written in MATLAB 5.2.1 using the Psychophysics Toolbox extensions (Brainard, 1997;Pelli, 1997).

The eye chosen for testing was dilated with 1% tropicamide and 2.5% phenylephrine, and head movements were minimized with the use of a bite bar. Trial lenses were used to correct sphere and cylinder for all experimental conditions to reduce the 2nd-order Zernike terms (defocus and astigmatism). This was to done to prevent the 2nd-order aberrations from dominating the stroke (dynamic range) of the DM. Due to the wavelength difference between the SLD used for wavefront sensing and the CRT, a trial lens of −0.75 D was placed at the pupil plane in the non-common path to correct for chromatic aberration (calculations based on a reduced-eye model; Thibos, Ye, Zhang, & Bradley, 1992). It has been previously noted that with a large degree of HOAs, additional defocus may actually improve optical quality (Liang et al., 1997). Because trial lenses at the eye were chosen to reduce the 2nd-order Zernike terms, some observers preferred a slightly smaller or larger defocus power (range of −0.25 D to +0.5 D). The total defocus power for each observer was determined based on their best corrected acuity with a Landolt C chart presented on the monochrome CRT while varying the trial lenses (accuracy within ¼ D) in the pupil plane of the non-common path. During trials with AO correction, an additional −0.5 D was placed at the pupil plane for most observers to achieve maximum acuity with the DM in closed-loop.

The effect of individual trial lens correction on stimulus magnification (and spatial frequency) was measured and found to shift spatial frequency by factors ranging from 0.96 to 1.17. The data were corrected for this effect by fitting the contrast sensitivity function with a double-exponential using the scaled spatial frequencies presented at the retina. The fitted values from the contrast sensitivity function at the intended spatial frequencies of 0.55, 1.125, 2.25, 4.5, 9 and 18 c/deg were used for statistical analysis.

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Acuity measurements

Visual acuity was measured for 6 of the young and 6 of the older observers with and without AO compensation. Custom software was written to replicate the Freiburg Visual Acuity test (Bach, 1996) in MATLAB 5.2.1 using the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997). Stimuli were presented on the monochrome CRT as increments (90 cd/m^2) on a dark background in one of 4 orientations: 0, 90, 180 or 270 deg. The task for the observer was to indicate the orientation of each stimulus by pressing one of four keys. A session consisted of a fixed number (22) of presentations during which the minimum resolvable angle of each randomly oriented Landolt-C was determined by a QUEST procedure. Visual acuity for the Landolt-C is defined as the minimum angle of resolution for the gap specified in minutes of arc. Measurements were obtained on the same day as the contrast sensitivity testing. The mean of 6 staircases was used as the observer's visual acuity.

Controlling for age-related miosis

In natural viewing conditions, the increased HOAs present in older eyes may have less influence on spatial vision performance due to age-related miosis (Applegate et al., 2007; Calver et al., 1999; Guirao et al., 1999). Pupil size decreases linearly with age after adolescence (Winn et al., 1994), which may serve to normalize retinal image quality by counteracting the effect of HOAs and increasing depth of focus. This poses a potential limitation on the application of our findings to natural viewing conditions when contrast sensitivity is measured through a 6 mm pupil. Therefore, we obtained an additional measure of contrast sensitivity over a 3 mm pupil for several of our observers.

Ancillary data were obtained with 4 young (mean age of 24.25 years, range 18–29 years, 2 male) and 4 older (mean age of 76.5 years, range 65–82 years, 1 male) observers, each recruited from the first experimental condition. Experimental set up and testing procedures were the same as the first condition, however the stimuli were viewed through a 3 mm pupil aperture at the pupil plane. Visual acuity was measured for all 8 observers.

Theoretical visual benefit

For a direct comparison between the optical improvement and the improvement in contrast sensitivity measured with AO compensation, we calculated a theoretical visual benefit (TVB). TVB is defined as the ratio of the degraded image contrast with AO correction over image contrast without AO correction (only sphere and cylinder correction) for each observer's individual aberrations. A value greater than 1 indicates image contrast on the retina was greater during AO correction than with defocus and astigmatism correction alone, a value of 1 indicates no change, and a value less than 1 indicates inferior image contrast during AO correction. The degraded image contrast was therefore calculated twice for each observer: once for HOAs present with trial lenses and no AO correction (including any residual defocus and astigmatism), and once for with AO correction including any residual aberrations present in the eye. Aberrations present due to the imperfections in the alignment of the AO set up were included in the calculations. Although these were minimal, measures of contrast sensitivity may be affected by these imperfections.

Studies linking the presence of HOAs to spatial vision have typically used the MTF as a reflection of retinal image quality (Guirao et al., 1999; Guirao, Porter, Williams, & Cox, 2002; Yoon & Williams, 2002). The MTF, however, does not include the phase transfer function (PTF), an important predictor of image quality at lower spatial frequencies with a broad spectrum, especially with a large pupil (Charman & Walsh, 1985). Although the MTF is a sufficient predictor of degraded contrast for single spatial frequencies, the PTF will predict how well each frequency is transferred to the retinal image (Williams & Hofer, 2003).

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Therefore, we used the point-spread function (PSF) to predict the degraded image contrast because both the MTF and PTF are represented in this measure.

The degraded image contrast was calculated as follows. For each observer, the centroid displacements of the WFS were recorded for a short period of time, providing a series of wavefronts that were reconstructed using a Fourier-based reconstructor (Poyneer, Gavel, & Brase, 2002). Each recording yielded approximately 70 frames both with and without AO correction for each observer on each day of testing. Individual wavefronts were reconstructed over a 7 mm pupil, and then cropped in size to remove the invalid sub apertures and to approximate the 6 mm (or 3 mm) viewing condition. After the final reconstruction, any frame where the observer clearly blinked was removed. The monochromatic PSF was calculated over each new wavefront frame by taking the Fourier transformation of the complex pupil function, and then averaging over the total number of frames.

The PSF was then resampled to match the physical size of the Gabor patterns. Single vertical spatial frequencies of 0.55, 1.125, 2.25, 4.5, 9 and 18 c/deg were used to produce 6 sample Gabor patterns generated at 99% Michelson contrast. Each sample subtended 1.5° with 144 pixels per degree. For each pupil size, the ideal PSF was calculated using the Raleigh criterion at a wavelength of 835 nm. The calculated spot size was converted from radians to degrees, then equated to match our stimulus by converting degrees to pixels.

The resampled PSF was convolved with each sample Gabor pattern to obtain the degraded image contrast. The convolution was calculated through an inverse Fourier Transformation of the product of the Fourier Transformation of each PSF and Gabor pattern. The convolved pattern was normalized by dividing by the maximum contrast. Degraded image Michelson contrast from each convolved pattern was averaged across all frames for both with and without AO compensation. Equation 1 summarizes the degraded image contrast calculation.

$$\text{Degraded image contrast} = \sum [\, \Im^{-1}(|\Im[\text{aperture} * e^{(i2\pi * \text{wavefront}/\lambda)}]|)^2 * \Im(\text{Gabor})], \quad (1)$$

where the aperture is the physical aperture, $\lambda = 835$, and the Gabor is the stimulus. TVB is the ratio of the degraded image contrast after AO compensation to that with no AO compensation.

Results

Optical quality of the eye

Individual Zernike modes up to the 6th radial order are presented in Figure 2 as the absolute average for both age groups over a 6 mm pupil, defined according to the OSA convention (Thibos, Applegate, Schwiegerling, & Webb, 2000). With trial lenses in place, younger observers had an average of 0.06 ± 0.03 D residual defocus (0.10 ± 0.02 μm Z_2^0) and 0.03 ± 0.003 D residual astigmatism (0.02 ± 0.003 μm Z_2^{-2} and 0.02 ± 0.003 μm Z_2^2). Older observers had 0.07 ± 0.01 D of residual defocus (0.12 ± 0.02 μm Z_2^0) and 0.04 ± 0.007 D of astigmatism (0.03 ± 0.007 μm Z_2^{-2} and 0.03 ± 0.005 μm Z_2^2). Older observers had a larger degree of HOAs overall than younger observers, especially for coma like modes and spherical aberration. This observation is consistent with previous reports (Applegate et al., 2007;Calver et al., 1999).

All observers showed a significant improvement in retinal image quality with AO compensation. Due to the increased HOAs present in the older eye (Applegate et al., 2007; Calver et al., 1999), the AO correction did not produce retinal image quality as good as that

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resulting from AO correction with young observers. Table 1 displays the mean and standard error of the optical quality metrics for both age groups calculated over a 6 mm pupil. These metrics include: the residual wavefront RMS with and without AO compensation, the Strehl ratio with AO compensation (calculated from the PSF), and the improvement in peak-to-valley wavefront error with AO compensation. The improvement in the Strehl ratio with and without AO compensation was not significantly different for the two age groups, increasing by a factor of 5.16 ± 0.89 for young, and 6.67 ± 0.9 for older observers. There was also no significant difference between young and old in the overall reduction in peak-to-valley wavefront error with AO correction.

Contrast sensitivity

Due to the large variation in the degree and type of HOAs between observers (and the ability to correct them), it is expected that the benefit of AO will vary. Figure 3 presents an example of the variation in contrast sensitivity among four observers, 2 younger and 2 older. Based on the factor of improvement in the Strehl ratio and the decrease in peak-to-valley wavefront error, one observer in each age group was chosen as an example of a superior case of AO correction (JF and AO), and one observer in each age group represents a case of poorer AO correction (MB and MP). Table 2 summarizes the optical quality metrics for each observer. These observers represent the range of variation seen in AO compensation during the experimental testing and show how these variations may influence perceptual measures of contrast sensitivity.

Average contrast sensitivity with and without AO compensation for the two age groups is presented in Figure 4. With AO compensation, clear improvements in contrast sensitivity can be seen for both age groups ($F_{(1,107)} = 24.90$, $p < 0.001$ MANOVA). Baseline contrast sensitivity (i.e., without AO compensation but with sphere and cylinder correction) for both groups is lower than that reported in previous literature (Owsley et al., 1983;Sloane et al., 1988a;Tulunay-Keesey et al., 1988). This could be a result of our lower retinal illuminance, the small size of our stimulus, and/or the use of a sine-wave temporal modulation during stimulus presentation. In addition, the presence of non-common path error of the AO system may reduce the contrast of each stimulus before it reaches the eye, but this loss would be consistent for both conditions and should not be a concern overall.

For a closer comparison of the benefit of AO compensation, the change in contrast sensitivity observed with AO compensation (CSF change) is plotted with the TVB in Figure 5. The CSF change is defined as the ratio of contrast sensitivity with AO compensation to that without AO compensation (only sphere and cylinder correction), therefore a value greater than 1 indicates a benefit of AO, a value equal to 1 indicates no change, and a value less than 1 indicates inferior contrast sensitivity with AO compensation. At low spatial frequencies, young and old observers showed the same degree of benefit, but at 4.5 c/deg, the patterns diverge. Older observers appear to have gained the most benefit of AO compensation at middle spatial frequencies (4.5 and 9 c/deg), while young observers gained more as the spatial frequency increased, showing a 2.5-fold increase in contrast sensitivity at 18 c/deg. However, due to the large variability within each age group, the main effect of age was not significant ($F_{(1,107)} = 0.02$ $p < 0.90$ MANOVA) nor was there a significant interaction between benefit at different spatial frequencies and age ($F_{(1,107)} = 2.35$ $p < 0.13$ MANOVA).

When these data are compared to the TVB, an interesting pattern emerges. Both age groups showed a similar degree of TVB, a further indication that AO correction was consistent for both age groups. Young observers show a close match between the CSF change and TVB, evidence that a decrease in HOAs and wavefront error leads to a comparable improvement in contrast sensitivity. On the other hand, older observers show a larger increase in CSF change than in TVB at 4.5 and 9 c/deg, and a reduced benefit at 18 c/deg.

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One possibility for the mismatch seen for older observers is that the TVB does not represent the wide variation in AO correction across time. TVB is calculated from one short record obtained during testing each day, rather than the entire AO system operation over the lengthy contrast sensitivity measures. AO performance tended to show a larger variation across time for older observers, likely due to their need for more frequent breaks during testing and the greater demands on the AO control loop due to larger head movements. The short, daily record of WFS lenslet displacements may not capture these wide variations.

A simple explanation for these results is that older observers have more optical aberrations to correct, and therefore more to gain with AO compensation. Older observers had a larger degree of residual HOAs, so neural limits on spatial vision performance may not have been reached. For young observers, neural limits achieved with lower overall correction may provide an upper limit to the improvement attainable in contrast sensitivity. Another consideration is that the interaction of different Zernike terms can significantly impact spatial vision performance. For instance, simulations comparing RMS wavefront error and visual acuity indicate a larger reduction in performance when RMS error is weighted in modes near the center of each radial order rather than modes near the edge (Applegate, Ballentine, Gross, Sarver, & Sarver, 2003a; Applegate, Sarver, & Khemsara, 2002), even when total RMS error remains constant (Applegate, Marsack, Ramos, & Sarver, 2003b). It is possible that the specific increase of coma-like and spherical aberration in our older population has a larger impact on contrast sensitivity, increasing the improvement with AO compensation. In fact, a large degree of coma-like aberrations has been linked directly with a reduction in spatial vision performance irrespective of age (Oshika et al., 2006).

The purpose of this study was to compare the improvement in contrast sensitivity for young and older observers relative to the reduction in HOAs, but this analysis does not account for factors that may play a large role in the *functional* PSF. For instance, psychophysical measures of intraocular scatter indicate that a point source will fall on a retinal area five times larger in a 69-year-old observer compared to a younger adult (Westheimer & Liang, 1995). This additional scatter will produce a veil over the retinal image, widening the skirt of the PSF, and will play the largest role at high-spatial frequencies and at threshold contrast levels, such as those used to obtain contrast sensitivity measures (Williams & Hofer, 2003). While most intraocular scatter is a product of optical changes not involving HOAs, the direct consequence of scatter on visual perception is not well understood. It is possible that the reduction of HOAs could influence other optical elements contained within the functional PSF, which may have a significant impact on perception that would not be seen in young adults.

What is important to note, however, is that even with AO compensation, contrast sensitivity was still reduced for the older age group when compared to the younger age group with no AO compensation. That is, older observers had better retinal image quality with AO compensation than young observers had without AO compensation, yet the age-related decline in contrast sensitivity is still apparent. To highlight this point, the dotted blue curve in Figure 5 shows the ratio of degraded image contrast for older observers with AO to the degraded image contrast for younger observers without AO compensation. If HOAs are the only limiting factor in contrast sensitivity, older observers with AO compensation should have higher contrast sensitivity than young observers with no AO compensation, but this is not the case.

Visual acuity

Figure 6 presents the visual acuity change with AO compensation for young and older observers. All observers showed an improvement with AO compensation ($F_{(1,10)} = 46.47$ $p < 0.0001$ MANOVA) with the exception of one young observer who showed a slight decline in visual acuity. Overall, older observers had a lower visual acuity when compared to young observers, consistent with previous research (Elliott et al., 1995), but this may also be a result

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of the larger increase in HOAs present for older observers with a large pupil (Applegate et al., 2007).

Generally, older observers showed a larger improvement in visual acuity with AO compensation when compared to young observers ($F_{(1,10)} = 11.91$ $p < 0.006$ MANOVA) increasing by a factor of 1.21 ± 0.04 and 1.08 ± 0.03, respectively. Because there were more HOAs in the older eye, there is the opportunity for larger improvement. The increased benefit in the functional PSF with AO compensation may also be responsible, but this increase will not be as substantial with suprathreshold stimuli. The interaction among different Zernike terms also provides a potential explanation for the larger improvement in older adults (Oshika et al., 2006).

The observed acuity change is slightly lower than previous reports using AO to measure acuity. Yoon and Williams (2002) report a 1.2 factor improvement in acuity measured at 2.8 log trolands (20 cd/m^2), while Rossi, Weiser, Tarrant, and Roorda (2007) show an estimated 1.5 factor improvement at 6.8 log trolands (227,280 cd/m^2). The age of the seven observers of Yoon and Williams (2002) was not reported, but their reported increase in acuity is consistent with that achieved by our older observers.

Controlling for age-related miosis

Figure 7 displays the Zernike coefficients (third and fourth radial order shown) calculated over the resampled wavefront for the 3 mm pupil. Table 3 summarizes the mean and standard error of the optical quality metrics for each age group. Figure 8 (left) shows the average contrast sensitivity for the two age groups measured over a 3 mm pupil with and without AO compensation. Curve fits for AO compensation were again used to scale the data depending on the magnification change caused by the placement of the additional trial lens at the pupil plane (magnification range of 0.96–1.12). All observers exhibited higher contrast sensitivity with AO compensation ($F_{(1,44)} = 4.26$ $p < 0.05$ MANOVA), but the benefit of AO is less for both age groups than observed for the 6 mm pupil. In addition, there is no significant difference between the benefit of AO for the two age groups ($F_{(1,44)} = 1.19$ $p < 0.29$ MANOVA). This is clearly shown in Figure 8 (right), where the CSF change is compared with the TVB. In this case, the benefit of AO compensation increases with an increase in spatial frequency for both age groups.

TVB is also reduced with the smaller pupil. This is to be expected as diffraction will dominate the optical PSF with the small pupil size. Our TVB is similar to other theoretical simulations using differences in the MTF in a larger population over a 3 mm pupil (Guirao et al., 1999; Yoon & Williams, 2002). In this case, both age groups show a larger CSF change than the theoretical benefit would predict. When compared to one previous report of AO compensation over a 3 mm pupil (Yoon & Williams, 2002), the CSF change is slightly larger for our young observers, however, the single observer in Yoon and Williams (2002) also showed a lower benefit of AO compensation with a 6 mm pupil compared to our population.

For a more direct comparison between the 6 and 3 mm pupil conditions, average contrast sensitivity over the 6 mm pupil was compared for the 4 young and 4 older observers tested in both conditions. These data are presented in Figure 9, along with the average contrast sensitivity obtained for the 3 mm pupil condition. Without AO compensation and a 3 mm pupil, young observers showed reduced contrast sensitivity when compared to the corresponding 6 mm condition (Figure 9, top), while older observers showed an improvement (Figure 9, middle). With a 3 mm pupil, retinal illumination is reduced, which may explain the decrease in sensitivity for young observers. However, the improvement in contrast sensitivity seen for older observers is likely due to the reduction in HOAs, as well as an increased depth of focus inherent with a smaller pupil, which may override the reduction in retinal illumination.

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Interestingly, contrast sensitivity with AO compensation for the older observers was similar for both pupil sizes. This similarity could result from a balance of the optical factors for the two different pupil sizes. That is, with a 6 mm pupil, the higher retinal illuminance will increase the benefit, but the presence of more residual HOAs will reduce that benefit. With a 3 mm pupil, the reduction in retinal illuminance will be balanced by the reduction in HOAs. It is also possible that the contrast sensitivity measures with AO compensation may be approaching a senescent neural upper limit on spatial vision performance.

A 3 mm pupil aperture was used as an estimate of a more natural pupil size for older observers, but this is not necessarily a natural pupil size for young observers. Therefore, Figure 9 (bottom) presents contrast sensitivity for the two age groups measured over their expected natural pupil size: 3 mm for the older age group, and 6 mm for the younger age group. Even with AO compensation, contrast sensitivity is slightly reduced for older observers compared to young observers with no AO compensation. Although this difference is not statistically significant, it is clear that HOAs can not account for the complete age-related decline in contrast sensitivity, even when comparing contrast sensitivity over the estimated natural pupil size for each age group.

Figure 10 shows that visual acuity is improved for all observers with AO compensation ($F_{(1,6)} = 20.16$ $p < 0.004$ MANOVA), but in this case, the two age groups were not significantly different ($F_{(1,6)} = 2.75$ $p < 0.15$ MANOVA). The lack of an age-related effect is likely due to the small number of observers as the ratio of improvement over the 3 mm pupil was similar to that measured over the 6 mm pupil, increasing by a factor of 1.23 ± 0.06 and 1.11 ± 0.04 for old and young, respectively.

Discussion

This study compared the spatial vision performance of healthy older observers to young observers while correcting for HOAs. Contrast sensitivity and visual acuity were first measured over a 6 mm pupil to maximize the benefit of AO correction. Due to age-related miosis, this large pupil does not produce natural viewing conditions for older adults, so additional data were acquired while correcting HOAs over a 3 mm pupil.

Comparison with previous AO psychophysics

The wavefront correction obtained in this study is comparable to previous reports, as evidenced in our TVB. At 18 c/deg, the improvement in wavefront error creates an average 3.36-fold improvement in image contrast for our young observers, whereas Yoon and Williams (2002) show a mean 2.6-fold improvement in the monochromatic MTF for their 2 observers. The peak-to-valley improvement and Strehl ratios are very similar for our young observers compared with Liang et al. (1997), despite the difference in the method of wavefront reconstruction and correction in our lab. The AO system used in previous AO psychophysics (Liang et al., 1997; Yoon & Williams, 2002) deconstructs the measured wavefront into 65 Zernike modes, whereas our AO system uses direct slope reconstruction based on centroid displacements alone, and reconstructs the Zernike modes offline.

Comparison of AO benefit on psychophysical measures with previous AO reports is more difficult. The current study used stimuli to emphasize the range of spatial frequencies readily encountered in the natural environment (Field, 1987) instead of maximizing the benefit of AO at the high spatial frequency limit. Observers in this study included a larger, naive population, whereas Liang et al. (1997) and Yoon and Williams (2002) each used only 2 observers, all of whom appear to be highly trained on psychophysical tasks. Contrast sensitivity was measured using a rigorous 2AFC task for our observers, as opposed to the method of adjustment, and used different luminance, size, and temporal frequency for stimulus presentation. Given these

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methodological differences, the CSF change after correcting HOAs over a 6 mm pupil appears surprisingly consistent across studies for comparable spatial frequencies. Younger observers in the current study exhibited an average 2.5-fold increase in sensitivity at 18 c/deg, comparable to the average 2-fold increase at 16 and 24 c/deg reported by Yoon and Williams (2002).

Results of AO compensation with a 6 mm pupil

Overall, AO correction produced better image quality in young observers than older observers, but this was to be expected due to the increased degree of HOAs present in older eyes (Applegate et al., 2007; Calver et al., 1999). More importantly, the ratio of optical quality with AO compensation to that over sphere and cylinder correction was comparable for both age groups, indicating a consistent reduction of HOAs with AO compensation across observers. Over a 6 mm pupil, both age groups showed a significant improvement in contrast sensitivity and visual acuity. Generally, the benefit of AO compensation improved as the spatial frequency increased, with very little benefit at lower spatial frequencies, consistent with previous reports (Liang et al., 1997; Yoon & Williams, 2002). Our older population had a slightly superior benefit at middle spatial frequencies, but interestingly, a lower benefit at the highest spatial frequency tested.

When the CSF change with a 6 mm pupil was compared to the TVB, it was apparent that the improvement in the optical PSF cannot account fully for the larger improvement in spatial vision performance for older observers. It is possible that optical factors contributing to the functional PSF may also be improved by AO, which could have a significant impact on visual perception. The increase in coma-like and spherical aberration near the center of each Zernike radial order may also account for the superior benefit (see Figure 2), especially for visual acuity. It has been suggested that the presence and interaction of these specific aberrations may produce more severe losses in spatial vision than the overall quantity of aberration alone (Applegate et al., 2002,2003a,2003b;Chen, Singer, Guirao, Porter, & Williams, 2005).

With AO compensation, contrast sensitivity was still lower for older than younger observers. There could be several reasons for this. Due to the stroke limits of the DM and the increased degree of HOAs present in older eyes, the residual aberration after AO compensation was larger than for younger observers. On the other hand, older observers obtained better optical quality with AO compensation than younger observers had without AO (see Figure 5), but contrast sensitivity was still reduced. In addition, AO compensation did not produce a large benefit at 18 c/deg for older observers, as it did for young observers. This supports the view that HOAs are not the only factor responsible for reduced contrast sensitivity. Additional optical factors not improved by AO compensation, as well as residual aberrations and intraocular scatter may override the benefit of AO beyond a certain spatial frequency.

Controlling for age-related miosis

Age-related miosis may counteract the increase in HOAs present in older eyes (Calver et al., 1999; Guirao et al., 1999), as HOAs increase faster with an increase in pupil diameter than with an increase in age (Applegate et al., 2007). When we measured contrast sensitivity and visual acuity over a 3 mm pupil, we found support for this view. The increased depth of focus and decrease in HOAs inherent for older eyes over a smaller pupil produced an improvement in contrast sensitivity when compared to results collected over a 6 mm pupil. Younger observers exhibited a reduced sensitivity over a 3 mm pupil compared to a 6 mm pupil, likely due to the reduced retinal illumination with a smaller eye pupil.

Overall, the benefit of AO compensation on contrast sensitivity over a 3 mm pupil was reduced compared to the 6 mm condition, and no distinct pattern emerged between the two age groups. Both age groups showed a larger benefit of AO compensation at higher spatial frequencies

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with an equivalent benefit of AO at all tested spatial frequencies. The benefit of AO compensation on visual acuity was also not significantly different for the two age groups. The average improvement in visual acuity was larger for older adults, and comparable to the benefit measured over a 6 mm pupil. Even over a small pupil, coma-like aberrations tend to increase with age (Applegate et al., 2007; see Figure 7), and this may explain the slightly improved benefit of AO compensation for visual acuity (Oshika et al., 2006).

Possible mechanisms mediating age-related contrast sensitivity loss

HOAs cannot account for the full decline in contrast sensitivity observed in senescence. Correcting HOAs over a pupil size closer to natural dimensions does generate improved spatial vision for older observers, but not more so than for young observers. Contrast sensitivity above 4.5 c/deg and visual acuity were still reduced both with and without AO compensation for our older population. Additional optical factors might contribute to the decrease in sensitivity, such as increased ocular media density (Weale, 1988; Werner, 1982) and intraocular scatter (Hennelly et al., 1998). While previous investigations do not support this explanation as a complete account of age-related losses in spatial vision (e.g., Elliott et al., 1990; Owsley et al., 1983; Whitaker & Elliott, 1992), it is possible that optical factors other than HOAs could play a significantly larger role when the impact of the HOAs is removed with AO. An age-related interaction of specific HOAs (Applegate et al., 2003a, 2003b; Chen et al., 2005; Oshika et al., 2006) is another intriguing possibility that has not been fully evaluated.

It is also possible that there is some form of spatial adaptation in cortical neural mechanisms that may further limit the benefit of AO with older observers. Recent evidence indicates that the best subjective image quality is obtained when some HOAs are present and are similar to the observer's own aberrations, suggesting that the neural system is adapted to the eye's aberrations (Artal et al., 2004; Chen, Artal, Gutierrez, & Williams, 2007). Elliott, Hardy, Webster, and Werner (2007) found no difference in the strength of adaptation to transient changes in image blur for young and older observers, revealing that cortical mechanisms of spatial adaptation remain largely intact with age, and thus could provide a mechanism of long-term blur adaptation to the increased degree of HOAs. However, because the change in contrast sensitivity and the increase in optical quality were similar for both age groups with AO compensation, it is likely that the effect of neural adaptation was also similar for both age groups.

The current results are consistent with the conclusion that neural factors contribute to the senescent decline in spatial vision. Loss of ganglion cells in the central retina of elderly individuals (Curcio & Drucker, 1993; Gao & Hollyfield, 1992) reduces spatial sampling, but other inefficiencies in retinal processing are also likely to be important. Functional changes beyond the retina may further contribute to age-related changes in spatial vision. For example, physiological evidence from rhesus monkeys (Schmolesky, Wang, Pu, & Leventhal, 2000) and cats (Hua, Li, He, Zhou, Wang, & Leventhal, 2006) suggests an age-related functional loss in cortical channel tuning, specifically a loss of orientation and direction selectivity of cells in the striate cortex, and an increase in spontaneous neural noise. Correcting HOAs does improve contrast sensitivity at high-spatial frequencies, but neural losses could set a hard upper limit to the improvement that is possible with AO compensation.

Conclusion

Contrast sensitivity and visual acuity were measured for young and old observers while correcting for HOAs using closed-loop AO correction. Measurements were obtained over a 6 mm pupil to maximize the benefit of AO compensation, and were repeated with a 3 mm pupil to simulate more natural conditions resulting from age-related miosis. Contrast sensitivity was reduced for older observers compared to younger observers both with and without AO compensation, irrespective of pupil size, but AO compensation did produce a larger benefit in visual acuity for older observers. When spatial vision performance is measured over a natural pupil size, the overall degree of HOAs cannot account for the reduced contrast sensitivity measured in senescence. Correcting HOAs may increase the relative impact of other optical factors, such as intraocular scatter, but may also provide further support for a neural contribution to the age-related loss of contrast sensitivity.

Acknowledgments

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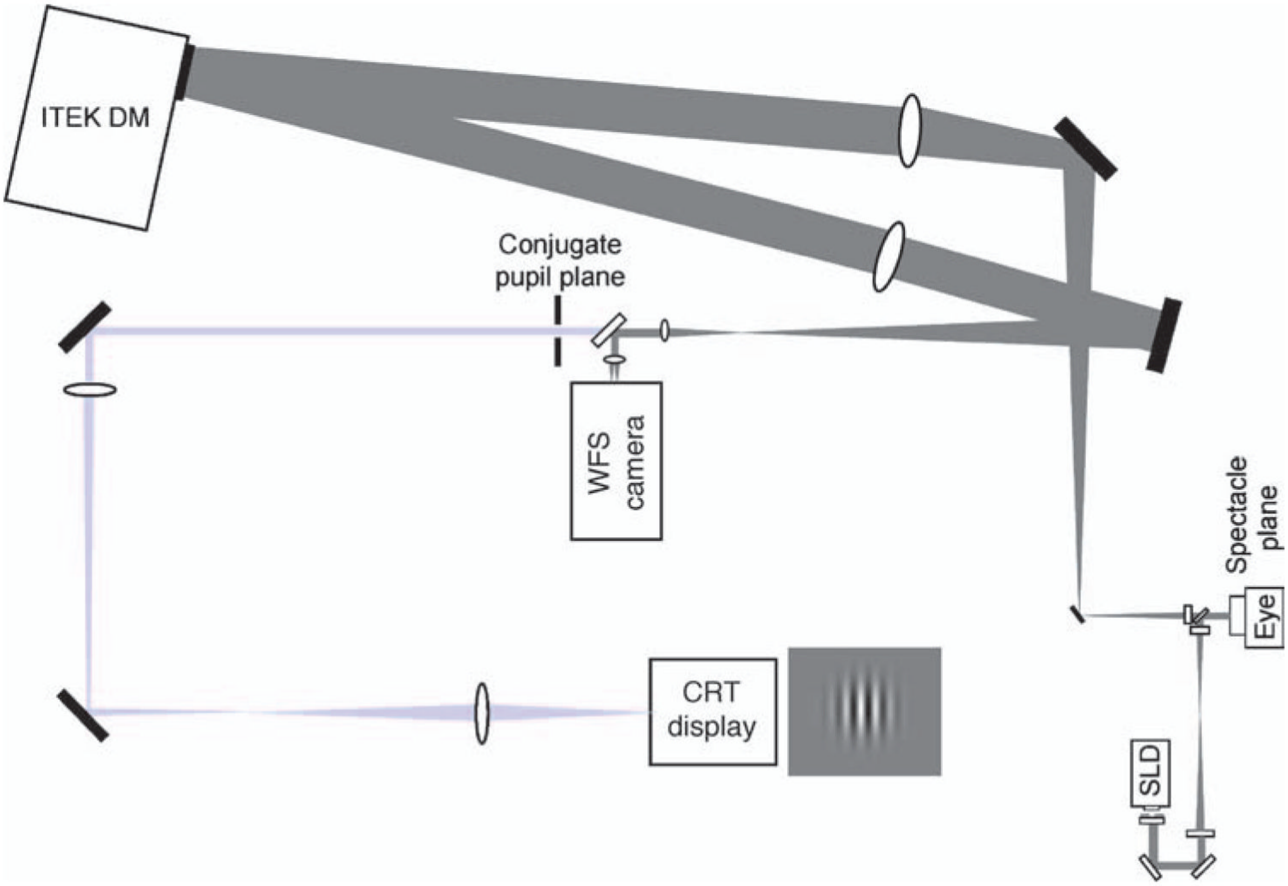

Figure 1.
Psychophysics arm of the AO system. *Dark gray:* AO control loop. *Light gray:* Non-common CRT light path. The aperture at the conjugate pupil plane was set at either 6 mm or 3 mm depending on the testing condition. Trial lenses were placed in the spectacle plane to correct for 2nd-order aberrations and an additional trial lens was placed at the conjugate pupil plane to correct for the difference in chromatic focus between the SLD and the CRT display.

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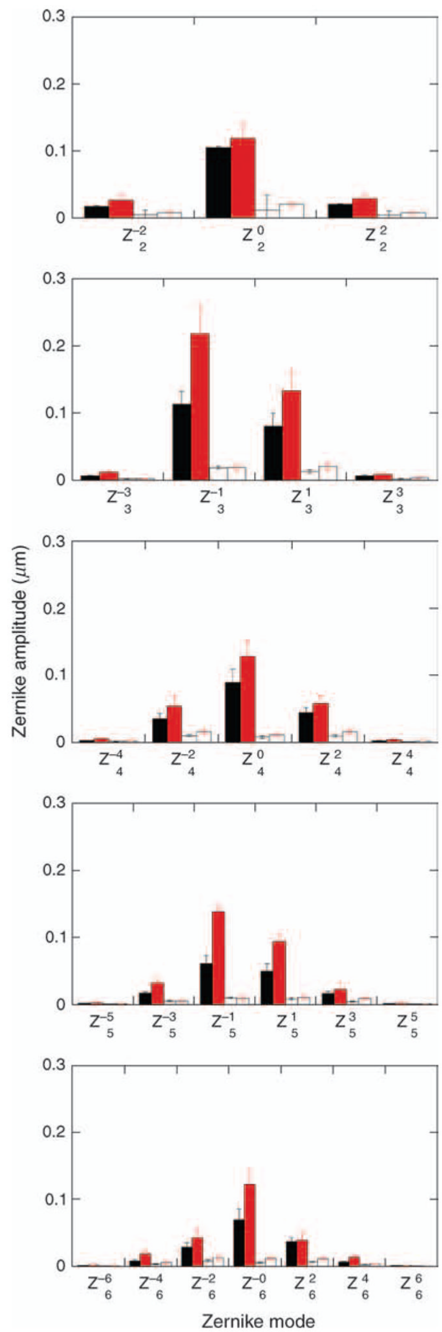

Figure 2.

Mean absolute Zernike modes for the younger (black bars), and older (red bars) age groups with (open bars) and without (solid bars) AO compensation over a 6 mm pupil. Each panel represents a separate Zernike radial order. Our DM is capable of correcting aberrations up to the 6th Zernike radial order. Error bars are ±1 *SEM*.

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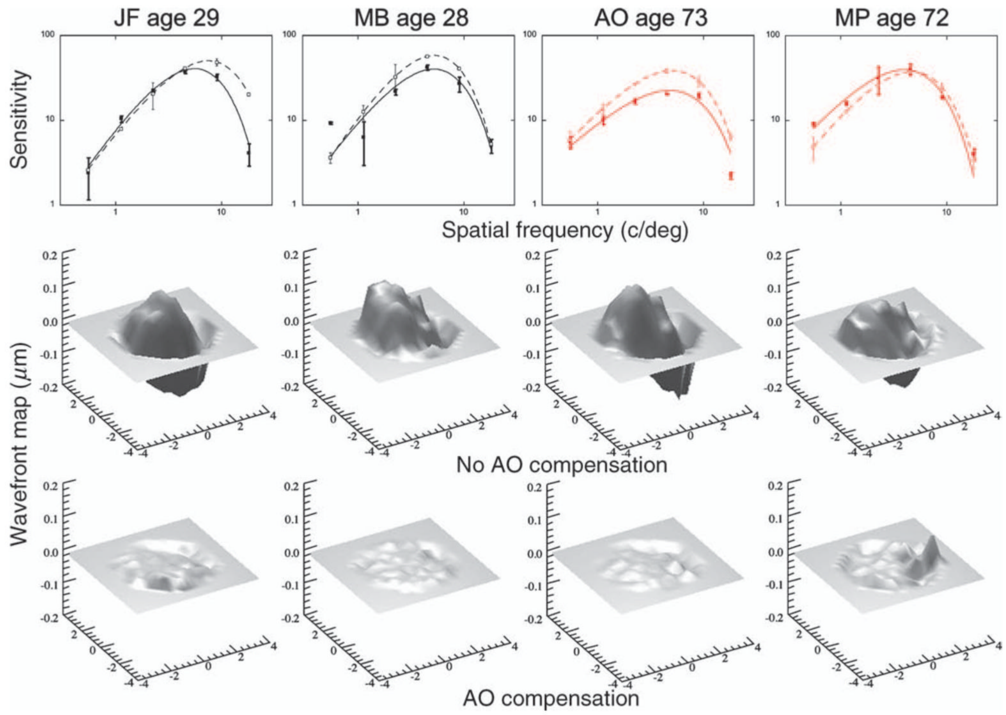

Figure 3.
Representative contrast sensitivity functions for two younger and two older observers. Solid symbols and curves denote measurements without AO correction; open symbols and dashed curves are measurements with AO compensation; black and red denote young and old, respectively. These observers were selected to represent the different degrees of AO correction, illustrated by wavefront maps over a 6 mm pupil with and without AO compensation. Wavefront maps below each contrast sensitivity curve correspond to that observer and represent the average wavefront error of approximately 10 frames. JF (29 years) and AO (73 years) are individuals who achieved superior improvement with AO compensation, while MB (28 years) and MP (72 years) are individuals with poor improvement during AO compensation. See Table 2 for additional optical quality metrics for each sample observer.

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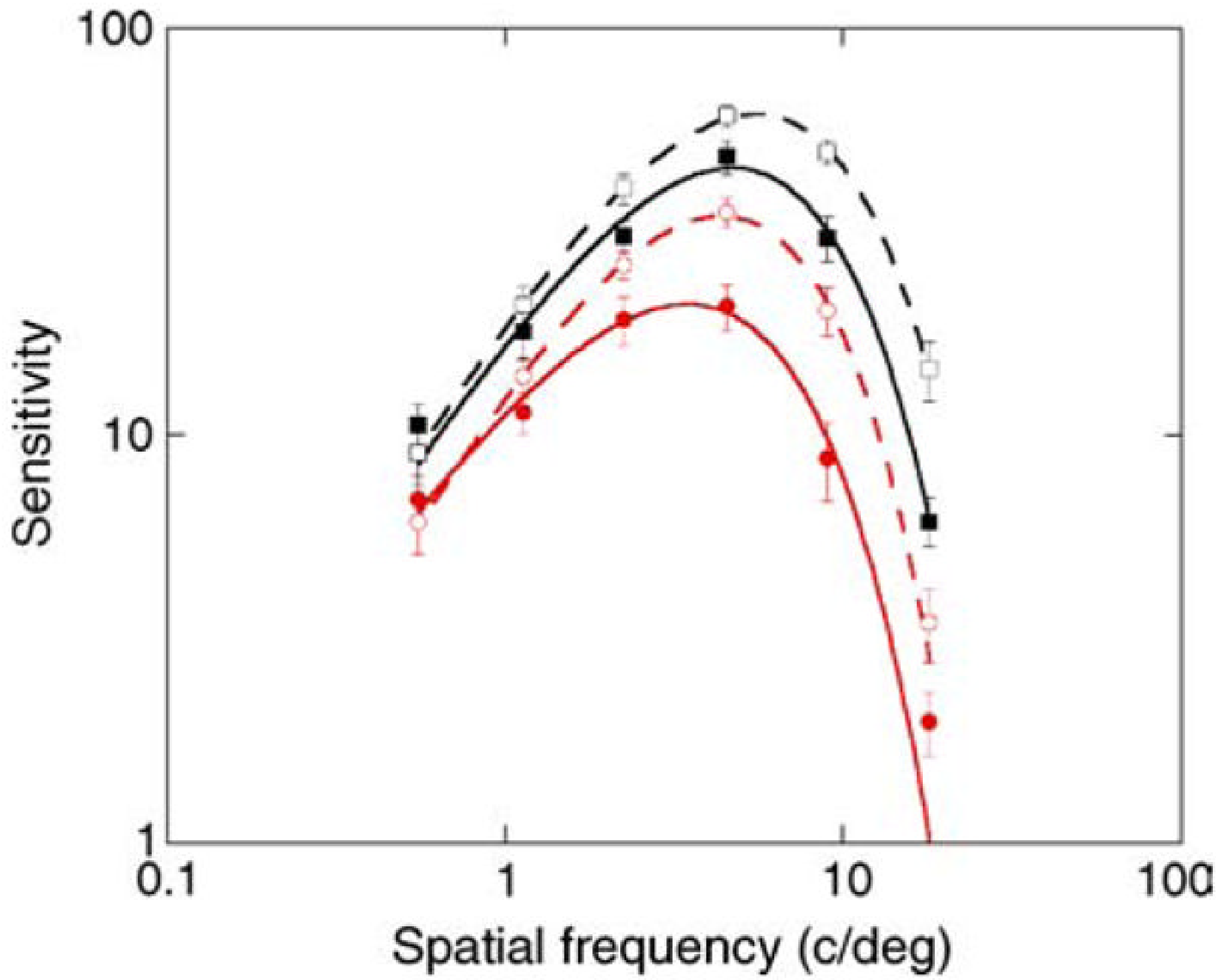

Figure 4.
Average contrast sensitivity on a log-log scale for young observers (black symbols and curves) and older observers (red symbols and curves). Solid symbols and curves represent measurements without AO compensation; open symbols and dashed curves denote measurements with AO compensation. Curves were fitted using a double-exponential function. Error bars are ±1 *SEM*.

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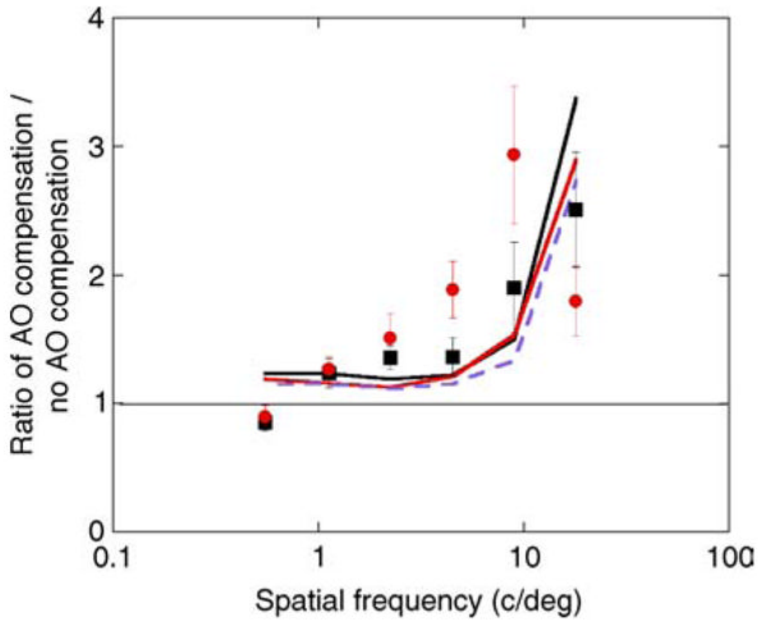

Figure 5.
CSF change compared with the TVB of AO compensation for each age group. Solid curves show the TVB, and solid symbols show the CSF change, black and red for young and old, respectively. CSF change is defined as the ratio of contrast sensitivity with AO compensation to that with no AO compensation. TVB is defined as the ratio of degraded retinal image contrast with AO compensation to that with no AO compensation. The dotted blue curve denotes the TVB of older observers with AO compensation relative to young observers with no AO compensation. Error bars are ±1 *SEM*.

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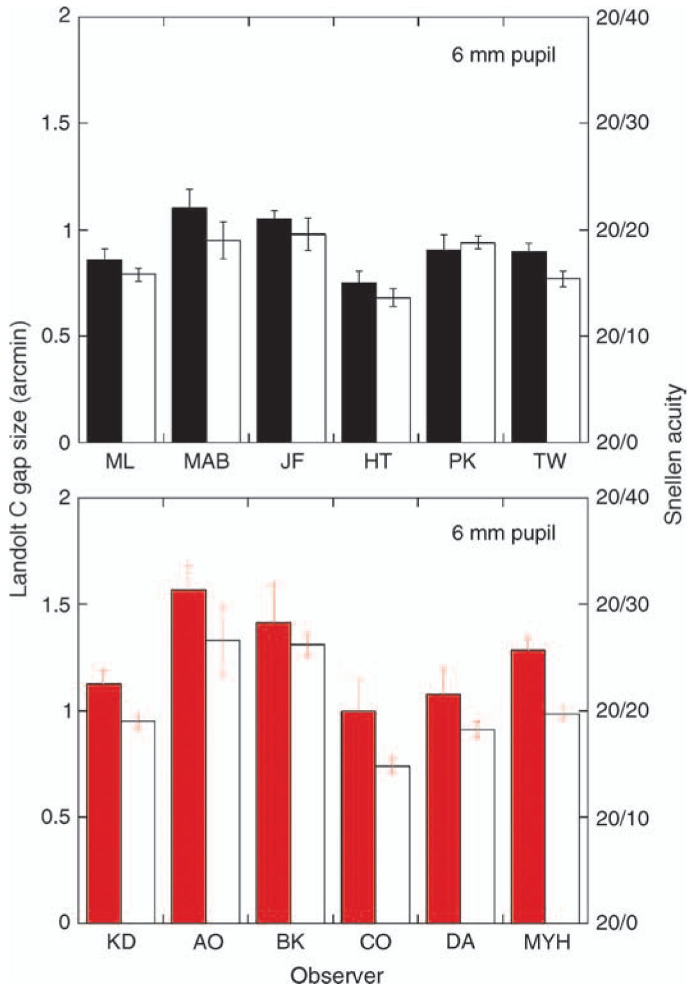

Figure 6.

Change in visual acuity with AO compensation plotted as the minimum resolvable angle in arcmin (left) or Snellen visual acuity (right). Individual young observers (black bars) are presented in the top panel, while individual older observers (red bars) are presented in the bottom panel. Solid and open bars show the visual acuity before and after AO compensation, respectively. Error bars are ±1 *SEM*.

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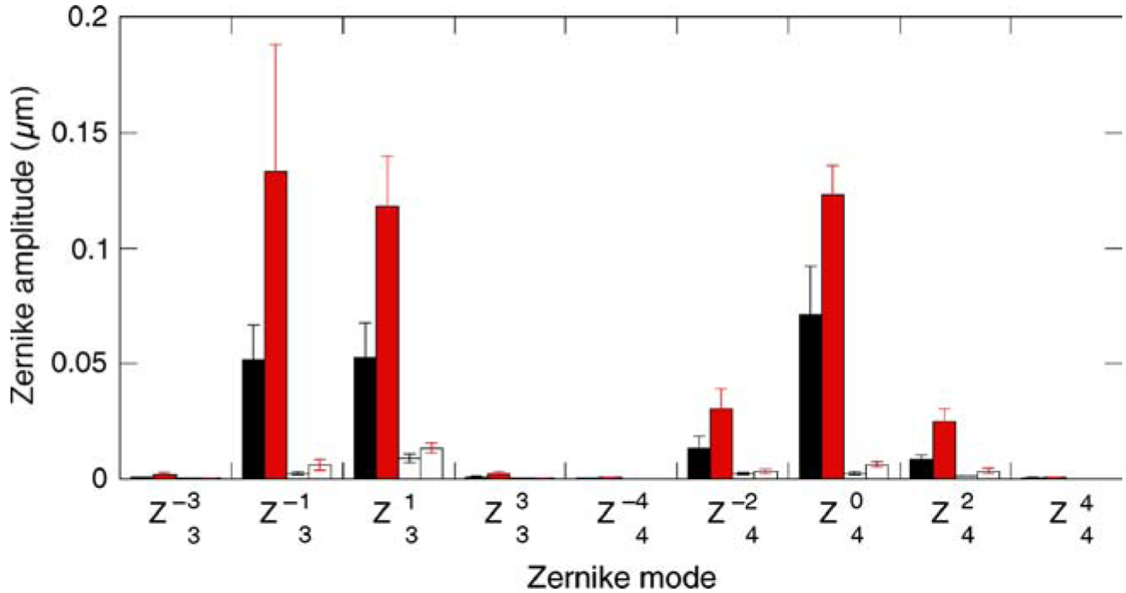

Figure 7.
Mean absolute third and fourth radial order Zernike modes for the younger (black bars), and older (red bars) age groups with (open bars) and without (solid bars) AO over a 3 mm pupil. Error bars are ±1 *SEM*.

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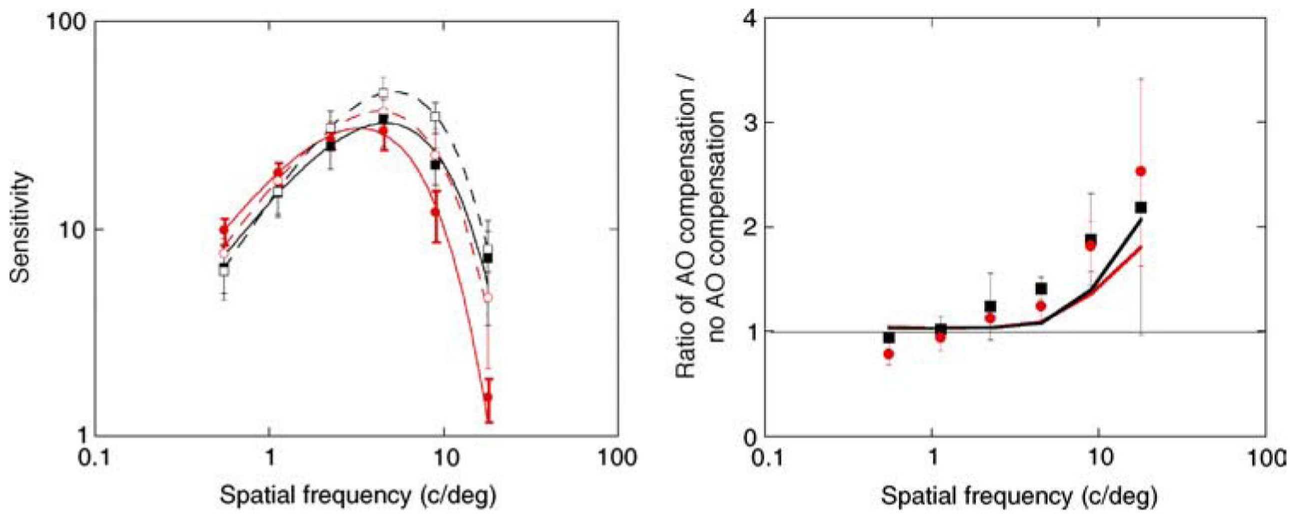

Figure 8.

Left: Average contrast sensitivity on a log-log scale for the 3 mm pupil for young (black symbols and curves) and older (red symbols and curves) observers. Solid curves and symbols denote measurements without AO compensation; open symbols and dashed curves denote measurements with AO compensation. *Right*: The CSF change compared with the TVB of AO compensation for each age group over the 3 mm pupil. Solid curves show the TVB, and solid symbols show the CSF change, black and red for young and old, respectively. Error bars are ±1 *SEM*.

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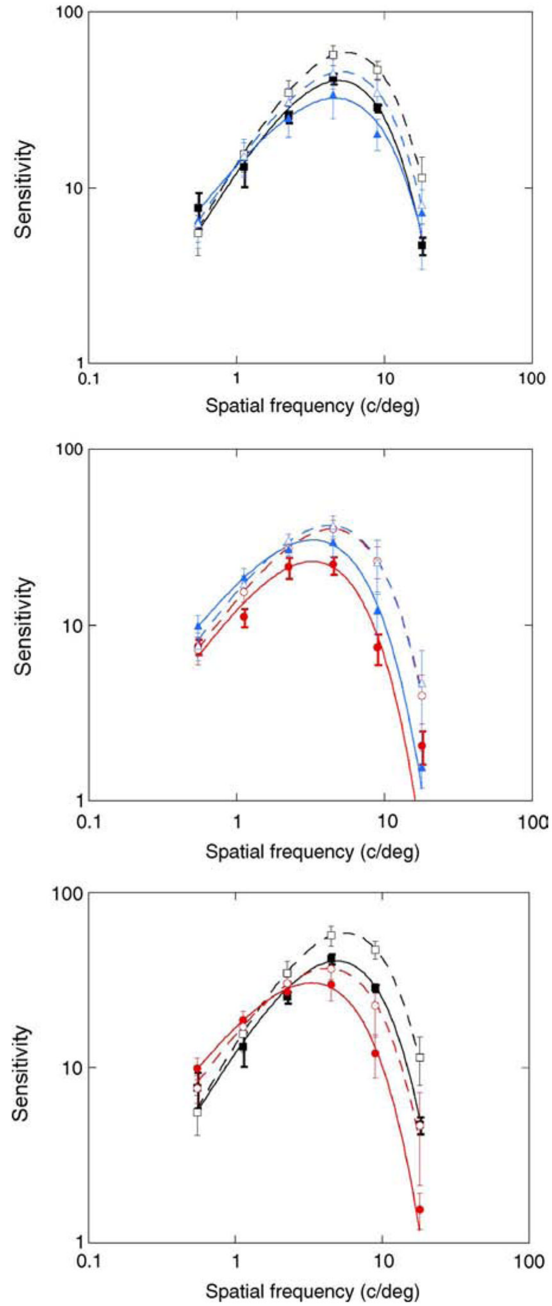

Figure 9.

Average contrast sensitivity on a log-log scale compared for the 8 observers used in both the 6 mm and 3 mm pupil conditions. Solid symbols and curves denote measurements without AO compensation; open symbols and dashed curves denote measurements with AO compensation. *Top*: Younger observer averages. Black symbols and curves signify the 6 mm pupil; blue symbols and curves show the 3 mm pupil. *Middle*: Older observer averages. Red symbols and curves show the 6 mm pupil average, and blue symbols and curves show the 3 mm pupil. *Bottom*: Black symbols and curves denote younger observer averages with a 6 mm pupil; red symbols and curves signify older observer averages over a 3 mm pupil.

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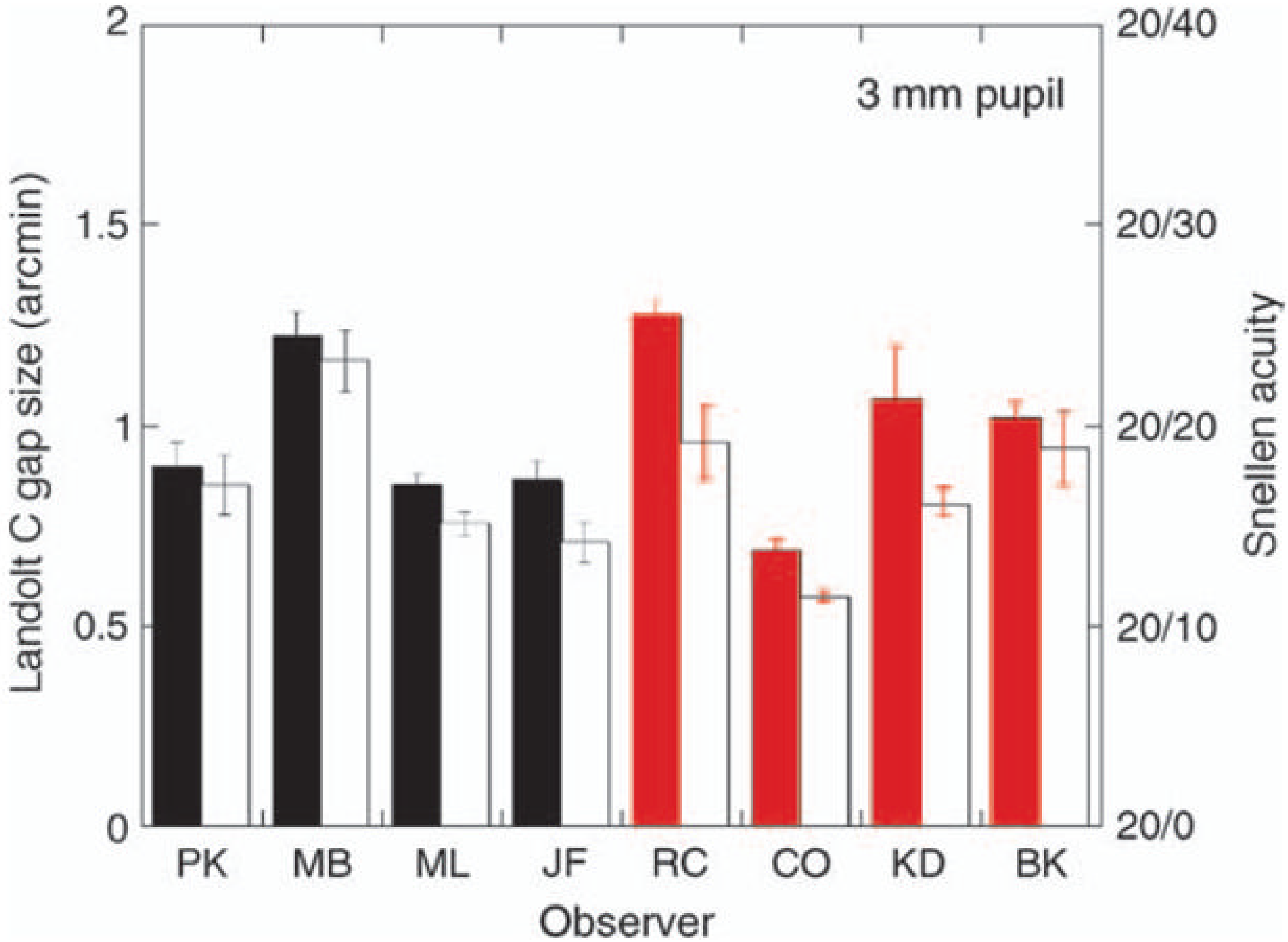

Figure 10.
Change in visual acuity with AO compensation for individual observers (black for young, red for older) when measured over a 3 mm pupil, plotted as the minimal resolvable angle in arcmin. Open bars denote visual acuity with AO compensation; solid bars denote visual acuity measured without AO compensation. The right ordinate is Snellen visual acuity. Error bars are ±1 *SEM*.

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Table 1

Mean optical quality metrics for both age groups over a 6 mm pupil.

Age group	Wavefront RMS no AO	Wavefront RMS with AO	Strehl ratio with AO	Peak-to-valley factor improvement with AO
Younger	0.49 ± 0.05	0.16 ± 0.02	0.47 ± 0.03	2.85 ± 0.26
Older	0.79 ± 0.08	0.22 ± 0.03	0.34 ± 0.04	3.27 ± 0.41

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Table 2

Optical quality metrics for individual observers (in Figure 3).

Observer (age)	Wavefront RMS no AO	Wavefront RMS with AO	Strehl ratio with AO	Peak-to-valley factor improvement with AO
JF (29 years)	0.70 ± 0.05	0.22 ± 0.05	0.47 ± 0.00	2.64 ± 1.03
MB (28 years)	0.44 ± 0.19	0.15 ± 0.04	0.47 ± 0.09	1.93 ± 0.72
AO (73 years)	0.75 ± 0.04	0.13 ± 0.00	0.54 ± 0.01	5.40 ± 0.43
MP (72 years)	0.68 ± 0.21	0.25 ± 0.02	0.24 ± 0.05	1.92 ± 0.68

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Table 3

Mean optical quality metrics for each age group over a 3 mm pupil.

Age group	Wavefront RMS no AO	Wavefront RMS with AO	Strehl ratio with AO	Peak-to-valley factor improvement with AO
Younger	0.40 ± 0.03	0.16 ± 0.02	0.50 ± 0.02	2.60 ± 0.44
Older	0.83 ± 0.25	0.17 ± 0.05	0.41 ± 0.03	4.03 ± 0.93