The Spherical Aberration of the Eye

M. KOOMEN, R. TOUSEY AND R. SCOLNIK
U. S. Naval Research Laboratory, Washington, D. C.
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The spherical aberration of the eye was measured by placing a series of centered annular apertures over the eye pupil, and determining the optimum spectacle correction for each aperture. A "double star" was used as a test object. Accommodation was controlled by reflecting a second test object into the field of view. The three eyes examined had positive (undercorrected) spherical aberration when unaccommodated; in one case 2 diopters at the pupil margin. The aberration was reduced with increasing accommodation and in one case became negative at high accommodation. Homatropine reduced the spherical aberration of two of the three eyes examined. A historical review of previous work is given.

INTRODUCTION

IN the course of experimental work on night vision and night myopia a search of the literature was made for data on the spherical aberration of the eye. From the published results it was evident that the aberration varied considerably among individuals, and that it would have to be measured for the individuals whose night vision was to be tested. Measurements described in the literature were usually made on selected quadrants of the pupil, or point by point along one or two selected meridians, and therefore gave a somewhat incomplete picture of the aberration of the entire eye. Moreover, a cycloplegic was used in many of these measurements, and there appeared to be a possibility that this changed the spherical aberration. Therefore, an experiment was devised to avoid these difficulties. A better over-all picture of the aberration was gotten by making the measurements on centered annular zones of the pupil, rather than points or quadrants, and the use of cycloplegia was avoided by controlling the accommodation by optical means. The results of the experiments with three subjects showed that positive (undercorrected) spherical aberration is present in the normal unaccommodated eye. The aberration was reduced when the eye accommodated and, in two individuals, became zero or even negative (overcorrected) at high values of accommodation. The use of homatropine changed the spherical aberration in two cases. The history of the subject will be covered briefly since it does not appear to have been assembled previously.

I. HISTORICAL

The presence of spherical aberration in the human eye appears to have been recognized at least as early as 1801. In that year Thomas Young[1] demonstrated the aberration by means of a simple experiment. He extended a thread from a point close to one eye, nearly along its visual axis, to a considerable distance away. Through four narrow slits placed directly over his eye pupil, he observed four separate images of the threads. All four images appeared to intersect at a single point, presumably his far point, when his accommodation was relaxed. When he accommodated for near vision, however, the two images formed through the outer slits appeared to intersect beyond the point where the inner ones crossed. Apparently Young's eye had little spherical aberration in its relaxed state, but exhibited negative or overcorrected aberration when accommodated.

In a similar experiment Volkmann,[2] in 1846, looked through four small openings placed across the eye pupil at a pin which he moved to different distances. As a measure of the spherical aberration, he determined the distance at which the pin was in sharp focus, using first the two more centrally located openings, and then the two located more laterally. Of nine observers tested, he found five with positive spherical aberration and four with negative aberration.

In his original papers Helmholtz,[3] in 1866, wrote, "the experiments of Young and Volkmann would undoubtedly have indicated the nature and magnitude of the spherical aberration of the eye;" but, "in most meridians of the ordinary eye the points of intersection of the refracted with the central ray do not form a continuous series at all, so that here the conception of spherical aberration does not apply." In his supplement, however, Helmholtz included the results of investigations by Donders (1861) who "moved about in front of the eye a small perforated screen so as to let light go sometimes through one sector of the lens and sometimes through another···each sector of the lens converged the rays approximately to a focus, but the focus was not the same for different sectors. And, moreover, the focusing was not quite accurate

[1] T. Young, Phil. Trans. 91, 69 (1801).

[2] A. W. Volkmann, Wagner's Handworterbuch der Physiologie (Vieweg and Son, Brunswick, 1846), p. 293.

[3] H. von Helmholtz, *Physiological Optics*, 1909 edition; translated by J. P. C. Southall (Opt. Soc. Am., 1924), pp. 199–201.

even for a single sector, the rays near the axis having apparently a longer focal length than those traversing the peripheral parts of the lens."

The characteristic skiascopic appearances produced by symmetrical positive and negative aberrations were first described by Jackson[4] in 1885. Within the next three years he measured skiascopically the aberration in one hundred eyes.[5] Of these, seventy-eight had one-half diopter or more of positive aberration, thirteen were within one-quarter diopter of zero, and only nine had negative aberration. The negative aberrations were largely associated with conical corneas, or with lens conditions which often led to nuclear cataract.

In 1898 Tscherning[6] devised his "aberrascope" for an investigation of the effect of accommodation upon spherical aberration. He ruled opaque lines on the flat side of a plano-convex lens. With the lens in front of his eye, he observed a distant luminous point. The opaque lines cast shadows in the blur circle produced on the retina by the "artificial myopia." From the direction of the curvature of the shadows Tscherning concluded that the aberration was positive when his eye was relaxed, tending toward the negative as his eye accommodated.

Gullstrand,[7] in 1909, described as mathematically impossible Tscherning's interpretation of the phenomena he had observed with his aberrascope, and declared that "subjective stigmatoscopy, employed as a scientific method, demonstrates a positive aberration inside the optical zone even with the most powerful accommodation." Nevertheless, Gullstrand acknowledged that "skiascopic investigation shows that in many instances a change of sign occurs in the peripheral aberration during accommodation."

In 1921 Ames and Proctor[8] measured the spherical aberration along two meridians in the relaxed eye. They directed at the eye two beams of light of small cross section. One beam passed through the center of the pupil while the second was made to pass consecutively through a series of points along a given meridian. The two beams were made to intersect on the retina by an adjustment of the inclination of the second beam. The spherical aberration was calculated from the angle between the beams. In three eyes measured, Ames and Proctor found that from the center of the pupil to a radius of about 1.5 mm the eye became increasingly myopic; that is, it showed positive spherical aberration. From 1.5 mm to the pupil margin the aberration decreased, tending to become zero again at the very edge. The maximum observed values of the aberration were between 0.4 and 0.8 diopter.

In 1925 Pi[9] made further use of the skiascopic method in a study of the spherical aberration of fifty patients at the Poliklinik in Vienna. Dividing the pupil area of the homatropinized eye into a central zone and four peripheral quadrants, he measured the difference in refraction between the central zone and each quadrant in turn. Pi found that all except one of his subjects possessed positive aberration, the individual magnitudes ranging from 0.25 to 5.0 diopters depending upon the subject and upon the quadrant. Most frequently, however, the peripheral quadrants were found to be only 1.0 to 1.5 diopters myopic relative to the center. In not a single instance was the aberration the same all around the periphery. Pi observed that the sequence of the magnitudes of the refractive errors among the four quadrants (superior, 1.89 D.; nasal, 1.50 D.; temporal, 1.37 D.; and inferior, 1.04 D.) was directly opposite to the sequence to be expected from a consideration of the measurements of corneal curvature made by Aubert, Sulzer, and Erikson, and by Gullstrand.

In 1930 Stine[10] made a similar investigation of the refraction by quadrants in 277 non-pathological eyes. He found the same sequence among the quadrants that Pi did with respect to the amount of the refractive error. Stine, however, measured differences between quadrants as high as 8 diopters, the greatest difference between periphery and center being 7.5 diopters. Some degree of aberration was found in every eye; 66 percent had some positive aberration, 46 percent had some negative aberration, and 17.5 percent showed mixed (scissors) aberration. Most of the negative and mixed aberration was found in young subjects, with not one instance of entirely negative aberration in an individual over nineteen years of age. Stine attempted to reconcile his data, and those of Pi, with Gullstrand's measurements of corneal flattening by placing upon the lens rather than upon the cornea the major responsibility for the resultant positive aberration of the entire eye.

More recently, in 1941, Otero and Duran[11] investigated the aberrations of the eye in the course of their studies of nocturnal myopia. Looking through each of a series of circular artificial pupils of different diameters, they determined the spectacle correction which yielded the best visual acuity while observing a grating type target. Their results

[4] E. Jackson, American J. Med. Sciences 89, 404 (1885).
[5] E. Jackson, Trans. Am. Ophth. Soc. 5, 141 (1888).
[6] M. Tscherning, Optique Physiologique (Carre et Naud, Paris, 1898), pp. 98 and 158.
[7] A. Gullstrand, *Supplement to Helmholtz's Physiological Optics*, 1909 edition; translated by J. P. C. Southall (Opt. Soc. Am., 1924), p. 437.
[8] A. Ames and C. A. Proctor, J. Opt. Soc. Am. 5, 22 (1921).
[9] H. T. Pi, Trans. Ophth. Soc. of United Kingdom XLV, 393 (1925).
[10] G. H. Stine, Am. J. Ophth. 13, Ser. 3, 101 (1930).
[11] J. M. Otero and A. Duran, Anales de Física y Química 38, 236 (1942).

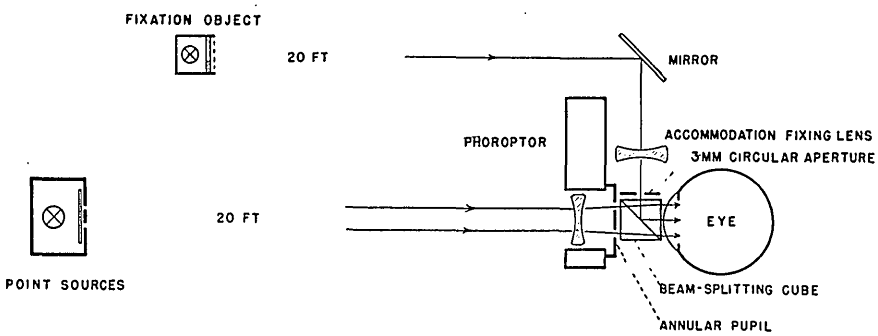

FIG. 1. Apparatus for measurement of the spherical aberration of the eye.

indicated the presence of spherical aberration somewhat similar to that found by Ames and Proctor. However, since the spectacle corrections were determined not zone by zone, but for circular areas of progressively increasing size, the results do not give directly the spherical aberration of the eye. They yield, instead, a value of aberration which is less than the maximum zonal aberration and which is determined by the way the various zones of the eye pupil contribute to the retinal image.

In 1944 Byram[12] measured the spherical aberration of his eye as a part of the study of the light distribution in the image on the retina. He reported that his eye became increasingly myopic from the center to the margin of the pupil, the aberration at the margin amounting to 1.3 diopters. Byram did not, however, describe his experimental method.

Von Bahr[13] in 1945 gave the results of his measurements of the spherical aberration of 30 eyes. He measured the aberration along the horizontal and vertical meridians of the pupil, using pairs of small pinholes to sample various zones along a meridian. He found that most of the eyes exhibited positive spherical aberration, the zones of the pupil becoming gradually more myopic from the center of the pupil outward. In a few eyes negative aberration was present. Also, a small number of eyes exhibited negative aberration in one-half of a meridian only. In such cases the aberration was usually small. Of all the eyes measured, there was none in which the aberration was completely symmetrical. In the most extreme cases of positive aberration, the pupil margin was measured to be about 3 diopters myopic relative to the center. However, the mean value for all eyes and all observations appeared to be about 0.5 diopter.

Ivanoff[14,15] in 1947, modified the Ames and Proctor technique to permit the use of vernier acuity in making settings and made measurements out to 2.5 mm from the center of the pupil. He found that along a single meridian the outer zones of the average eye exhibited approximately 0.9 diopter of positive spherical aberration when in the relaxed state, and 1.25 diopters of negative spherical aberration when accommodated 3.0 diopters. When accommodated at 1.5 diopters, there was practically no aberration present. While the magnitude of the aberration varied from individual to individual, the amount of the accommodation necessary to eliminate the aberration was about the same for all individuals. As plotted by Ivanoff, the curves show the major change in refractive power occurring within 0.5 mm of the center of the pupil, with little additional change beyond this zone. This is unexpected in a reasonably simple image-forming system, and it does not agree with our findings or those of other investigators.

This account of the developments in the measurement of spherical aberration shows the general agreement among the investigators that the average eye in the relaxed state is characterized by positive aberration. Some investigators found, in addition, that with accommodation the aberration is diminished, and sometimes it even becomes negative. It is with respect to the magnitude of the aberration and to its change as one considers more and more marginal pupil areas that there is less agreement among investigators.

Much of the disagreement can undoubtedly be attributed to real differences in the characteristics of the eyes examined. Measurements made by individual experimenters using a single technique with many subjects would bear this out. In addition, however, there were considerable differences in the experimental methods employed. Several investigators divided the eye pupil into quadrants. Others measured very small areas along a few selected meridians. Otero and Duran's data referred to circular pupils of different areas. As a result nearly every investigator measured a slightly different aspect of the spherical aberration of the eye, and the results varied accordingly.

II. EXPERIMENTAL

The experiments to be described were made in an attempt to measure spherical aberration in such

[12] G. M. Byram, J. Opt. Soc. Am. 34, 590 (1944).
[13] G. Von Bahr, Acta Ophth. 23, 1 (1945).
[14] A. Ivanoff, Rev. d'Optique 26, 145 (1947).
[15] A. Ivanoff, J. Opt. Soc. Am. 37, 730 (1947).

a manner as to relate it most directly to vision, in order to determine its true role among the causes of nocturnal myopia. For the purpose of measurement, the eye pupil was subdivided into a central circular area of two millimeters diameter and five to seven distinct annular areas of increasing mean diameter extending to the limit imposed by the fully dilated pupil. Measurements consisted, essentially, of determining the spectacle lens power which produced most acute vision while the observer was using, in turn, each of the chosen pupil areas. The spectacle corrections for the annular zones, considered relative to the correction required for the small central area, gave the magnitude and the sign of the aberration. The measurements were made under conditions of controlled accommodation ranging from complete relaxation to the maximum the observer could exert without undue distress.

The arrangement of the apparatus is shown in Fig. 1. The observer looked through the right eye-aperture of an additive phoroptor. The phoroptor is an instrument which permits spectacle lenses of powers varying by quarter-diopter steps to be placed before the eye by turning a lens-bearing disk. Supplementary lenses provide eighth-diopter steps when desired. The annular apertures used for dividing the eye pupil into the selected zones were placed in turn in front of the right eye-aperture of the phoroptor. The annular apertures consisted of transparent rings in an opaque background printed on thin photographic film. The dimensions of the annular apertures are shown in Fig. 2, with the mean diameters noted above. The mean diameter is defined as that diameter which divides the transparent zone into equal inner and outer areas. The target observed through the annular aperture and phoroptor consisted of a distant pair of point sources whose separation was held just above the resolution threshold for each annular zone. The intensity of the double star source was high enough for cone vision.

To fix the state of accommodation of the eye, a second target was introduced by means of a small beam-splitting cube placed between the phoroptor and the observer's eye. This accommodation-fixing target consisted of an opaque sheet of photographic film with four transparent letters printed upon it. The target was illuminated from the rear through a sheet of ground glass. The observer thus saw the double star source surrounded by four bright letters. A spectacle lens of the proper power was inserted into the optical path of the accommodation-fixing target in order to place the target at any desired optical distance from the eye. The accommodation was therefore stimulated for this distance. The maximum accommodation which the observer could attain with this arrangement was somewhat less than could be reached with binocular vision.

The accommodation-fixing target was viewed through an artificial circular pupil of 3 mm diameter placed on the side of the cube in the path to the accommodation-fixing target. This circular pupil was used in order to define the portion of the eye pupil which determined the accommodation. The 3 mm diameter was found to be the most satisfactory size because it produced a sharp retinal image and avoided excessive depth of focus.

The eye pupil was centered relative to both the annular ring and the 3 mm pupil by the observer himself. A negative lens was set up in the phoroptor so that the double star source was thrown out of focus and looked like a large single bright ring. The observer then positioned his head and eye so that the ring appeared as circular and as uniformly bright as possible. This position was maintained by the use of a bite plate. The adjustment was checked during a set of determinations by throwing the double star out of focus and noting the symmetry of the blur image.

A check on the circular symmetry of each eye was obtained by changing toward more positive or negative values the power of the lens used to throw the image of the points out of focus. As the powers changed, the cone of rays entered the eye through different zones of the eye pupil because of the separation between the annular pupil and the eye. Once the pupil was centered by the observer, a nearly circular out-of-focus blur circle was obtained for all powers, indicating that the aberrations of the eye were approximately independent of the meridian.

The Stiles-Crawford effect was sometimes of aid in the centering. Decentering of the 2.1 mm central pupil caused the brightness and the sharpness of the image, whether in-focus or out-of-focus, to be reduced. Decentering of the annular apertures

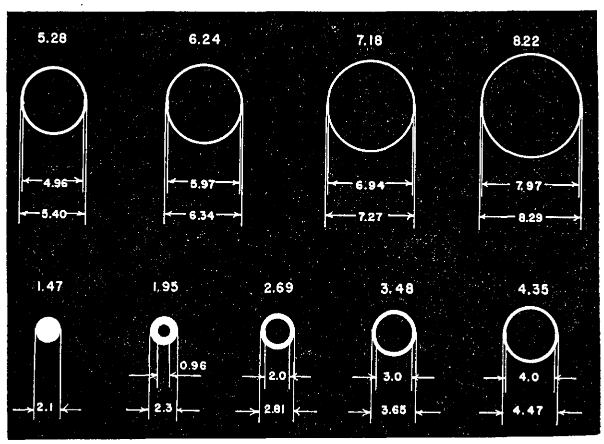

FIG. 2. Annular pupils for measurement of the spherical aberration of the eye. Dimensions are in mm. The mean diameter is given above each annulus.

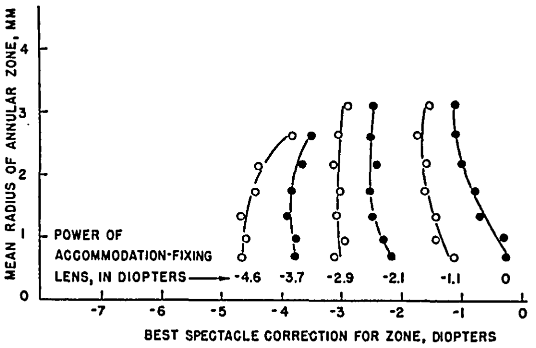

FIG. 3. Spherical aberration curves of the right eye of subject M.K. (emmetrope).

caused in-focus images to increase in brightness as one edge of the annulus approached the pupil center. With out-of-focus images, the side of the blur ring produced by the side of the annulus nearer the pupil center increased in brightness while the brightness of the opposite side decreased.

In making a measurement, the observer held the fixation letters in sharp focus while manipulating the phoroptor lenses until the best resolution of the double star was obtained. Starting with the smallest pupil, the observer repeated this procedure with larger and larger annular apertures, up to the limit set by the natural pupil. Because the annular apertures were constructed of equal areas, the intensity of the double star was increased to compensate roughly for the Stiles-Crawford effect as larger annular rings were used.

The writers themselves served as observers. Each observer had 20/20 vision; M.K. and R.S. without correction, R.T. with his −4.25 diopters prescribed correction. Their ages were respectively 29, 30 and 39. No other observers were used because it was believed that untrained observers would require a considerable amount of instruction and practice before they could produce consistent results.

III. RESULTS

The results of the experimentation are shown in the spherical aberration curves for various states of accommodation plotted in Figs. 3–5. The ordinates are the mean radii of the annular zones. The abscissae are the best spectable corrections for the zones. Below each curve is indicated the power of the "accommodation-fixing" lens; that is, the power of the lens inserted into the path to the accommodation-fixing target. The powers indicated are referred to the cornea, and indicate the refractive effect, in diopters, of the lens measured at the vertex of the cornea. The best spectacle corrections for the zones, plotted as abscissae of the curves, are also for lenses placed at the cornea. Positive spherical aberration is indicated by points to the left of the point for the central zone, and negative aberration by points to the right. The plotted points are the average of several independent determinations taken over a period of nearly a year. The data on different runs agreed to within $\pm\frac{1}{4}$ diopter except for an occasional erratic setting. In Figs. 3 and 5, the curves marked zero represent the spherical aberration of the relaxed eyes of M.K. and R.S., respectively. The curves for myope R.T. are shown in Fig. 4, and the curve marked −4.6 represents the spherical aberration of his relaxed eye. The curves to the left of the relaxed accommodation curves show the spherical aberration for various states of accommodation. If, with accommodation, the spherical aberration remained unchanged, or, to put it another way, if all zones of the eye accommodated equally, the curves would simply be displaced to the left by amounts equal to the accommodation and would suffer no change in shape. Generally this did not occur, and the curves illustrate the relative change in refractive power of the several zones of the eye as the eye accommodated.

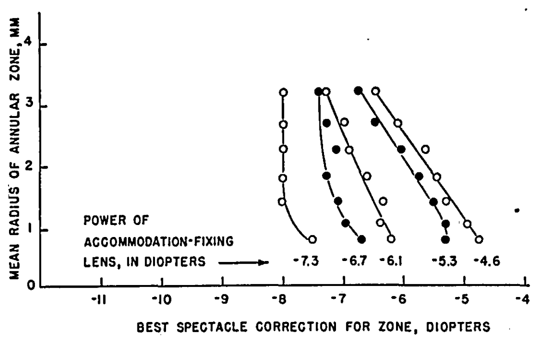

FIG. 4. Spherical aberration curves of the right eye of subject R.T. (myope, −4.25 D prescribed correction).

Since the accommodation-fixing target was viewed through an aperture of 3 mm diameter (mean radius of 1 mm), it may be expected that the curves would have an abscissa at the 1 mm mean radius annular zone equal to the value of the accommodation-fixing lens. This does occur to within 0.2 diopter and is a measure of the success with which the desired accommodation was achieved by the experimental arrangement. However, it will be noted that in all 3 figures the curve for relaxed accommodation lies too close to the other curves. This indicates that all three observers had some uncorrected myopia. M.K. and R.S., for example, were not quite emmetropic, but were myopic by about $\frac{1}{4}$ diopter. Figure 5 shows that the myopia of R.T. was not fully corrected by his −4.25 diopter prescribed correction, and that his full correction was nearly five diopters.

Observer M.K. showed a maximum of about 0.75 diopter of positive spherical aberration when his eye was unaccommodated (Fig. 3), the marginal zone being myopic by that amount relative to the center. The aberration decreased with increasing accommodation and became nearly zero for about three diopters accommodation. With still greater accommodation the marginal zones showed definite negative aberration. The outermost zone could not be measured for more than 3 diopters accommodation because of the accompanying pupil constriction.

Observer R.T. showed positive aberration with no accommodation, the maximum being 1.6 diopters for the marginal zone, (Fig. 4). This was reduced to about 0.5 diopter with an accommodation of 2 diopters, the maximum he could exert consistently. It can be seen that the amplitude of accommodation of his marginal zones is considerably less than for the inner zones of his eye.

Observer R.S. (Fig. 5) had a maximum of 2 diopters of positive aberration in the marginal zone with relaxed accommodation. This aberration was reduced considerably, although by no means eliminated, when he accommodated strongly. Indeed, the shapes of the curves out to a 2-mm radius remained substantially the same for all except the strongest state of accommodation. At the strongest state of accommodation the aberration was reduced to 0.7 diopter in the 3-mm radius zone. The aberration of more marginal zones could not be measured, because of the pupil constriction accompanying the accommodation.

Because of the considerable difference in the magnitude of the spherical aberration found among our three observers it was not considered meaningful to make a close comparison with the results reported by previous investigators; qualitatively, however, the agreement was satisfactory. Positive aberration was found for the relaxed eye; the aberration was reduced as the eye accommodated; and, in one instance, negative aberration was reached at high accommodation.

Within the central zone of 2.1-mm diameter it was not possible to make measurements by means of the annular zone method because the depth of focus of the eye was too great and because the acuity was reduced by diffraction. There was, however, no reason to expect appreciable aberration in this area for a simple lens system like the eye. Ivanoff,[14] nevertheless, reported large aberrations across the center of the pupil, measured by introducing a pair of pencils of light into the eye and arranging them so that the vernier acuity of the eye was utilized in making settings. The pencils were of 0.5-mm cross section at the pupil. The average aberration for the unaccommodated eye was found by him to be 0.75 diopter positive between the center and a point 0.75 mm out. This aberration was reduced to zero for 1.3 diopters accommodation and became 1.4 diopters negative for 3 diopters accommodation.

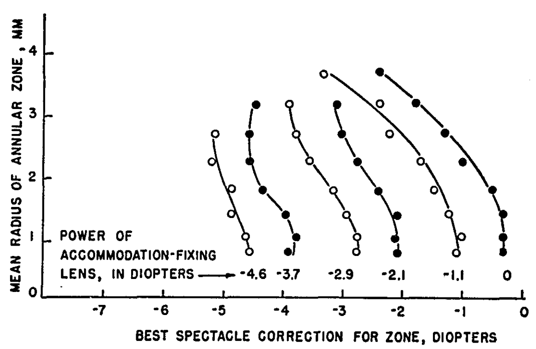

FIG. 5. Spherical aberration curves of the right eye of subject R.S. (emmetrope).

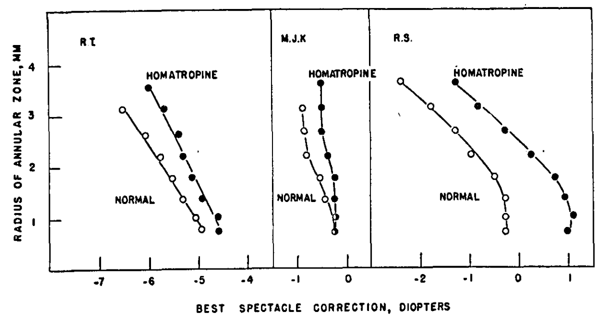

FIG. 6. The spherical aberration of the homotropinized eye compared to that of the normal unaccommodated eye.

We have repeated Ivanoff's experiment in modified form using pencils of 0.2-mm cross section at the eye. The results we obtained across the horizontal meridian were in good agreement with our data obtained with annular pupils. No aberration was detected, however, inside the 1.5-mm diameter zone, with or without accommodation. The lower limit which could be detected was about 0.2 diopters for entering pencils separated by 0.75 mm. Our results therefore do not agree with those of Ivanoff for the center of the eye pupil.

It has been noted in the historical review that many determinations of spherical aberration have been made while the eyes were under cycloplegia. This was done to dilate the pupil and to relax the accommodation, and it was assumed that the aberration under these conditions remained unchanged. In order to determine whether cylcoplegia might change the spherical aberration, our measurements were repeated for the same observers after instillation of two drops of 2 percent homatropine into each eye. The resulting aberration curves are plotted in Fig. 6, along with the curves for relaxed accommodation, obtained before the homatropine was instilled. A comparison of the curves in each pair shows that in the case of M.K. and R.T., the spherical aberration was somewhat reduced by homatropine, the curves becoming more

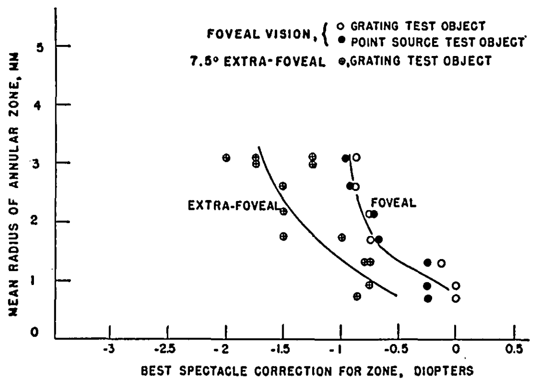

FIG. 7. The spherical aberration of the eye $7\frac{1}{2}°$ nasal from the fovea, compared with the aberration at the fovea.

nearly vertical. For the marginal zones, this reduction amounted to about 0.5 diopter. Also, the curve of R.T. was displaced slightly in the direction of hyperopia. For observer R.S., the homatropine did not change the shape of his spherical aberration curve measurably, but shifted the entire curve in the direction of hyperopia by approximately one diopter. Otero and Duran have also reported changes in the spherical aberration of their observers caused by the use of atropine, and they found one case where the drug made an observer hyperopic. On the other hand, the curves of Ames and Proctor seem to show no change in the aberration with the use of homatropine. Apparently cycloplegia has unpredictable effects upon the characteristics of the eyes of different individuals and does not necessarily leave the eye in its normal state of refraction.

An attempt was made to measure the extra-axial spherical aberration of the eye. Although such a measurement is complicated by the presence of other extra-axial aberrations, it was belived that the result would be of some significance, since it would be more directly related to night vision, which involves the extra-axial portions of the retina. The same experimental setup was used, but with a fixation target placed at a given angle from the test object. The measurements could not be made with accuracy because the extra-foveal acuity is low. Furthermore, it was difficult to obtain proper centering of the annular pupils for extra-foveal vision. A typical result of the measurements, using relaxed accommodation, is shown in Fig. 7. The retinal image was 7.5 degrees to the nasal side of the fovea. A grating type of test object was used. Each point represents a single measurement. In spite of the scatter, the extra-axial points indicate a possibly greater aberration than the axial aberration, a curve of which is reproduced for comparison. There is also an indication that the whole eye became 0.5 diopter myopic for vision at 7.5 degrees from the fovea.

In conclusion, it is apparent that when considering the effect of spherical aberration on vision, the aberration must be measured for the individual under examination. Furthermore, the experimental method should be as directly related as possible to the phenomenon of vision being investigated. For the study of night myopia, for example, the determination of the zonal aberrations of the eye by means of centered annular zones as here described appears to be a very suitable method. A close relation between night myopia and spherical aberration when measured in this fashion was found for our observers and will be discussed in another paper.