A population study on changes in wave aberrations with accommodation

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Wave aberrations were measured with a Shack-Hartmann wavefront sensor (SHWS) in the right eye of a large young adult population when accommodative demands of 0, 3, and 6 D were presented to the tested eye through a Badal system. Three SHWS images were recorded at each accommodative demand and wave aberrations were computed over a 5-mm pupil (through 6th order Zernike polynomials). The accommodative response was calculated from the Zernike defocus over the central 3-mm diameter zone. Among all individual Zernike terms, spherical aberration showed the greatest change with accommodation. The change of spherical aberration was always negative, and was proportional to the change in accommodative response. Coma and astigmatism also changed with accommodation, but the direction of the change was variable. Despite the large inter-subject variability, the population average of the root mean square for all aberrations (excluding defocus) remained constant for accommodative levels up to 3.0 D. Even though aberrations change with accommodation, the magnitude of the aberration change remains less than the magnitude of the uncorrected aberrations, even at high accommodative levels. Therefore, a typical eye will benefit over the entire accommodative range (0-6 D) if aberrations are corrected for distance viewing.

Keywords: wave aberrations, accommodation, spherical aberration, coma, wavefront sensing, customized corrections

Introduction

Wave aberrations have been measured in large populations when the eye's accommodation is relaxed under natural viewing condition or paralyzed with cycloplegic agents (Porter, Guirao, Cox, & Williams, 2001; Thibos, Hong, Bradley, & Cheng, 2002b; Castejon-Mochon, Lopez-Gil, Benito, & Artal, 2002). In an accommodated eye, wave aberrations are expected to change because ocular structures, particularly the shape, position, and refractive index gradient of the crystalline lens change during accommodation (Garner & Yap, 1997; Garner & Smith, 1997; Koretz, Cook, & Kaufman, 2002). In fact, many studies have demonstrated such accommodation-induced changes in aberrations, which include changes of defocus (Ciuffreda, 1991), astigmatism (Millodot & Thibault, 1985; Ukai & Ichihashi, 1991; Mutti, Enlow, & Mitchell, 2001; Tsukamoto, Nakajima, Nishino, Hara, Uozato, & Saishin, 2000), spherical aberration (Ivanoff, 1956; Jenkins, 1963; Koomen, Tousey, & Scolnik, 1949; van den Brink, 1962), and other higher order aberrations (Atchison, Collins, Wildsoet, Christensen, & Waterworth, 1995; He, Burns, & Marcos, 2000; Ninomiya et al., 2002; He, Marcos, Webb, & Burns, 1998; Howland & Buettner, 1989; Lu, Campbell, & Munger, 1994; Vilupuru, Roorda, & Glasser, 2004).

A review of the literature revealed a general tendency for spherical aberration to change in a negative direction with increases in accommodation, although large variability existed among individuals and studies (Koomen et al., 1949; Ivanoff, 1956; Jenkins, 1963; He et al., 2000; Ninomiya et al., 2002). For example, all subjects in the He et al. study (2000) showed a decrease in spherical aberration with accommodation, whereas only half the subjects in a study

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by Atchison et al. (1995) had a similar trend. Fewer studies investigated high-order aberrations other than spherical aberration in accommodated eyes and the results were less conclusive. It seemed the direction and magnitude of the change in coma varied greatly between subjects and no clear trend was observed (He et al., 2000; Howland & Buettner, 1989; Lu et al., 1994; Atchison et al., 1995). For aberrations with orders above fourth, He et al. (2000) reported a minimum near the resting state of accommodation (around 2 D), which was not confirmed in a recent study by Ninomiya et al. (2002). In addition to the above-mentioned changes in individual aberration terms, several authors have reported the effect of accommodation on overall wave aberrations measured by the root mean square (RMS), or variance of the wavefront error (He et al., 2000; Ninomiya et al., 2002; Atchison et al., 1995). According to He et al. (2000), despite large individual variation, the average RMS (excluding defocus term) decreased from 0 to 1 D and remained minimum between 1 to 3 D, then increased with higher accommodation. Ninomiya et al (2002), however, found no change in the RMS of the total higher order aberrations with a 3 D accommodation, which was consistent with Atchison et al (1995), who reported no change of variance between 0 to 3 D accommodation.

Previous studies of ocular aberrations in accommodated eyes used different techniques and investigated relatively small populations [e.g., Atchison et al. (1995) studied 15 subjects with an objective aberroscope, and He et al. (2000) applied a psychophysical ray-tracing test called the spatially resolved refractometer on eight observers (Webb, Penney, & Thompson, 1992)]. The range of accommodation studied and the pupil sizes used for analyzing aberrations also varied among studies. All of these make direct comparisons between studies difficult. To date, no sufficient data are available to characterize the individual variation in aberrations for eyes with accommodation. Such information is crucial for understanding the fundamentals of the visual system (Thibos, Bradley, & Hong, 2002a) and has important implications in clinical applications (Williams, Yoon, Guirao, Hofer, & Porter, 2001; Applegate, Thibos, & Hilmantel, 2001; Macrae, Schwiegerling, & Snyder, 2000).

The recent development of the Shack-Hartmann wavefront sensor for vision science has allowed rapid, accurate and objective measurements of wave aberrations and made large population studies possible (Liang & Williams, 1997; Porter et al., 2001; Thibos et al., 2002b). In this study, we measured wave aberrations with a Shack-Hartmann wavefront sensor in a large young adult population for accommodative stimuli up to 6 D. Zernike coefficients up to the sixth order were studied.

Methods

This research followed the tenets of the Declaration of Helsinki, and was approved by the University of Houston Human Subject Review Committee. Informed consent was obtained from subjects after they received a verbal and written explanation of the nature and possible risks of the study.

Subjects

Ninety-one optometry students at the University of Houston, College of Optometry, participated in the study. Measurements were taken only for the right eye. Of the 91 subjects, the excluded subjects included two amblyopic eyes, one eye which had undergone a corneal transplant, 10 subjects who did not maintain at least a 5-mm pupil size for all accommodative states, and 2 subjects whose accommodation during the repeated measurements was unstable (>1 D *SD* for any of the accommodative stimuli). For static population statistics, two additional eyes that had undergone LASIK refractive surgery were also excluded. Therefore, a total of 76 subjects are reported for the changes in aberration with accommodation, and 74 subjects for the population statistics. All subjects had good ocular health with best-corrected visual acuity better than 20/30 (average 20/17) in the tested eye. The subjects ranged in age from 21-40 years with a mean (+/− *SD*) of 24.8 +/− 4.0 years. The spherical refractive error ranged from + 1.25 D to −8.25 D with a mean (+/−*SD*) of −2.50+/−2.25 D; and the astigmatism ranged from −0.25 D to −2.75 D with a mean (+/−*SD*) of −0.70+/−0.54 D. Significant refractive errors were corrected with spectacles or trial lenses during the experiment. The mean (+/−*SD*) residual uncorrected refractive error was −0.43+/−0.60 D for the sphere and -0.17+/−0.31 D for the cylinder.

Dilation was achieved with one drop of 2.5% phenylephrine preceded by one drop 0.5% proparacaine (Lyle & Bobier, 1977; Jauregui & Polse, 1974). Subjective refraction and best corrected visual acuity were obtained with Bailey-Lovie charts for the dilated eyes prior to the aberration measurements.

Experimental design and procedures

A custom-built Shack-Hartmann wavefront sensor (SHWS) was used to measure the wave aberration. The design of the SHWS followed the basic principles described in Liang and Williams (1997). In brief, a focused beam of low-intensity laser light (10 μW at 830 nm) projected on the retina acted as a point source, and the light emerging from the pupil was imaged onto a lenslet array (0.4-mm spacing, 24-mm focal length), which focused onto a CCD camera placed in the focal plane of the lenslet array. An array of spots (an SHWS image) was thus recorded. To control accommodation, a Maltese cross target (McLin, Schor, & Kruger, 1988) was set behind a Badal system, and projected to the tested eye through a beam splitter attached in front of the SHWS.

During the imaging process, the Maltese cross target was initially located at optical infinity for low hyperopic or emmetropic eyes or slightly behind the subject's far point for low myopic subjects (< – 2 D) to ensure relaxed accommodation. An accommodative response was elicited by moving the target behind the Badal lens to create 3 D and 6 D of accommodative demand. Subjects were instructed to focus on the target and maintain the focus while aberration measurements were being performed. At least three SHWS images were recorded at each accommodative demand for every subject.

Data analysis

The digitized spot images taken by the SHWS were analyzed using custom written software. The local slopes of the wavefront were computed based on the displacement of spot centroids from the reference array of the lenslet centers. The local slopes were fitted to the derivatives of a Zernike polynomial function using the method of least squares. The wave aberration function, $W(x, y)$, is represented by a weighted sum of the series of Zernike modes:

$$W(x,y) = \sum_{n,m} C_n^m Z_n^m \left(x,y\right) \tag{1}$$

where $W(x, y)$ is defined over the x, y coordinates of the pupil, C is the Zernike coefficient corresponding to a particular Zernike mode, Z, and n and m refer to the different radial and angular orders, respectively. Zernike coefficients representing the wave aberration were specified using the standard nomenclature defined with reference to the standard coordinate system recommended by the Optical Society of America (Thibos, Applegate, Schwiegerling, Webb, & VSIA Standards Taskforce Members, 2000).

Wave aberrations were computed over a 5-mm pupil up to 6th order Zernike polynomials. For every subject, three sets of SHWS images were analyzed for each accommodative stimulus. The subject's wave aberration under a particular stimulus condition was represented by the mean Zernike coefficient of three measurements.

The accommodative response was calculated from the Zernike defocus term over the central 3-mm diameter zone as the difference between the defocus at 3 D or 6 D stimulus and that at 0 D stimulus. A smaller pupil diameter was used for the calculation of accommodative response to prevent the high-order aberrations of larger pupil sizes from affecting the overall refraction.

Results

Population statistics on wave aberrations in relaxed eyes

Figure 1 illustrates the average value (1a) and the mean absolute magnitude (1b) of each Zernike term for 74 relaxed eyes (0 D stimulus) (two subjects who had undergone LASIK surgery were excluded from the population statistics). Most noticeable from Figure 1a is the large dispersion of each Zernike term indicating large inter-subject variability in the population. In addition, most Zernike terms average around zero except for spherical aberration, which is biased toward positive. Figure 1b compares the magnitude (RMS) of wavefront errors for different high-order aberrations. Compared to the 3rd and 4th order aberrations, the 5th and 6th order wavefront errors contribute much less to the total variance of the wave aberration.

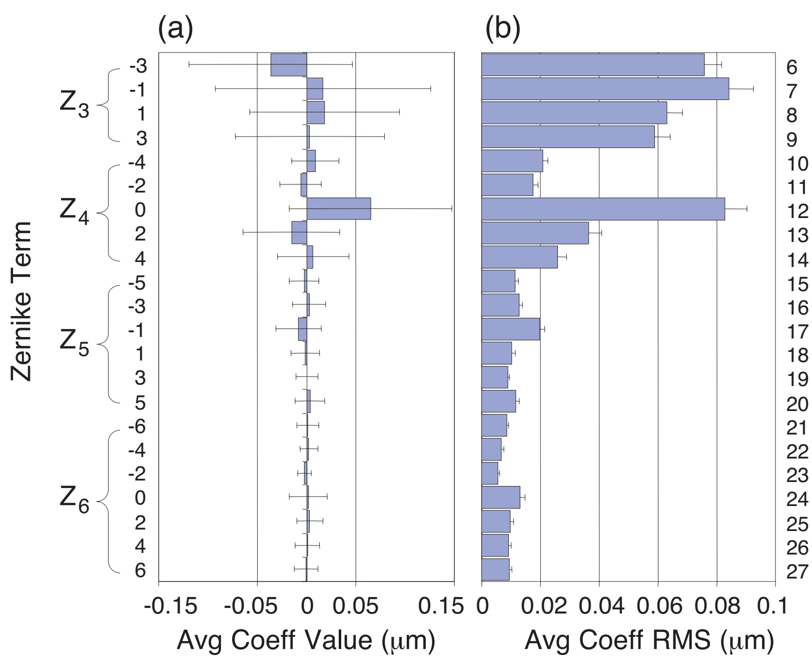

Figure 1. Population statistics of high-order aberrations for 74 relaxed eyes over a 5-mm pupil. (a). Mean values of Zernike coefficients. Error bars represent 1 *SD*. (b). The mean absolute magnitude (RMS) of Zernike terms. Error bars represent 1 SEM.

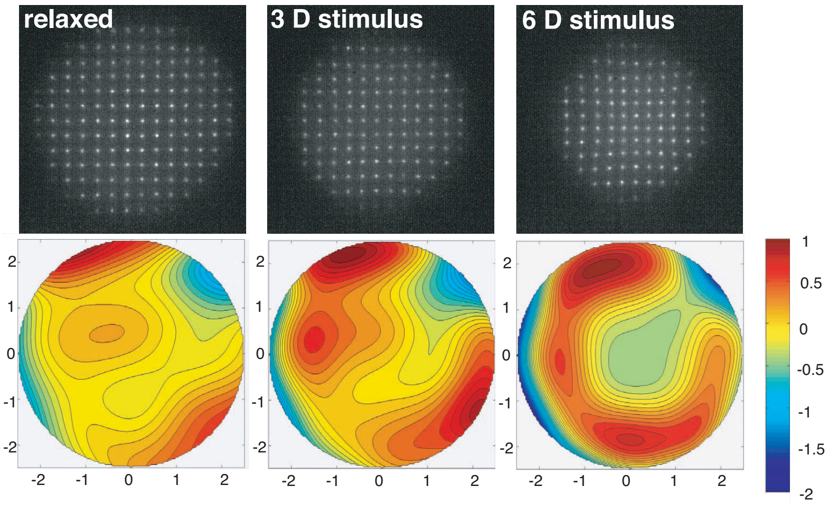

Figure 2. The SHWS spot patterns and the corresponding wave aberration plots (with 2nd order aberrations excluded) for a typical eye under three accommodative conditions. The contour interval in the aberration map is 0.1 micrometers.

SHWS images for an eye before and after accommodation

Figure 2 shows the SHWS spot patterns (top row) and the corresponding wave aberration maps (bottom row) in an eye under three accommodative conditions. The horizontal and vertical axis indicates the pupil position, with zero at the center of the pupil and positive values for temporal and superior locations. Defocus and astigmatism are excluded from the aberration map. When accommodation increases, the SHWS spot patterns show a more pronounced pincushion effect, indicating an introduction of negative spherical aberration. The sequential changes in the three contour maps clearly depict how negative spherical aberration and coma-like aberrations emerged with increased accommodation. For this subject, the overall wave aberration increased with accommodation.

Change in individual aberration terms with accommodation

Figure 3 plots the change in each Zernike term (2nd through 6th order, excluding defocus) as a function of the change in accommodative response for individual subjects. Among all the aberrations, spherical aberration (Z12) shows the largest change with accommodation. The change in spherical aberration is always negative, indicating that spherical aberration always moves in a negative direction with increased accommodation. The amount of change in spherical aberration is linearly related to the amplitude of accommodation (slope = -0.0435 micrometers/D, $r = 0.85$, 95% confidence predictive range at any level of accommodation is +/– 0.085 micrometer). Coma (Z7, Z8) and astigmatism (Z3, Z5) also change with accommodation, but the direction of the change varies, going in either a positive or negative direction. The change in other terms is much smaller and reveals no clear trend. Figure 4 plots the RMS of the change in the astigmatism terms (Z3 and Z5 combined), the coma terms (Z7 and Z8 combined), and spherical aberration term (Z12) with accommodation. The rates of change of coma and astigmatism are about one third that of spherical aberration for a 5-mm pupil size. Special considerations taken while computing the RMS of the difference between two measured variables are described in the appendix.

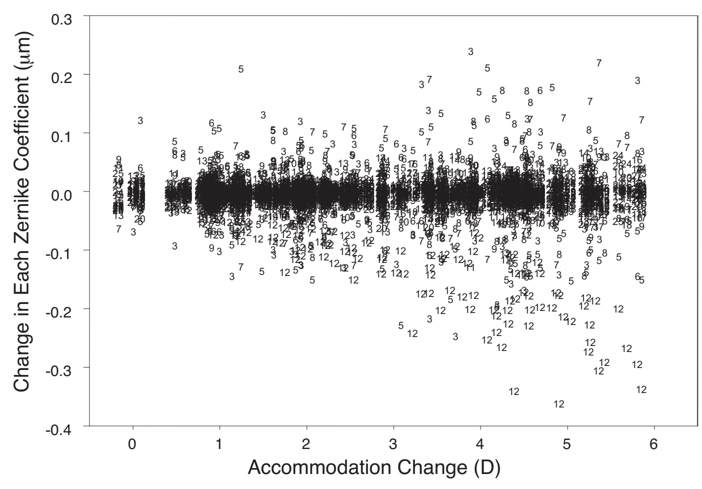

Figure 3. Change in 2nd through 6th order Zernike coefficients from those in the relaxed state as a function of the change in accommodation for all subjects. The symbols in the plot are labeled according to their respective Zernike terms (3, 5-27). Zernike values that undergo small changes are not visible due to overlap. Dominant terms, such as astigmatism (Z3 & Z5) and coma (Z7 & Z8), are visible on either side of zero. The most dominant term, spherical aberration (Z12), is consistently below zero and becomes more negative with accommodation.

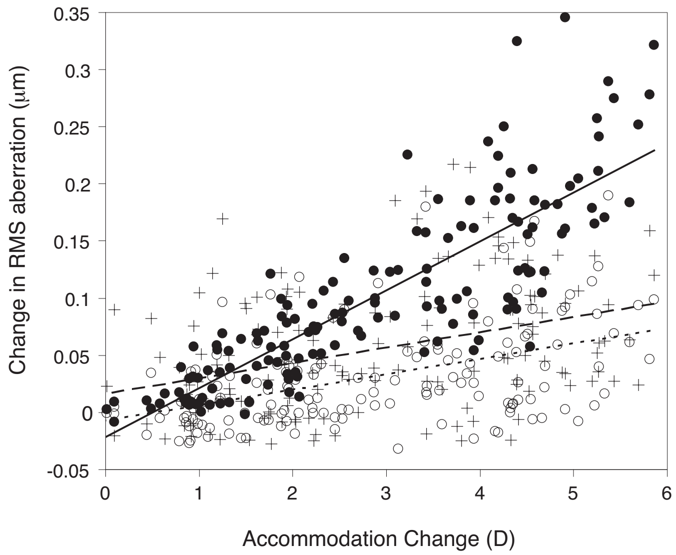

Figure 4. Changes in the RMS of spherical aberration (Z12, solid circles, solid line), coma (Z7 & Z8, open circles, dotted line), and astigmatism (Z3 & Z5, crosses, dashed line) with accommodation for all subjects. The slopes for the three scatter plots are 0.0428 (spherical aberration), 0.0135 (coma), and 0.0134 (astigmatism).

Figure 5 compares the population average of the change in each aberration term, excluding defocus, at different levels of accommodative response. Clearly, spherical aberration becomes more negative as accommodation increases, whereas the average change for other terms is around zero. The only exception is at the highest accommodative state where several additional terms, most notably Z5 and Z7, are significantly different from zero. The negative shift of Z5 indicates that the eye undergoes a small shift (average change = −0.1 D axis 180) toward with-the-rule astigmatism at the highest level of accommodation. The tendency for vertical coma (Z7) to become more positive at the highest accommodative state could be explained by the lens with negative spherical aberration dropping relative to the pupil. However, our results cannot confirm that.

Discussion

The distribution of high-order aberrations in the relaxed eyes in our study is in good agreement with previous studies (Porter et al., 2001; Thibos et al., 2002a, 2002b). Each high-order Zernike coefficient averages around zero, with the exception of spherical aberration. The average spherical aberration (+/- SD) at the resting state is +0.065 +/- 0.083 micrometers in our study, smaller than that re-

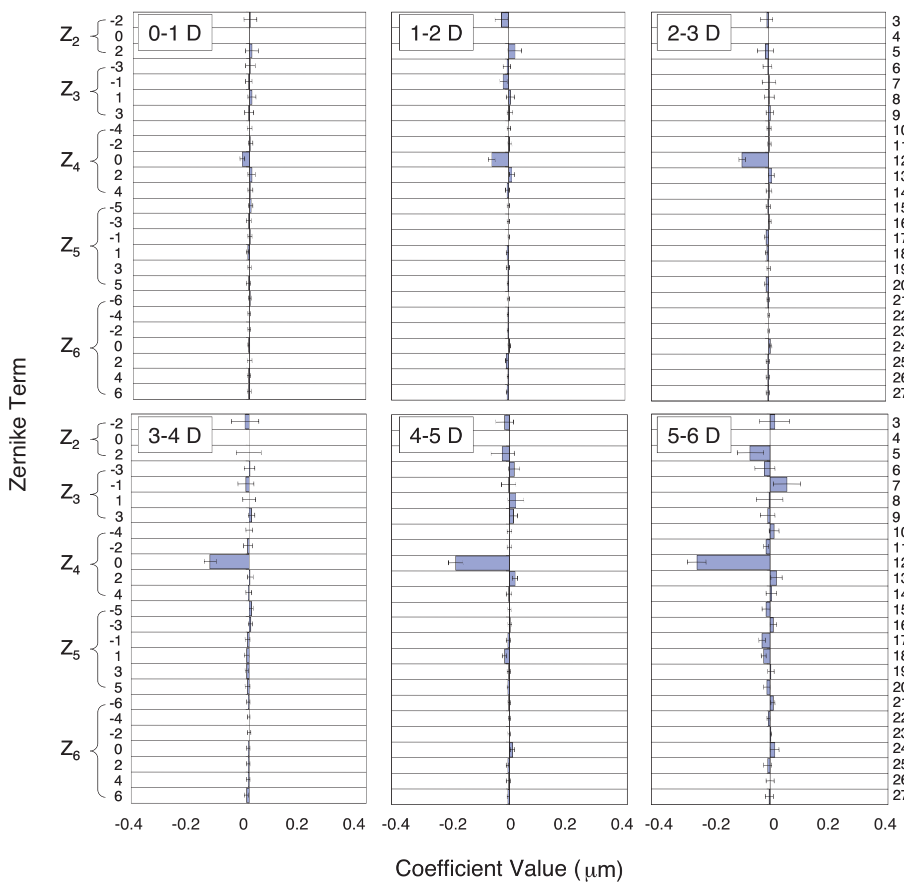

Figure 5. Average change in each Zernike coefficient as a function of accommodation. All terms average to zero, indicating that the changes are not systematic, except for spherical aberration, which becomes more negative. Error bars represent 95% confidence intervals.

ported by Porter et al. (2001). This is likely due to our younger population because spherical aberration becomes more positive with age (McLellan, Marcos, & Burns, 2001; Glasser & Campbell, 1998). Although the effect of natural accommodation could not be completely ruled out, it probably did not play a significant role because care was taken to relax the accommodation. The average *SD* for all subjects for the 0 D stimulus was +/– 0.135 D for defocus, indicating a stable accommodative state. In young human eyes, it is known that the positive corneal spherical aberration is partially balanced by the negative spherical aberration of the internal optics, mainly the crystalline lens (Artal, Guirao, Berrio, & Williams, 2001; He, Gwiazda, Thorn, & Held, 2003a; El Hage & Berny, 1973; Smith, Cox, Calver, & Garner, 2001). The positive spherical aberration we observed for the whole eye thus represents the residual positive spherical aberration from the anterior corneal surface.

It is still controversial if the cornea changes shape and curvature during accommodation. Some found a steepened corneal curvature during accommodation (Yasuda, Yamaguchi, & Ohkoshi, 2003), others found no change (Buehren, Collins, Loughridge, Carney, & Iskander, 2003) or a flattened corneal curvature (Pierscionek, Popiolek-Masajada, & Kasprzak, 2001). Despite possible changes in the corneal shape and curvature with accommodation, it seems that the change of corneal aberrations during accommodation is relatively small (He, Gwiazda, Thorn, Held, & Huang, 2003b). Actually, He et al. (2003b) reported a very small positive shift of corneal spherical aberration with accommodation.

The change in optical aberrations with accommodation can be attributed largely to the changes of the crystalline lens. The crystalline lens shows an increase of the anterior lens curvature centrally and possibly a flattening of the lens peripherally during accommodation (Brown, 1973; Koretz, Handelman, & Brown, 1984; Garner & Yap, 1997). In fact, a negative shift in the spherical aberration has been observed in the in vitro lenses of both young humans (Glasser & Campbell, 1998) and monkeys (Roorda & Glasser, 2004). A tilt or vertical shift of the lens during accommodation may create a change in coma and astigmatism, although the direction of such changes is less predictable, consistent with the largely variable changes observed for both of these terms in the current study.

In the results, we described in detail how individual aberration terms change as a function of accommodation. However, the image quality is related to the overall wavefront errors, thus it is important to know how accommodation affects the RMS of the total aberrations. We are beginning to learn that for the level of aberration in the human eye, the RMS wave aberration is not the best indicator of image quality (Applegate, Marsack, Ramos, & Sarver, 2003) and that other metrics may be more suitable (Guirao & Williams, 2003; Marsack, Thibos, & Applegate, 2004; Cheng, Bradley, & Thibos, 2004; Thibos, Hong, Bradley, & Applegate, 2004). However, the RMS is a standard metric to quantify the magnitude of the change in aberration, which is why we report it here. In Figure 6, the blue bars represent the population average of the RMS of all aberrations (excluding defocus) as a function of the change in accommodative response. Despite large individual variations, the mean RMS does not change for accommodation up to 3.0 D, after which there is a tendency for the RMS to increase. For accommodation levels greater than 3.0 D, the mean RMS is significantly different ($P < 0.05$) from that at the relaxed state. The trends in the RMS-accommodation function described above can be predicted by looking closer at the changes of individual Zernike terms with accommodation. As shown in Figure 7, spherical aberration generally decreases from an average positive to an average negative value and, plotted alone, would generate a V-shaped RMS

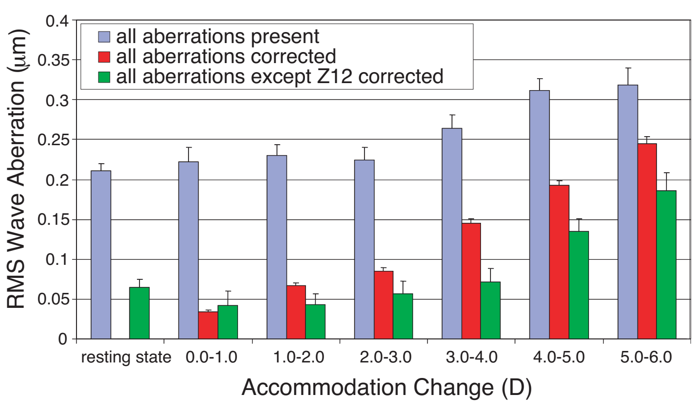

Figure 6. The population mean for the RMS of all aberration terms (Z3, Z5-Z27) for 74 subjects as a function of accommodation under three different conditions: all aberrations present (blue bars), all aberrations corrected for the relaxed state (red bars), and all aberrations except spherical aberration corrected for the relaxed state (green bars). For each condition, the astigmatism is corrected in the resting state and only the changes in astigmatism are included for the accommodated states. Error bars represent 1 SEM.

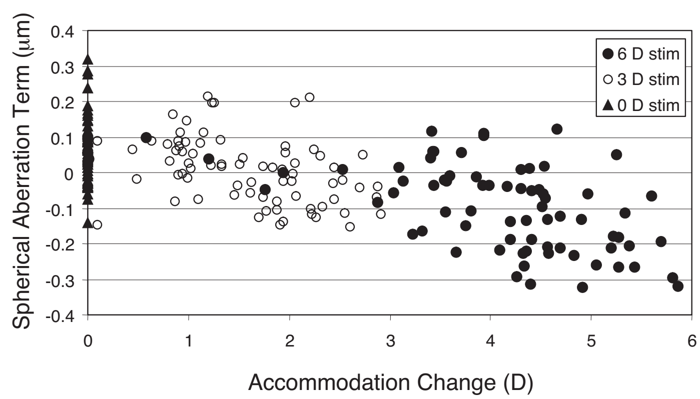

Figure 7. The coefficient for spherical aberration as a function of the change in accommodative response for all subjects under three different stimulus conditions: triangles for 0 D, empty circles, and filled circles for 3 D and 6 D, respectively.

function. The RMS of spherical aberration reaches a minimum at an accommodative level near 2 D. The RMS of astigmatism and third-order coma should gradually increase with accommodation. Other terms' contribution to the RMS is largely unchanged with accommodation. So the overall effect on the total RMS reflecting the RMS of spherical aberration, astigmatism, and coma is a flat curve up to a moderate accommodative level followed by a tendency to increase at higher accommodative levels.

The systematic decrease in spherical aberration with accommodation raises an interesting question regarding the strategy of wavefront correction for high-order aberrations. Is it advantageous to leave spherical aberration uncorrected when attempts are made to eliminate all high-order aberrations for distance vision in a young eye (Ninomiya et al., 2002)? Figure 6 compares the mean RMS of total aberrations (excluding defocus) as a function of accommodation under three different conditions: all aberrations present (blue bars), all aberrations corrected for the relaxed state (red bars), and all aberrations except spherical aberration corrected for the relaxed state (green bars). (See the "Appendix" for a description of the special considerations taken when computing the RMS of the difference between two aberration measurements.) The mean RMS is reduced under both corrective conditions for all accommodative levels, although the benefits are less for higher accommodative levels. Obviously, the distance vision benefits the most when all aberrations are corrected for distance. At moderate accommodative levels (1-3 D), there is no significant difference whether correcting spherical aberration or not. However, at high-accommodative levels, it is slightly more advantageous if spherical aberration is left uncorrected (to the extent that RMS wave aberrations can be used to measure changes in image quality). Previous reports on the overall benefits of correcting the aberration for a single accommodative state underestimated the benefit because the noise floor was not properly taken into account (Artal, Fernández, & Manzanera S., 2003) (See "Appendix").

Conclusion

This study includes the largest sample size to date on the changes in aberrations with accommodation in a young population. The data reported generally support the previous literature. However, where several other papers report some variability in the results, particularly with respect to the fact that spherical aberration becomes more negative with accommodation, the current results indicate some strong and predictable trends. For example, given a subject's spherical aberration at the resting state, the spherical aberration in the accommodated state can be predicted (with 95% confidence) to within +/– 0.085 micrometers for a 5-mm pupil.

A typical human eye will benefit at all accommodative states if the aberrations are compensated for the infinity corrected eye. Correcting all aberrations except spherical aberration will provide a slightly lower RMS wave aberration for the highly accommodated eye, but at a cost of a higher RMS wave aberration for distance vision.

Appendix: Noise floor calculations

Care must be taken when computing the RMS of the difference between two wave aberration measurements. This is because there is uncertainty in the estimated value of each Zernike term that describes the wavefront, which will always amount to a positive and finite difference when the RMS of the difference is computed. For example, consider two measurements of a static optical system. Even if the aberration is based on several measurements, the average value of each Zernike term between the two measurements will not be the same. The difference between the terms will average to zero, but the RMS of the difference will always have a positive value. Therefore, the RMS of a *change* of aberrations will be elevated because each value is sitting on a noise floor caused by uncertainty in the measurements. The size of the noise floor depends on the noise in each measurement and is specific to each device and method of data collection.

For our experiment, we computed the value of the noise floor by first determining the average *SD*, term by term, for all of the subjects in the study. The *SD* for each subject was based on three measurements, which itself is not a sufficient number of samples to determine the error, but the average of many subjects is. Once the average *SD* for each term was known, we computed the SEM for each term (SEM = $SD/\sqrt{3}$), considering three measurements. The SE of the difference between two repetitive measurements for each term was calculated as $\sqrt{2}\cdot\mathrm{SEM}$. The noise floor was calculated as the RMS of the SE of the difference for all the terms. For the plots on Figure 4, the noise floor for astigmatism (Z3 and Z5 combined), coma (Z7 and Z8 combined), and spherical aberration (Z12) were 0.044, 0.033, and 0.013 micrometers, respectively. For the total 2^{nd} to 6^{th} order RMS values (excluding defocus), the noise floor was 0.075 micrometers. These amounts were subtracted from each difference value in the scatter plots of Figure 4 and the bar graphs of Figure 6. Not subtracting the noise floor values gives rise to erroneous overestimations of the RMS of the change in aberrations. Incidentally, computing the noise floor also provides a value that indicates the repeatability of the wavefront measurement.

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