Does the chromatic aberration of the eye vary with age?

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The longitudinal chromatic aberration of the eye has been reported to decline with age. Using three different methods, we have measured the aberration in a group of young subjects (27–33 years old) and a group of older subjects (48–72 years old). In two of the methods we used a Badal optometer, either with or without an achromatizing lens incorporated, to examine the effect of wavelength on refractive error. In the third method we used a vernier-alignment apparatus to assess chromatic dispersion directly. None of the results of the experiments performed revealed any difference in aberration between the groups. Furthermore, a linear regression of aberration against age showed no relationship between these variables. We conclude that, for human adults, the magnitude of chromatic aberration is independent of age.

INTRODUCTION

The refractive indices of the ocular media are wavelength dependent, and, as a consequence, the power of the human eye varies over the visible spectrum. Both Young and Helmholtz demonstrated this variation in power, or longitudinal chromatic aberration, in their own eyes.[1] Subsequently Wald and Griffin[2] and Bedford and Wyszecki[3] measured this aberration and showed that the power of the human eye changes by slightly more than 2 D over the visible spectrum.

In 1976 Millodot[4] reported that the longitudinal chromatic aberration of the human eye declined with age. This was taken as evidence that the dispersions of the ocular media change as a person gets older.[4,5] Millodot reported that subjects over 50 years of age became almost achromatic; however, subsequent studies failed to confirm this surprising result. Although Ware[6] and Pease and Cooper[7] argued that longitudinal chromatic aberration does not change with age, Mordi and Adrian[8] agreed with Millodot that the aberration declines with age; however, they reported a smaller decrease than that found by Millodot.

In most of the above-mentioned studies,[2–4,6] the change in power of the eye with wavelength was measured by using techniques that required subjects to assess the clarity of focus of a target. Either the position of the target or the power of an optical system was altered until the subject judged the target to be in focus. The validity of this technique for investigating changes in chromatic aberration with age rests on the assumption that the subjects' ability to assess the precision of focus does not vary with either age or wavelength. However, it is known that both the pupil size (and hence the depth of field of the eye) and the transmission characteristics of the eye change with age.[9,10] Therefore this assumption may not have been correct in all the studies of age-related changes in longitudinal chromatic aberration, a possibility that could account for the discrepancies among the results of these studies.

If chromatic aberration does decrease with age, there are a number of important consequences both for ocular measurements and for vision itself. Many ocular instruments, such as infrared optometers, are designed and used with the implicit assumption that human chromatic aberration is invariant.[11,12] The magnitude of the aberration is assumed to be that of young subjects, and any age-dependent changes would then invalidate the instrument calibration for older people. Similarly, the same implicit assumption is present in vision experiments in which a standard achromatizing lens is used by subjects of various ages.[11–14] If the aberration declines with age, then the efficacy of the achromatizing lens will be reduced for the older subjects, who will be overcorrected by it.

To determine whether chromatic aberration changes with age, we used three separate approaches: two that involved best-focus judgments and one that did not. First, using a Badal optometer, we measured the change in power of the eye with wavelength for a group of young subjects and a group of old subjects. Second, we repeated these measurements while subjects used an achromatizing lens to correct their longitudinal chromatic aberration.[14] Third, we used a different technique, vernier alignment, to measure the aberration.[15,16] In this method, which is based on Newton's chromatic parallax demonstration,[17] subjects are not required to assess the clarity of focus. If the discrepancies in the results of previous studies were related to the psychophysical task, a method involving a different judgment could provide an unambiguous answer to the question of whether human ocular chromatic aberration varies with age.

METHODS

Subjects

Ten subjects participated in the experiments reported here. Four were less than 34 years old (ages 27, 32, 33, and 33 years), and six were considerably older (ages 48, 52, 58, 64, 68, and 72 years). The reduction in aberration reported by

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Millodot[4] was essentially absent for his subjects who were under 40 and almost complete for his subjects who were over 50. Therefore any age-related changes should be clearly evident from a comparison of our two groups.

One of the older subjects (GH, age 64 years) had bilateral intraocular lenses (IOL's), and another (MA, age 68 years) had a similar lens in one eye. The data from these IOL eyes, although not relevant for the question of the age dependence of the complete eye, were taken to permit comparison with phakic eyes. Recently pseudophakes were reported[18] to have slightly less chromatic aberration than phakic subjects, and we wished to examine this finding.

In the experiments described here, subjects had to have a dilated pupil and fixed accommodation. All four younger, prepresbyopic subjects were given two drops of 0.5% cyclopentalate hydrochloride. The pupils of older, presbyopic subjects were dilated with two drops of 1.0% tropicamide as a mydriatic. Pupil diameter and amplitude of accommodation were monitored to ensure effective mydriasis and cycloplegia.

Experiment 1

In the first experiment we used the experimental design and equipment described previously by Howarth and Bradley.[19] A Badal optometer, which has the advantages of a linear scale and a constant retinal image size, was used to measure subjects' far points. A +4.50-D achromat was used as the optometer lens, and hence a 1-cm change in object position corresponded to a 0.2025-D change in vergence at the Badal plane. A movable target, consisting of two vertical hairs, was viewed through the achromat. Light from a tungsten source was collimated and passed through interference filters before backilluminating this target. The filters were calibrated individually by multiplying their radiometric transmission spectra by the human spectral luminosity function and by the spectral output of the tungsten source. The central moments of the resulting distributions were used as our wavelength estimates. Five measurements were taken at each of nine randomly ordered wavelengths: 420, 460, 490, 518, 554, 567, 597, 619, and 645 nm. The subject's task was to move the target back and forth until the position of best focus was found. When a range of settings was acceptable, the subject was instructed to determine the midpoint of the range.

Experiment 2

Using the same equipment and technique as in the first experiment, we obtained a second set of measurements with each subject. However, this second experiment was performed with an achromatizing lens[3,14] placed in front of the eye. This lens was designed to have chromatic aberration equal to but opposite that of the average (young) eye; hence the optical power of the eye–lens combination should be the same at all wavelengths for the younger subjects.

This second experiment served two functions. First, any change in chromatic aberration with age would be seen because the eye–lens combination would no longer be achromatic. If the older eyes showed less aberration than the young eyes, for which the achromatizing lens was designed, then the lens would overcorrect them. However, if there was no change in the aberration with age, then the lens would correct all subjects irrespective of their age. Second, the experiment permitted a quantitative check of the equipment calibration. At each wavelength the difference between the with-lens data from experiment 2 and the without-lens data from experiment 1 should be equal to the power of the achromatizing lens. If the experimental equipment was calibrated incorrectly or if the subjects were not performing the task correctly, an inequality in this comparison would occur.

Experiment 3

In the third experiment we used a separate apparatus, taking advantage of the principle of chromatic parallax used by Ivanoff.[15,20] When viewed through a decentered artificial pupil, a red vernier line and a blue vernier line that are physically collinear appear to be misaligned. For them to appear aligned, an offset must be introduced between them. The size of this offset is a function of both the magnitude of the eye's chromatic aberration and the amount of pupil decentration. By varying the relative position of the artificial pupil, the rate of change of the offset with pupil decentration may be determined. This rate of change, measured in units of radians per meter, was shown previously[15,16] to be equal to the longitudinal chromatic aberration of the eye, in diopters.

Subjects viewed a 2-deg screen, placed 3 m from the eye, the upper half of which was illuminated by 466-nm (blue) light and the lower half of which was illuminated by 615-nm (red) light. The vernier target consisted of two opaque rods, 1 deg long and 7 arcmin wide, that were viewed against this background. The lower rod was movable, its position being read from a machinist's micrometer, and the upper rod was fixed.

Each subject's head was held firmly in position with a head restraint and a bite bar. This rigid assembly was mounted in a machinist's vise, allowing the experimenter to translate the subject's head horizontally, behind a fixed artificial pupil, in 0.05-in. (~0.13-cm) steps. Measurements commenced with the subject positioned so that this aperture was at one edge of the subject's dilated pupil. At each position the subject made four vernier settings, and the experimenter recorded the offset present when the rods appeared to be aligned. When the pupil had been traversed fully, a 0.025-in. (~0.064 cm) shift was introduced, and the sweep was then repeated in the reverse direction. In this way two sweeps were interleaved, and measurements were taken at every 0.025 in. across the pupil.

Most subjects also participated in a control experiment in which both vernier targets were backilluminated by white light.

RESULTS

Experiment 1

In experiment 1 we measured the far-point positions at nine different wavelengths. The dioptric change in power of the eye with wavelength, or longitudinal chromatic aberration, could then be found for each subject.

Data from the right eye of each of the four young subjects are shown in Fig. 1(a), and data from the five phakic older subjects are shown in Fig. 1(b). In order to compare subjects, we first needed to factor out any overall refractive

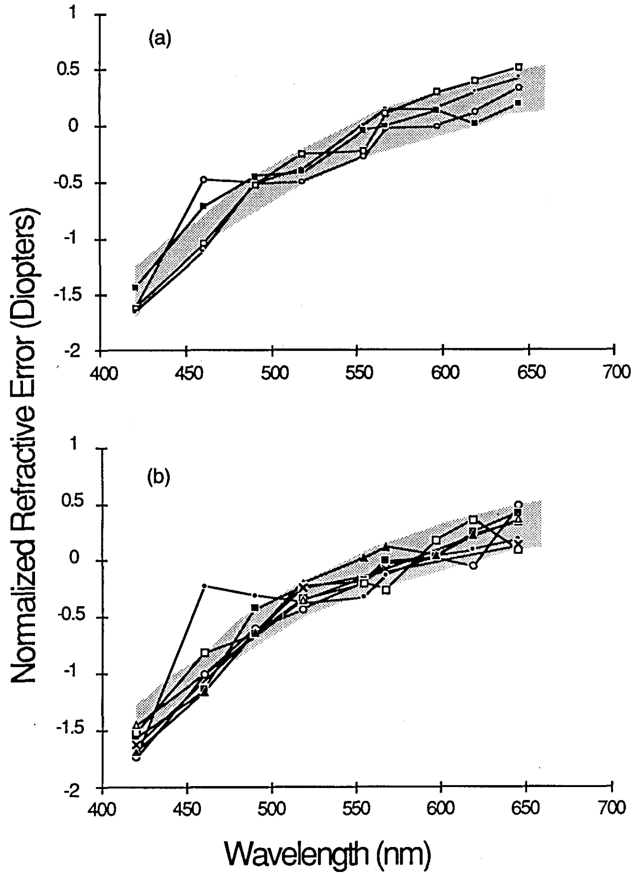

Fig. 1. Results of experiment 1. The change in refractive error, in diopters, is plotted as a function of wavelength, in nanometers. (a) Data from the four young subjects: AB (age 32, filled squares), PH (age 33, open squares), DS (age 33, filled circles), and XX (age 27, open circles). (b) Data from the five older phakic subjects: HH (age 72, filled circles), SH (age 48, open circles), CS (age 58, filled squares), RR (age 52, filled triangles), and MA (age 68, crosses). Also shown in the lower graph are the data from the two eyes with intraocular lenses: GH (age 64, open squares) and MA (age 68, open triangles). For comparison, the shaded area on each graph shows data from the 20 young subjects reported by Howarth and Bradley[19]; the shading indicates ±2 SD from the mean aberration at each wavelength tested. By moving individual data sets vertically, data from each subject have been fitted into these normal limits.

error that an individual may have had. This was done by adding a constant amount at each wavelength to a subject's data, a procedure that affects the vertical position of an individual's function but leaves the change in power with wavelength unaffected. The shaded area of each graph shows normal limits [±2 standard deviations (SD) from the mean of the 20 young subjects, ages 23–43 years, reported by Howarth and Bradley[19]], and the data presented here were normalized by eye to fit within these limits. Whereas some individual points in both Fig. 1(a) and Fig. 1(b) fall outside the shaded area, each subject's data set as a whole can be seen to be within the normal limits. This occurs irrespective of the subject's age and is not simply an artifact of the normalization procedure. A reduction in aberration would reduce the slope of the function, placing it outside the shaded area at both ends of the spectrum, an effect that cannot be produced by the normalization procedure. Hence one conclusion from the first experiment is that the magnitude of each subject's aberration, irrespective of age, was within normal limits.

Also shown in Fig. 1(b) are the data from the two subjects with IOL's [MA (Δ) and GH (□)]. Each function is similar in shape to those of the phakic normals. Although the slopes are shallow, each function falls within the shaded normal area. The aberration shown in these two eyes is slightly less than average, which is consistent with the finding of Rog[18] that chromatic aberration is less in pseudophakic eyes than in phakic eyes. However, surprisingly, the aberrations measured for MA are similar in magnitude in his pseudophakic eye and in his phakic eye.

Experiment 2

The first experiment was repeated, with an achromatizing lens[14] positioned in front of the subject's eye. This lens approximately corrects the average ocular chromatic aberration, providing 1.60 D. of negative aberration between 420 and 645 nm at the Badal plane. If our subjects had exactly this amount of aberration, the lens would correct them; however, if they had either more or less aberration than this it would undercorrect or overcorrect them.

Figures 2(a) and 2(b) show the results for the groups of young and old subjects, respectively. Figure 2(b) also shows

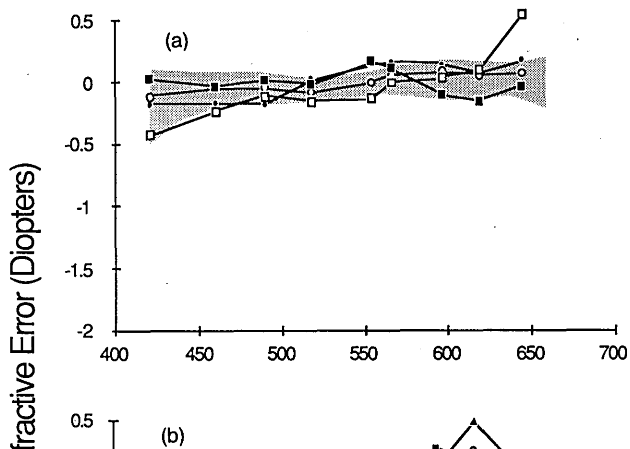

Fig. 2. Results of experiment 2. The change in refractive error is plotted as a function of wavelength; in this experiment subjects used an achromatizing lens to correct their chromatic aberration. (a) Data from the four young subjects. (b) Data from the five older subjects and the two pseudophakic eyes. Symbols are as in Fig. 1. Again, for comparison, the shaded area on each graph shows normal data (±2 SD) from the mean aberration of the 20 young subjects, corrected with the same achromatizing lens, reported by Howarth and Bradley.[19]

the data from the two pseudophakic eyes. The shaded area in each figure shows ±2 SD from the mean of 20 young subjects who were measured by Howarth and Bradley[19] using the same lens that was used in this experiment. The present data have again been normalized by eye, and, as in Fig. 1, it is possible to fit each subject's function to the shaded area. All functions are approximately flat, showing that the lens provides an adequate correction for each subject, irrespective of age.

It is important to note here that data from a subject with little or no chromatic aberration would show a large negative slope. This is clearly not the case for any subject, phakic or pseudophakic, old or young. Although some individual data points from older subjects do fall outside the shaded area, there is no large systematic trend present in any subject's data. We conclude that the magnitude of longitudinal chromatic aberration does not vary with age.

Equipment Calibration

As was explained above, a quantitative comparison between the with-lens and the without-lens data from each subject allows us to assess whether our equipment was calibrated accurately. Over the wavelength range used, we would expect a change in this difference value of 1.60 D. The average change for our normal subjects was 1.69 D (SD = 0.30 D), and the consistency between the prediction and the experimental results confirms the accuracy of the calibration.

Experiment 3

If the human eye had no chromatic aberration, then alignment of the vernier targets would be independent of the position of the artificial pupil in the third experiment. Plotting vernier offset against pupil position should then produce a graph with a slope of zero. Similarly, for the white-light control condition in which the spectral composition of the two sources was identical, the vernier alignment should be independent of pupil entry position.

Data from the two groups are shown in Figs. 3(a) and 3(b), where angular vernier offset is plotted against pupil entry point. Zero on the x axis corresponds to the geometrical center of the subject's dilated pupil. Experimental data are plotted as individual symbols, and average white-light control data from each group are shown as solid lines. The control data confirm that vernier alignment is not biased by pupil entry point; best-fit lines for the two groups have slopes of 0.0016 (young) and 0.0038 (old) arcmin/mm of pupil displacement. In contrast, the experimental data clearly exhibit nonzero slopes. As the artificial pupil is moved away from the center of the natural pupil, an increasingly large offset is needed to achieve vernier alignment, indicating that the eye has chromatic aberration.

At each pupil entry point the offset needed depended both on the amount of ocular chromatic aberration and on the distance from the eye's achromatic axis[15,16] to the aperture. By measuring the vernier offset at a number of different pupil entry points, these two factors may be separated. In Fig. 3, for each subject the point at which zero vernier offset is needed is determined by the position of the achromatic axis relative to the geometrical center of the pupil, and the *slope* of the function is determined by the amount of ocular chromatic aberration. A comparison between the amounts

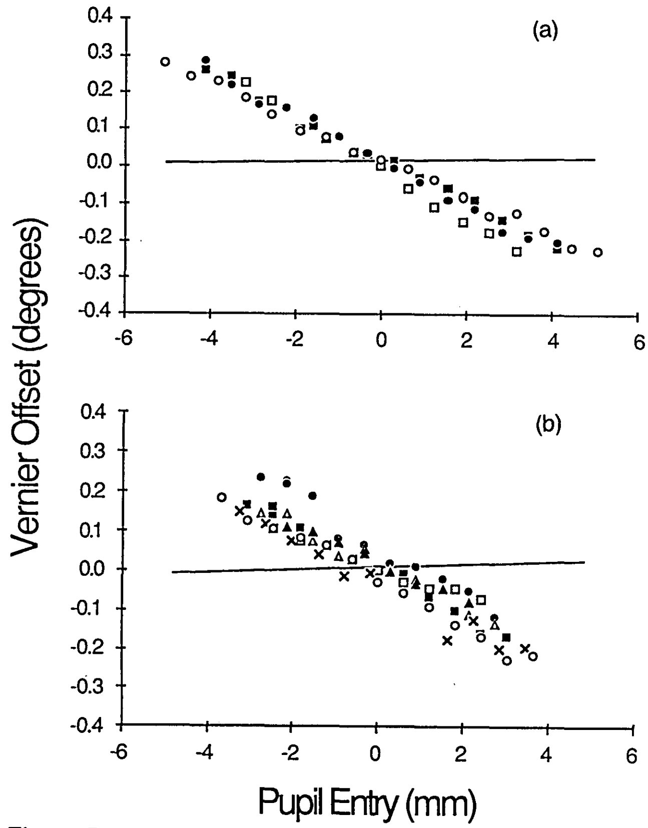

Fig. 3. Results of experiment 3. The amount of offset needed, in degrees, to align a 466-nm vernier line and a 615-nm vernier line when both are viewed through a decentered artificial pupil. (a) Data from the four young subjects. (b) Data from the five older subjects and the two pseudophakic eyes. Symbols are as in Fig. 1.

of chromatic aberration in the two subject groups therefore involves simply a comparison of the slopes.

Data from each observer are well fitted by straight lines ($r^2 > 0.96$). The slopes of the lines for the two groups are similar, with an average slope for the young group [Fig. 3(a)] of 3.6 arcmin/mm (SD = 0.5) and an average slope for the older group [Fig. 3(b)] of 3.4 arcmin/mm (SD = 0.4). This indicates that the two groups have essentially identical amounts of chromatic aberration. Data from the two IOL subjects, MA and GH, are also shown in Fig. 3(b). These eyes had slightly lower slopes of 3.1 and 2.2 arcmin/mm, respectively.

Although the slopes of Figs. 3(a) and 3(b) are similar, there is more within-subject variation in the data from the older subjects. There are a number of potential causes of this increased noise, such as less-homogeneous media and difficulty in maintaining head position. The strategy of evaluating the aberration at a number of points across the pupil minimizes the deleterious effect of this noise, as increased variation at any individual point has little effect on the overall slope of the function. Hence the increased noise shown within the older group does not affect the conclusion that the two groups have the same amount of chromatic aberration.

Summary

The data shown in Figs. 1–3 indicate qualitatively that the magnitude of longitudinal chromatic aberration is independent of the age of the subject. However, appreciable between-subject differences in the magnitude of longitudinal chromatic aberration were reported previously for young subjects,[2,3,19,21] and minor changes in aberration could have left the older subjects still within the normal range. In order to assess whether there are any slight changes of chromatic aberration with age, we have analyzed the data from the three experiments further.

With small subject numbers, accurate assessment of the magnitude of the aberration is crucial. Previous analyses quantified longitudinal chromatic aberration simply as the numerical difference between the eye's refractive error at a long wavelength and that at a short wavelength. With this method, individual error at these two measurement points is reflected in the estimate of the eye's chromatic aberration. We modified this approach with the data from the first experiment by fitting each subject's entire data set with a third-order polynomial and then evaluating the aberration between 420 and 645 nm from these fitted curves. In this way, noise at any one wavelength should not unduly affect the value obtained for the subject's aberration.

We took a similar approach with the data from experiment 2. Here, however, a straight line gave a good fit to each subject's data set. This was to be expected, as the curvilinear change in power of the achromatizing lens was designed to match the curvilinear change in power of the human eye. The magnitude of the residual aberration present was then evaluated, over the same range of 420–645 nm, from these best-fit straight lines.

For each subject in experiment 3, the eye's chromatic aberration was again evaluated from the complete data set. The average change in vernier offset for a given aperture displacement is given by the slope of each individual's function in Fig. 3, and this value was converted to diopters for comparison with the data from the first two experiments.

Figure 4 shows data from experiments 1 (filled circles), 2 (filled squares), and 3 (open circles), with the amount of chromatic aberration exhibited by each phakic subject plotted against the subject's age.

Because the wavelength range in experiment 1 is greater than than in experiment 3, the aberration appears to be larger in the former experiment than in the latter. By evaluating the aberration from the generated best-fit curves, we may directly compare the two data sets. Over the smaller

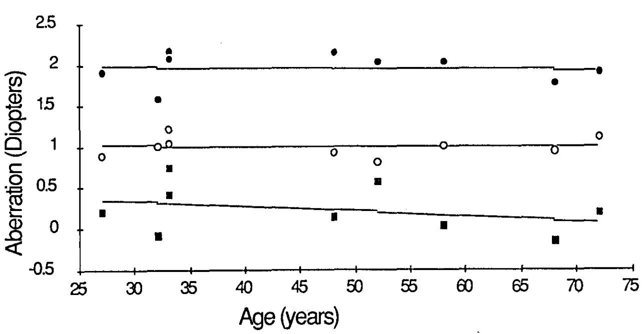

Fig. 4. The ocular chromatic aberration of the phakic eyes, in diopters, is plotted as a function of age. Data from experiments 1, 2, and 3 are plotted as filled circles, filled squares, and open circles, respectively, and straight lines have been fitted to the data by linear regression. As explained in the text, the three data sets reflect the same amount of underlying aberration, although the dioptric values differ because of the different conditions of the three experiments.

range, 466–615 nm, the mean aberration for the phakic subjects in experiment 1 is 0.97 D (SD = 0.26), whereas for experiment 3 the mean aberration is 1.00 D (SD = 0.13 D). Similarly, although the aberration is virtually absent in the data of experiment 2, because an achromatizing lens was used, when the lens power is deducted the mean aberration shown is 1.08 D (SD = 0.19 D) over the same wavelength range. Thus, although the three data sets of Fig. 4 differ in absolute magnitude, each reflects the same underlying amount of ocular longitudinal chromatic aberration.

Using a least-squares procedure, each data set shown in Fig. 4 was fitted with a straight line. The resulting slopes for experiments 1, 2, and 3 are −0.001, −0.006, and −0.0004 D/year, respectively. Although these slopes are all negative, none is significantly different from zero. We conclude that the longitudinal chromatic aberration of the adult human eye does not vary with age.

DISCUSSION

Our data show that the long-held assumption that chromatic aberration does not change with age is indeed correct. However, we cannot necessarily conclude that no changes in ocular dispersion occur over time. The majority of the eye's chromatic aberration occurs at its first refracting surface,[16,20] and small dispersion changes within the eye would not be expected to produce large effects on the magnitude of the aberration. For example, pseudophakic subjects have less lenticular dispersion than normal phakic subjects,[18,22,23] yet the reduction in aberration seen in the data from our pseudophakes, as is the case with those measured by Rog,[18] is small.

How can previous data showing an age dependence of longitudinal chromatic aberration be explained? In the study by Mordi and Adrian,[8] the subject numbers were small, no statistical analysis was performed on the data, and normal intersubject variability probably accounts for the result. In Millodot's study,[4] which reported a larger decline in longitudinal chromatic aberration with age, the results are more puzzling. A large number of subjects were tested, and a clear age dependence is seen in their data. Two age-related explanations, other than a decline in chromatic aberration, are possible. The first is that the aberration was measured correctly but that the spectral composition of the retinal image was not as specified. In Millodot's experiment,[4,24] light from a projector was shone through a monochromator to illuminate a target on a ground-glass screen. However, other light was present, and the target may not have been truly monochromatic. The reduced short-wavelength transmission of the older lens would then influence the results. For short wavelengths the weighted mean of the spectral stimulus reaching the retina would have been appreciably higher than the peak transmission of the monochromator: the reported stimulus wavelength. However, Millodot[4] also found a reduction in chromatic aberration in older aphakic subjects, so an explanation based on changes in the short-wavelength transmission of the human lens is not in itself adequate. A second explanation is that the aberration measurements were in error. If standard optometric procedure were used in the experiment, subjects would have been given the maximum plus-powered trial lens consistent with best visual acuity. One edge of the dioptric range in focus at each wavelength is identified by this technique, and a comparison across subjects relies on the assumption that at all wavelengths the eye's depth of focus is independent of age. However, because of the smaller pupils and the reduced short-wavelength lenticular transmission found in older subjects, this assumption is unlikely to be correct. For the older subjects, this would lead to an illusory reduction in ocular chromatic aberration.

In conclusion, it is clear from each of the three experiments reported here that, over the ranges examined, the magnitude of adult ocular chromatic aberration is independent of age. Small changes in the refractive indices of the eye's media were reported previously to occur with age, leading to age-dependent changes in refractive error.[9] However, the eye's chromatic aberration is determined by the dispersion of the media rather than by the refractive index itself. Our data show that any changes in ocular dispersion that occur along with the changes in refractive index are too small to be of practical significance. Hence, when the magnitude of the eye's chromatic aberration is considered for vision experiments, for correction of aphakia with intraocular lenses, and for the design of optical instruments, the age of the person is not a relevant factor.

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