Accommodation-Related Changes in Monochromatic Aberrations of the Human Eye as a Function of Age

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Purpose. To investigate the relationship between accommodation and the optical aberrations of the whole human eye, as a function of age.

Methods. Sixty healthy subjects with spherical ametropia in the range ±3 D, astigmatism less than 1 D, corrected visual acuity of 20/18 or better, and normal findings in an ophthalmic examination were enrolled. Subjects were divided into four groups, with age ranges of 19 to 29, 30 to 39, 40 to 49, and 50 to 60 years. Monochromatic optical aberrations and pupil size were measured with a Hartmann-Shack wavefront sensor under monocular viewing conditions, without pharmacological dilation or cycloplegia. Stimulus vergences were in the range of 0 to 5 D, with an increment of 0.5 D. The change in aberration during accommodation for different groups and different pupil conditions (natural and fixed 4-mm pupil) was compared.

Results. Fourth-order spherical aberration (SA) became more negative with accommodation, and the rate of this change was greater in older individuals. For natural pupil conditions, there were no significant differences between age groups in the changes of the higher-order aberrations, coma, and trefoil with accommodation. However, for a 4-mm pupil, the youngest and oldest group showed significant differences in higher order RMS (root mean square) and spherical aberration compared with the other groups. High-order RMS showed a lower increase during accommodation when the pupil accommodative miosis was taken into account (natural pupil condition) than when a fixed 4-mm pupil was used.

Conclusions. Aberrations change with accommodation and with age. SA changes more with accommodation do than other higher-order aberrations. SA becomes more negative with accommodation, and this change is larger in older individuals. Accommodative miosis is useful for ameliorating the increase in higher-order aberrations with accommodation. (*Invest Ophthalmol Vis Sci.* 2008;49:1736–1743) DOI:10.1167/iovs.06-0802

Accommodation in humans is achieved by a change in the dioptric power of the crystalline lens.[1] The accommodative system maintains the image plane close to the fovea, even as the distance of an object changes. Accommodative ability declines progressively during the first 50 years of life. Presbyopia ("aged eye" in Greek) is defined as the slow, normal, naturally occurring, irreversible reduction in maximum accommodative amplitude with increasing age.[2]

As near-work tasks become more important in the evolution of the human species, presbyopia becomes significant, as it is probably the first degenerative physiological process to decrease the quality of life as one ages.[2] For the most part, accommodation and its reduction with age have been measured using two subjective methods, the push-up[3] and the minus lens[4] techniques. Objective methods were commonly based in the use of open-field-of-view autorefractors.[5–8] Several laboratories have used these methods to obtain accurate measurements of accommodation[7–11] and to investigate factors in the response such us ocular monochromatic[12] and chromatic aberrations,[13] object contrast,[14] pupil size,[15] and age.[16]

Recently, automated wavefront sensing has been used to measure the eye's optics in detail for monochromatic light. Nevertheless, investigations of the eye's monochromatic aberrations as a function of accommodation had been made long before these aberrometers become available. To the best of the authors' knowledge, the first of such studies was made by Tscherning.[17] Using subjective methods, he demonstrated a decrease in spherical aberration (SA) with accommodation. The relationship between SA and accommodation has attracted the attention of other well-known researchers in the field of physiological optics. Allvar Gullstrand[18] mentioned it in his acceptance speech to the Swedish Academy of Sciences when he received the Nobel Prize in 1911. Some years later,[19–24] a decrease in SA was found with accommodation, as well as differences between vertical and horizontal meridional powers during accommodation,[21,24–26] indicating that asymmetric aberrations, such as coma or trefoil, can also change with accommodation.

At the end of the past century other researches used an objective aberroscope technique[27,28] to compute third- and fourth-order monochromatic aberrations in three accommodative states—0, 1.5, and 3 D—in 15 subjects aged 17 to 30 years.[29,30] They noted an important contribution of the symmetric aberrations to total aberration, and found considerable variations in aberrations between subjects, as well as a reduction of approximately 0.3 D in longitudinal SA as the accommodation response increased from 0 to 3 D. The same authors reported in a another study[31] a similar change in SA (~0.2 D) over the same range of accommodation, but in a larger sample of subjects. Similar results were being obtained in 1993 by other investigators[32] who computed the wavefront aberration along the horizontal meridian (over a 6-mm pupil) in four subjects aged 22 to 31 years, as the accommodative stimulus was set to 0.5, 1, 2, 2.5, or 4 D. Recently, a decrease in SA with accommodation was measured in young subjects (mean age, 29 years) with a spatially resolved refractometer.[33] Similar

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results were obtained by using a Shack-Hartmann wavefront sensor-based aberrometer[34] in 33 subjects (mean age, 28.7 years).

In addition to changes in individual aberration terms, several investigators have reported the effect of accommodation on overall wave aberrations, as measured by the root-mean-square (RMS) or the variance of the wavefront error.[30,31,33,34] A few research groups[30,34] found no change in the RMS of the total higher-order aberrations over the accommodative range of 0 to 3 D. One of the largest studies[35] reported a wide variability between subjects, and a significant decrease in SA during accommodation (76 subjects, mean age 24.8 ± 4.0 years). Coma and second-order astigmatism also changed, but in a manner that was idiosyncratic to individual subjects.

Considering the existing literature, it may be concluded that aberrations differ considerably between individuals, which means that higher-order RMS is similar for different states of accommodation and that SA decreases for most individuals with increasing accommodation. In some individuals, the sign of SA changes from positive to negative with increasing accommodation. However, despite the large number of research studies, the subjects in these studies were all young—rarely older than 35 years. In addition, pupil size plays a crucial role in determining the effects of higher-order aberrations on visual performance[36] and to our knowledge, no studies reporting aberration changes with age during accommodation considered accommodative miosis.

The purpose of the present study was to investigate the relation between accommodation and the optical quality of the eye as a function of age.

METHODS

Subjects

Sixty subjects were enrolled in the study. They had a mean age of 41.27 ± 13.11 years. Subjects were divided into four groups based on age: group A (12 subjects; age range, 19–29 years; mean, 21.08 ± 2.27); group B (13 subjects; age range, 30–39 years; mean, 36.08 ± 1.55); group C (14 subjects, age range, 40–49 years, mean 44.43 ± 3.01 years); and group D (21 subjects, age range, 50–60 years, mean 53.90 ± 2.76 years). All subjects had healthy eyes with no history of ocular abnormality. Spherical ametropia was in the range −3 D through +3 D, astigmatism was less than 1 D, and best-corrected visual acuity was equal to or better than 20/18. The subjects were recruited in Murcia, Spain, and Paris, France. Experimental procedures and data analysis were the same at both sites. The tenets of the Declaration of Helsinki were adhered to, and informed consent was obtained from each subject.

Experimental Procedures

Ocular wavefront aberrations were recorded using a wavefront aberrometer (irx3; Imagine Eyes, Orsay, France). This device is based on the Hartmann-Shack aberrometer technique previously introduced by Liang et al.[37] It uses a near-infrared light source of wavelength 780 nm, and a 32 × 32 microlens array sensor with an acquisition time of 33 ms. The built-in fixation target is a letter E or a polychromatic drawing of a balloon at the end of a road. Target luminance was held at approximately 50 cd/m^{-2}.

We performed the same series of experiments in right and left eyes. Each subject viewed targets monocularly under natural conditions, without pharmacological dilation or cycloplegia. Subjects did not wear refractive corrections during experimental trials because the aberrometer's internal Badal system can compensate for spherical refractive error. We first measured ocular aberrations with minimal accommodation (when the eye focuses at its far point). An automatic iterative fogging procedure minimized the subject's accommodation. Then, the stimulus vergence was increased from 0 to 5 D (near vision) in steps of 0.5 D. Thus, 11 wavefront measurements were recorded for each eye. After each step, the target paused for 2 seconds to allow an appropriate accommodation response. Wavefront aberrations and pupil size were measured at the end of each of these 2-second intervals. The stimulus vergence was calculated in diopters as the difference between the subject's spherical equivalent refraction measured in the nonaccommodated state, and the applied target vergence. According to this convention, 0 stimulus vergence is achieved when the target vergence corresponds exactly to the subject's far point spherical refraction. When the target is moved closer to the eye, its vergence becomes more negative, whereas the stimulus vergence becomes more positive.

Before recording data, we ran at least one training trial for each subject. The subject was asked to continue looking at the smallest visible detail in the stimulus target. After ensuring that the task was well understood, we repeated the procedure and recorded the resultant wavefront data in the form of Zernike expansions. The subject was allowed to blink during the procedure, to avoid increased tear film aberration that might otherwise have occurred during an extended interblink interval.[38–40]

Data Analysis

All Zernike expansions were computed up through the eighth order at two pupil diameters, a natural pupil size, and a 4-mm pupil size. The natural pupil size varied between subjects. It also varied with accommodation level for individual subjects. A 4-mm pupil size was chosen for analysis because it was the smallest diameter measured in the experiment. Zernike coefficients for a 4-mm pupil were obtained from the natural pupil data by masking of lenslet data by a 4-mm aperture and recalculation of coefficients. For each stimulus, we computed the subject's accommodation response by using

$$\text{Accommodation} = \frac{\begin{gathered}-12\sqrt{3}[c(2,0)-c_{\mathrm{F}}(2,0)]+48\sqrt{5}[c(4,0)-c_{\mathrm{F}}(4,0)]\\ -96\sqrt{7}[c(6,0)-c_{\mathrm{F}}(6,0)]\end{gathered}}{-d^2}, \quad (1)$$

where accommodation is expressed in diopters, Zernike coefficients in micrometers, and pupil diameter (*d*) in millimeters. The coefficients $c(2,0)$ $c(4,0)$ $c(6,0)$ and $c_F(2,0)$ $c_F(4,0)$, and $c_F(6,0)$ are the normalized Zernike coefficients for second-order defocus, and fourth- and sixth-order spherical aberration, respectively. Coefficients without a subscript were collected at a particular stimulus level, whereas coefficients with the subscript F where collected with the stimulus placed at the subject's far point.

We computed the change in each Zernike coefficient with accommodation by age group (groups A–D) and plotted it as a function of both accommodation response (equation 1) and stimulus vergence. In this calculation, each Zernike coefficient and paired accommodation response (equation 1) were obtained from the same trial. Then, for each eye, we obtained a maximum of 11 values for each Zernike coefficient, some of which could correspond to the same amount of accommodation. Each Zernike coefficient was then offset in the far point (0 D of accommodation).

Before the procedure, we calibrated the aberrometers by assessing their accuracy and repeatability. We first calibrated the two aberrometers by means of a point source of light placed in front of the instrument at different distances and centered perfectly with respect to its optical axis. The maximum values and standard deviations of the total higher-order aberration, and the Zernike coefficients for coma, trefoil, and SA (fourth- and sixth-order) are shown in Table 1. Coefficients are expressed over a 7.3-mm pupil diameter. Errors were larger when the lag or lead of the measurement was ≤3 D.

Second, we estimated the repeatability of the procedures by obtaining 20 repeated measurements of accommodation on the same eye

TABLE 1. Aberrometer Calibration for Total Higher-Order Aberration, Coma, Trefoil and Fourth- and Sixth-Order SA

	Higher-Order	Coma	Trefoil	Fourth-Order SA	Sixth-Order SA
Maximum error	0.0492	0.0339	0.0160	0.0028	0.0051
SD	0.0059	0.0102	0.0046	0.0083	0.0023

Data are maximum error and SD in micrometers.

of a trained 38-year-old subject with a natural pupil diameter. The range of stimulus vergences studied was 8 D, larger than the subject's amplitude of accommodation. In this report we use negative values for the stimulus vergence when the object is in front of the subject (real objects). Results are depicted in Figure 1.

The standard deviations of the Zernike coefficients (in micrometers) in 20 repeated measurements are shown in Table 2 for the same subject. Coefficients are expressed over a 3-mm pupil diameter.

The relationship between change in RMS wavefront error, SA, coma, and trefoil as a function of accommodation, was modeled by using linear regression. A best-fit line was calculated, thus, differences in tendencies between age groups manifested as changes in the slope of the linear fit. These differences were analyzed with a commercial software package (SPSS, ver. 11.5.1; SPSS, Chicago, IL).

RESULTS

Results were analyzed for the natural pupil size, and for a 4-mm pupil size and are depicted in Figures 2 through 6. For clarity, Figures 2, 3, 5, and 6 show the change of the aberration (RMS or SA) during accommodation with respect to the value obtained in the unaccommodated state. The relationship between higher-order RMS error (micrometers) and accommodation for a natural pupil is shown in Figure 2. The RMS value is calculated on the third though eighth Zernike orders. The relationship between spherical aberration (c_4^0) and accommodation for a natural pupil is shown in Figure 3. Each figure is divided into four panels labeled according to the four age groups considered; consequently, as the age of the group increases, its corresponding panel shows lower values of accommodation.

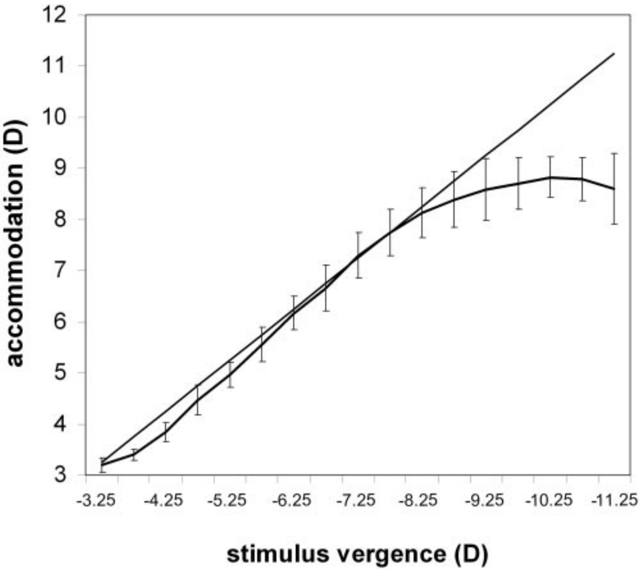

FIGURE 1. Accommodation response as a function of stimulus vergence, based on 20 measurements in the same 38-year-old eye. Error bars, 2 SD.

Group D showed the largest change in higher-order RMS error with accommodation (slope = 0.034) and group C the smallest (slope = 0.017; Fig. 2). There is a strong correlation between SA and accommodation in all age groups (Fig. 3), even though accommodation in the two older groups (C and D) has a restricted range, especially in group D. For all age groups, there is a trend toward more negative (or less positive) SA values with increasing accommodation. Negative changes increased with accommodation and age (up to about -0.2 μm). By comparing the slopes in each age group (Fig. 3 caption), one may observe a similar change in each group with accommodation.

The data in Figures 2 and 3 represent the change in RMS and SA values with accommodation, rather than the actual values. In addition, the actual Zernike coefficients at various accommodation states are not strictly comparable because they were obtained with natural pupil diameters that differed between subjects. To gain an understanding of the role of the pupil, the change in pupil diameter as a function of accommodation for each age group is plotted in Figure 4. The mean pupil diameter in the unaccommodated state (0 D of accommodation) was: 6.52 ± 0.90, 5.86 ± 1.02, 5.48 ± 0.94, and 4.9 ± 0.64 mm in groups A, B, C and D, respectively.

The change in higher-order RMS error and SA as a function of accommodation for a 4-mm pupil are shown in Figures 5 and 6, respectively. The results for a 4-mm pupil differ from those for the natural pupil. The higher-order RMS increased with accommodation in all age groups (Fig. 5). Note that the slope increases with age, by a factor of 5.6 from the youngest to the oldest group. When SA was analyzed, we found a strong correlation between changes in RMS SA and accommodation in all groups (Fig. 6). As for natural pupils, the trend in all age groups was toward more negative (or less positive) SA values with increasing accommodation. However, with a 4-mm pupil there were important differences in the slope values ([μm/D] $-$ 1) between young and old subjects. The slope magnitude decreases by a factor of 6.4 between groups A and D.

To describe the trends that emerged among the age groups, we performed a statistical analysis to compare linear tendencies between groups for natural and 4-mm pupils (Table 3). Pair-wise comparisons by *t*-test were made between age groups by using as a dependent variable the slope of the linear regression for change in (1) higher-order aberration, (2) spherical aberration, (3) coma, and (4) trefoil, as a function of accommodation. A general linear model was used to test the null hypothesis of equality of slopes. A nominal type-I error rate of 0.05 was used. However, due to multiple pair-wise comparisons, a Bonferroni correction was applied. With this correction, a significance difference in slopes occurred at $P < 0.0083$.

Several conclusions may be drawn from the statistical analyses presented in Table 3. (1) Groups B and C have similar slope tendencies for higher-order aberrations, coma, trefoil, and SA, for natural and 4 mm pupils. (2) With a natural pupil, there are no significant differences in slopes between groups

TABLE 2. Standard Deviation of Zernike Coefficients Obtained in 20 Repeated Measurements in a 38-Year-Old Eye

	Stimulus Vergence (D)							
	−3.25	**−4.25**	**−5.25**	**−6.25**	**−7.25**	**−8.25**	**−9.25**	**−10.25**
c_2^{-2}	0.0376	0.0256	0.0353	0.0374	0.0368	0.0365	0.0296	0.0396
c_2^{0}	0.0533	0.0661	0.0482	0.0645	0.0779	0.0834	0.1588	0.0885
c_2^{2}	0.0464	0.0374	0.0309	0.0372	0.0364	0.0493	0.0384	0.0369
c_3^{-3}	0.0183	0.0161	0.0213	0.0150	0.0265	0.0176	0.0228	0.0185
c_3^{-1}	0.0141	0.0150	0.0169	0.0173	0.0154	0.0236	0.0243	0.0246
c_3^{1}	0.0148	0.0174	0.0279	0.0198	0.0229	0.0138	0.0228	0.0206
c_3^{3}	0.0179	0.0181	0.0195	0.0180	0.0231	0.0177	0.0208	0.0294
c_4^{-4}	0.0097	0.0132	0.0133	0.0134	0.0112	0.0088	0.0156	0.0131
c_4^{-2}	0.0087	0.0075	0.0112	0.0135	0.0119	0.0096	0.0114	0.0135
c_4^{0}	0.0081	0.0118	0.0147	0.0116	0.0125	0.0116	0.0140	0.0150
c_4^{2}	0.0106	0.0147	0.0160	0.0205	0.0092	0.0158	0.0176	0.0181
c_4^{4}	0.0131	0.0129	0.0121	0.0120	0.0129	0.0145	0.0147	0.0096
c_6^{0}	0.0111	0.0085	0.0102	0.0106	0.0096	0.0067	0.0082	0.0074

Data are standard deviation of Zernike coefficients in micrometers. Coefficients are expressed over a 3-mm pupil. Stimulus vergence varied between 3.25 and 10.25 D.

for any aberration except for high-order RMS between groups C and D. (3) For a 4-mm pupil, significant differences in slopes appear between the youngest (A) and the oldest (D) groups, but only for higher-order aberrations and spherical aberration.

In addition, we performed similar *t*-tests with pupil as the factor (natural, or 4-mm), using as the dependent variables the slope of change in higher-order RMS or SA as a function of accommodation. This analysis was restricted to subjects in the same age group. Statistically significant differences ($P \leq 0.015$) in the higher-order RMS were found between pupil conditions for all age groups. In the case of SA the test revealed that only the slopes that are significantly different between pupil conditions correspond to groups A and C: $P = 0.542$ for group A, $P \leq 0.001$ for group B, $P = 0.569$ for group C, and $P \leq 0.001$ for group D.

DISCUSSION

In the present study we investigated further the relationship between accommodation and the optical quality of the eye as a function of age. The importance of this research lies in extending basic knowledge of physiological optics and in clinical applications such as the optical designs of ophthalmic lenses, contact lens, or intraocular lenses to correct presbyopia.

Objective Measurement of Accommodation

These are the first objective accommodation measurements obtained by means of wavefront aberrometry over a large range of ages. The results of repetitive measurements in the same subject showed small variations (<1 D) in the accommodation response and small values for the SD of the Zernike coefficients (< 0.05 μm for a 3-mm pupil, excluding defocus). Moreover, values for the maximum apparatus errors for different aberrations (Table 1) are small compared with values typically present in normal eyes.[41-45] This demonstrates that the aberrometer provided reliable results, even in aged eyes where the pupil is usually small. The experimental system also allowed us to introduce two important variables in our study: pupil size and accommodation. Pupil size varies both with the subject's age and during accommodation. In addition, pupil size is critical for determining the accommodation level from aberrometer readings (equation 1). Pupil size, and more recently SA,[46-48] have been crucial in the precise determination of the accommodation state.

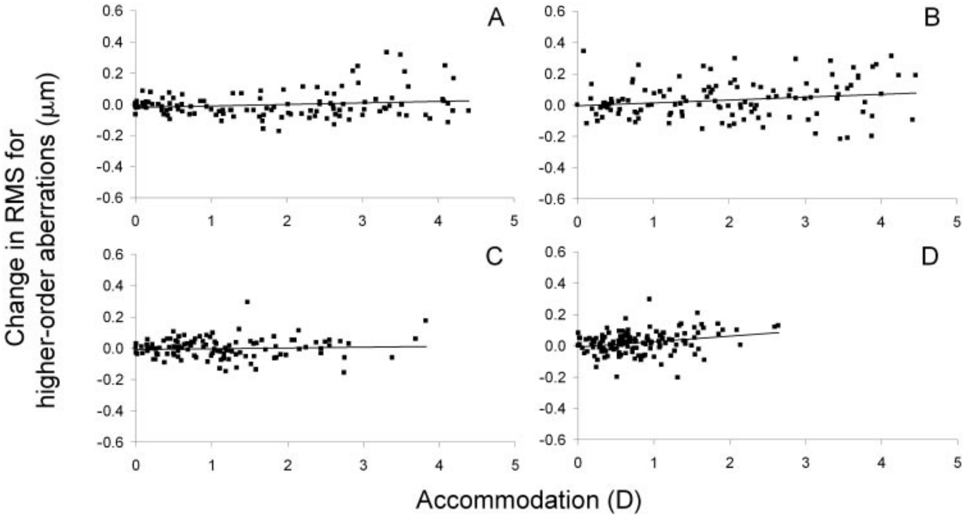

FIGURE 2. Change in RMS wavefront error for third- through eighth-order Zernike coefficients as a function of accommodation for the natural pupil, shown by a series of four age graphs. Continuous lines represent the best linear trend equation. (**A**) 19–29 year group, $y = 0.010x - 0.022$, $r = 0.163$. (**B**) 30–39-year group, $y = 0.017x - 0.002$, $r = 0.205$. (**C**) 40–49-year group, $y = 0.005x - 0.006$, $r = 0.071$. (**D**) 50–60-year group, $y = 0.034x - 0.006$, $r = 0.297$.

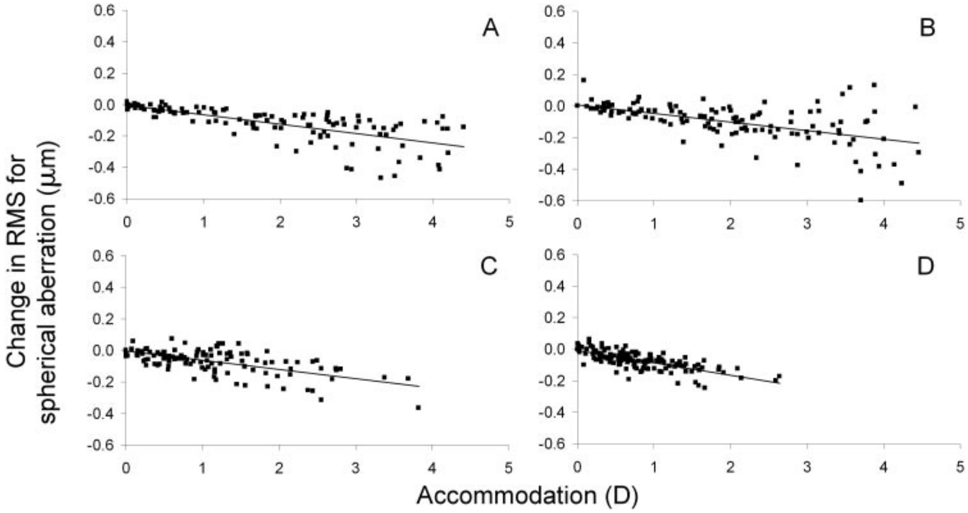

Figure 3. Change in RMS wavefront error for spherical aberration (c_4^0) as a function of accommodation for the natural pupil, shown by a series of four age graphs. Continuous lines represent the best linear trend equation. (**A**) 19–29-year group, $y = -0.059x - 0.006$, $r = 0.739$. (**B**) 30–39-year group, $y = -0.054x + 0.006$, $r = 0.596$. (**C**) 40–49-year group, $y = -0.057x - 0.005$, $r = 0.652$. (**D**) 50–60-year group, $y = -0.078x - 0.008$, $r = 0.767$.

Effect of Changes in Pupil Miosis

As mentioned in the results, the effect of pupil miosis with accommodation on the optical quality of the eye may be observed by comparing the slopes of the fits for natural and 4-mm pupil (Figs. 2, 5 and Figs. 3, 6). With no exception, the slopes of the high-order RMS corresponding to the natural pupil are smaller than those for the 4-mm pupil: $P \leq 0.001$ for group A; $P \leq 0.001$ for group B; $P = 0.004$ for group C; and $P = 0.015$ for group D. This result was expected due to the effect of pupil size on higher-order aberrations.[36] However, it is interesting to point out that in several cases, such as with coma RMS and trefoil RMS, the slope passes from a positive to a negative value in most of the groups, showing the optical benefit of the accommodative pupillary miosis. A comparison of Figures 2 and 5 and Figures 3 and 6 shows that the eye tends to avoid, partially, the effects of higher-order aberrations and that the change in spherical aberration increases during accommodation. This increase is accomplished through optical changes in the lens that take place as the pupil size is reduced (Fig. 4 shows the reduction in the different age groups). However, *t*-tests for differences in slopes between pupil conditions (natural, or 4-mm) within the same age groups only showed significantly different slopes between groups A and C in the case of spherical aberration.

Effects of Age

Intergroup comparisons show the effect of aging on the changes of aberration with accommodation. In general, the slopes did not change sign, except for coma in group B and trefoil in group D. However, the values of the slopes were very small (≤0.005), so that these statistically significant changes (Table 3) could be considered a result of the number of the subjects analyzed. The increase in higher-order aberrations with age observed in our study (and by other groups[44,45]) is more pronounced with higher accommodation, as shown in Figure 2. It could be argued that this increase is due to the smaller accommodative pupillary miosis observed in older individuals (see slope values in Fig. 4). However, even when pupil diameter is fixed (at 4 mm), there is a larger and significant increase (Table 3) of higher-order aberration per diopter of accommodation in the oldest group (D) compared with the youngest group (A), while groups B and C do not follow this tendency (Fig. 5).

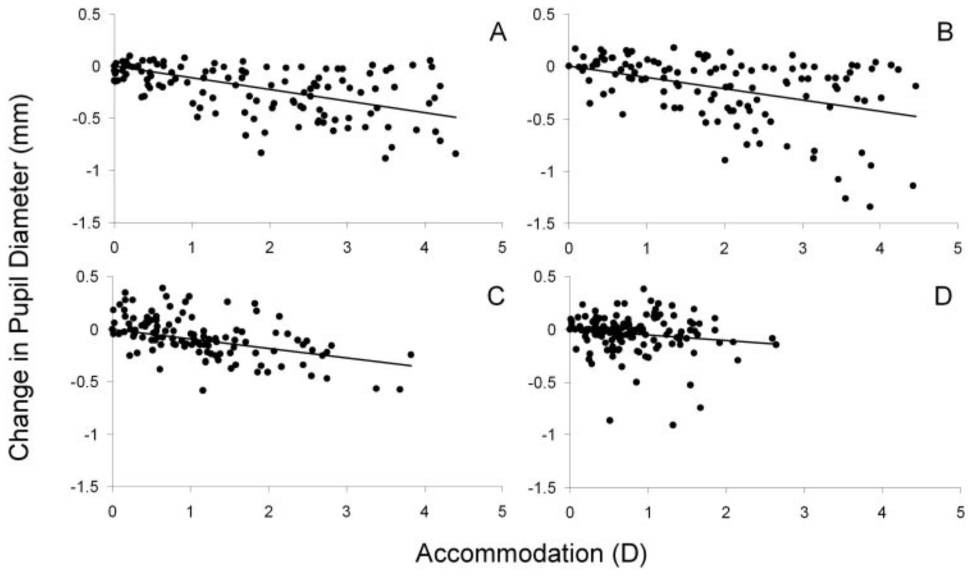

Figure 4. Change in pupil diameter in each age group as a function of accommodation. Continuous lines represent the best-fit linear equation. (**A**) 19–29-year group, $y = -0.111x$, $r = 0.510$. (**B**) 30–39-year group, $y = -0.106x$, $r = 0.473$. (**C**) 40–49-year group, $y = -0.093x$, $r = 0.523$. (**D**) 50–60-year group, $y = -0.053x$, $r = 0.164$. See the text for the mean and SD values for 0 D of accommodation.

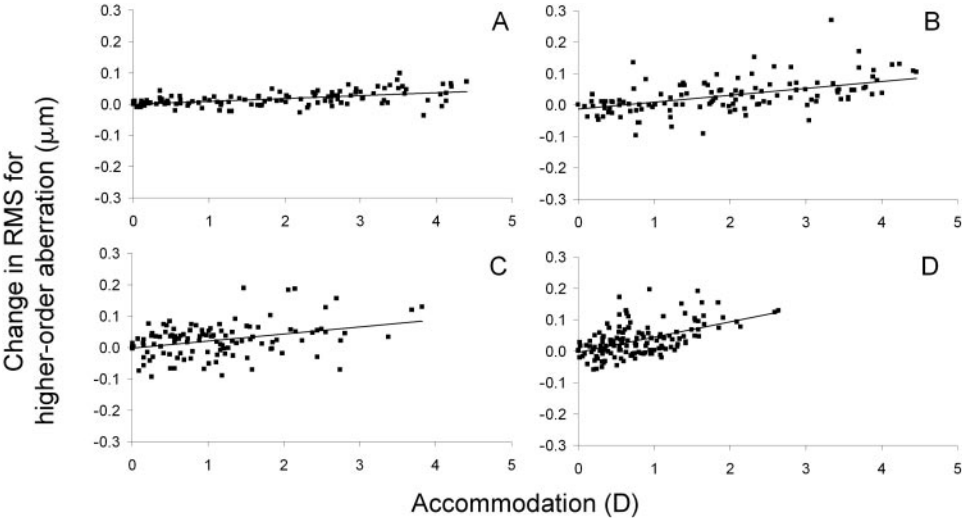

FIGURE 5. Change in higher-order RMS wavefront error for third- through eighth-order Zernike coefficients as a function of accommodation for a 4-mm pupil, shown by a series of four age graphs. Continuous lines represent the best-fit linear trends. (**A**) 19–29-year group, $y = 0.009x - 0.001$, $r = 0.544$. (**B**) 30–39-year group, $y = 0.022x - 0.014$, $r = 0.552$. (**C**) 40–49-year group, $y = 0.022x - 0.002$, $r = 0.382$. (**D**) 50–60-year group, $y = 0.048x - 0.004$, $r = 0.563$.

Although some higher-order aberrations such as fourth-order spherical aberration decrease with accommodation, we found a small increase of higher-order aberration RMS with accommodation. This change can be explained by taking into account that other higher-order aberrations (not shown) increase with accommodation.

Spherical Aberration Changes: Comparison with Eye Model

Among the many eye models that have been proposed,[49] some include optical changes with accommodation[50] and others with age.[51–53] In some cases, models include a gradient index lens,[54–57] but to our knowledge, none include all three variables of age, accommodation, and a gradient index for the crystalline lens. Probably, the most popular eye model that includes accommodation was proposed by Navarro et al.[50] Their model, which was based on measurements of adult eyes, modifies its anterior chamber depth, and crystalline lens radii of curvature and index of refraction with accommodation. The change in SA with accommodation for a young subject using the Navarro eye was computed with a ray-tracing program (Zemax, Bellevue, WA) and is plotted in Figure 7. The figure also includes the slopes obtained after fitting our results (Figures 2, 3, 5, 6) with a straight line.

It may be observed in Figure 7 that for a 4-mm pupil, our results lay between the eye model proposed. For a natural pupil, we repeated the procedures by including in the eye model the mean pupil diameters obtained in our own study (Fig. 4). Thus, the model considers accommodative pupil miosis as well. In this case, the model in Navarro et al. predicts our results very well.

There is also an interesting effect produced by the changes in spherical aberration during accommodation, if we calculate the real accommodation level with equation 1. That equation indicates that accommodation depends on the SA. Thus, when large values of SA (fourth- and sixth-order) are present during a brief change of accommodative response, a form of negative feedback occurs. This reduces the change of defocus to obtain the same amount of accommodation. The effect of fourth-order spherical aberration in the accommodative response has been noted by other researchers[46–48] and, together with sixth-order spherical aberration, has recently been shown to have an important effect on accommodation. In our study, this effect is so important that if we do not take into account the slope for the fourth-order SA in the oldest group, the slopes in Figures 3D and 6D would be positive instead of negative.

Finally, our results show that there is a small amount (<1.5 D) of real accommodation (not pseudoaccommodation) in eyes

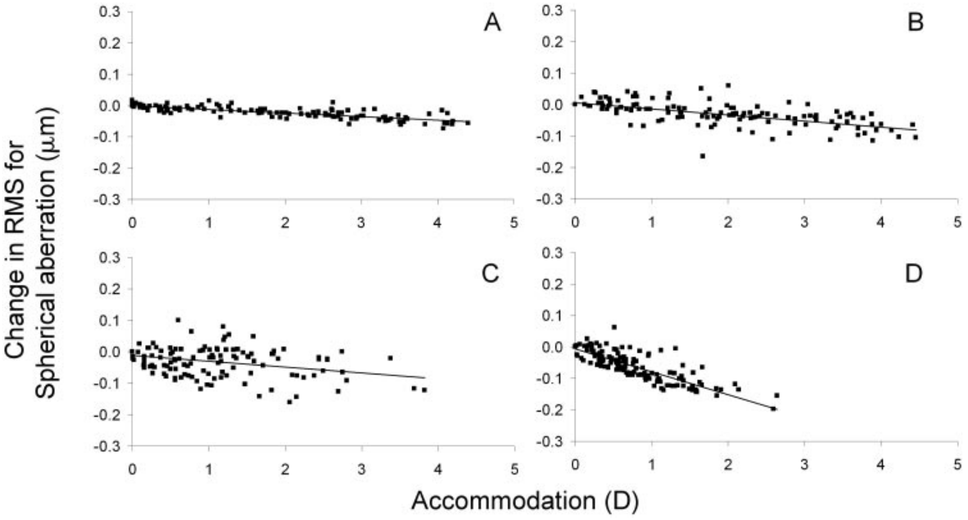

FIGURE 6. Change in RMS wavefront error for spherical aberration (c_4^0) as a function of accommodation for a 4-mm pupil, shown by a series of four age graphs. Continuous lines represent the best-fit linear trends. (**A**) 19–29-year group, $y = -0.011x - 0.001$, $r = 0.811$. (**B**) 30–39-year group, $y = -0.019x + 0.005$, $r = 0.655$. (**C**) 40–49-year group, $y = -0.018x - 0.011$, $r = 0.347$. (**D**) 50–60-year group, $y = -0.072x - 0.005$, $r = 0.844$.

TABLE 3. Pair-Wise Comparisons between Age Groups

	Natural Pupil Age Group (y)				4-mm Pupil Age Groups (y)		
Age Group (y)	**19–29**	**30–39**	**40–49**		**19–29**	**30–39**	**40–49**
Higher-order aberrations							
30–39	0.394	1	0.242	30–39	0.000*	1	0.935
40–49	0.564	0.242	1	40–49	0.002*	0.935	1
50–60	0.028	0.218	0.006*	50–60	0.000*	0.000*	0.001*
Coma							
30–39	0.54	1	0.639	30–39	0.017	1	0.219
40–49	0.172	0.639	1	40–49	0.895	0.219	1
50–60	0.222	0.755	0.927	50–60	0.466	0.766	0.632
Trefoil							
30–39	0.135	1	0.646	30–39	0.087	1	0.182
40–49	0.400	0.646	1	40–49	0.733	0.182	1
50–60	0.330	0.934	0.762	50–60	0.793	0.351	0.964
Spherical Aberration							
30–39	0.526	1	0.765	30–39	0.000*	1	0.911
40–49	0.786	0.765	1	40–49	0.000*	0.911	1
50–60	0.034	0.032	0.013	50–60	0.000*	0.000*	0.000*

Comparisons (*P*) are shown for higher order RMS, coma, trefoil and spherical aberration, with a natural pupil or a 4-mm. Probabilities obtained by *t*-test for pair-wise comparisons between age groups.

* Probability values significant at the Bonferroni-corrected level are denoted by an asterisk.

older than 50 years, mainly because of pupil miosis and the decrease in spherical aberration.

CONCLUSIONS

As has been reported before,[1,17,19,30,32–35,44,45] our results confirm that aberrations change with accommodation and with the age of the subject. Although there is large intersubject variability, the change of RMS higher-order aberrations with accommodation remains similar with age for a natural pupil, and increases for a fixed pupil diameter (4 mm). Then, in addition to increasing the depth of field, accommodative pupillary miosis seems to ameliorate, partially, the increase in higher-order RMS error caused by optical changes in the eye during accommodation (as could be expected, because the eye increases its power). We conclude that this "defense" against higher aberrations—which reduces the losses in retinal image quality—occurs not only in the young eye, where accommodative miosis is more pronounced, but also in the presbyope.

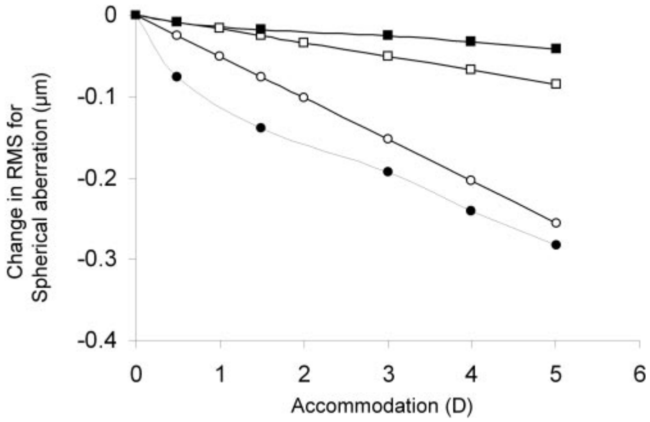

FIGURE 7. Change in RMS wavefront error for spherical aberration (c_4^0) as a function of accommodation for Navarro's eye model, and laboratory measurements. (■) Navarro's eye model for a 4-mm pupil; (□) laboratory measurements for a 4-mm pupil; (●) Navarro's eye model for the natural pupil of the laboratory study; (○) laboratory measurements for a natural pupil.

As previously reported by others,[1,19,20,29,30,32–35,46,47] SA shows greater changes as a function of accommodation than any other higher-order aberrations. Without exception, SA becomes more negative (or less positive) with accommodation. The ratio of change in SA per diopter of accommodation becomes larger as the eye ages. This effect could assist the aged eye by increasing slightly its amplitude of accommodation. Finally, the measured change in fourth order SA during accommodation is similar to that predicted by the Navarro eye model.

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