OPTICAL ABERRATIONS

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INTRODUCTION AND OVERVIEW

This chapter includes a review of:

- Monochromatic aberrations
- Chromatic aberration

Optical aberrations are defects in an optical system that degrade the quality of the dioptric image, even when the image is 'in focus'. They prevent the rays from a point object from coming to a focus as a point image. The eye suffers from all of the optical aberrations that are characteristic of most lens systems. From a theoretical point of view, it is important to have a knowledge of the aberrations of the eye because they impair the quality of the retinal image and because they may play an important role in normal ocular functions; for example, it has been hypothesized that spherical and chromatic aberration may help control the level of accommodation. From a clinical point of view, it is important to have an understanding of the aberrations of the eye because a number of common clinical tests take advantage of the eye's optical aberrations to measure the eye's optical characteristics (e.g. the bichrome or the Red-Green test) and because a number of common patient complaints may be caused by these aberrations.

There are two general categories of optical aberrations. Aberrations that occur when a single wavelength of light is employed are called **monochromatic aberrations**. Monochromatic aberrations are a characteristic of the shape or configuration of an optical system and are sometimes referred to as von Seidel aberrations after the mathematician who provided the first quantitative description of these 'third-order' aberrations. Aberrations that result from the use of mixed wavelengths of light (e.g. white light) are called **chromatic aberrations**. Chromatic aberrations are a property of the material forming the optical system and occur because the refractive index of a given media varies directly as a function of the frequency of the light employed (i.e. the reciprocal of the wavelength of the light).

MONOCHROMATIC ABERRATIONS

There are five monochromatic aberrations that can affect the quality of the retinal image.

1. Spherical aberration
2. Coma
3. Oblique or radial astigmatism
4. Curvature of field
5. Distortion

Spherical aberration affects the clarity of both 'on-axis' and 'off-axis' images. Coma and oblique astigmatism only affect the clarity of off-axis images. Distortion and curvature of field affect the shape of off-axis images.

SPHERICAL ABERRATION

Spherical aberration is the most important monochromatic aberration. Spherical aberration exists when the marginal rays (i.e. rays that are refracted through the peripheral parts of the optical system) and the paraxial rays fail to come to a focus in the same plane. If the refracting elements of an optical system have truly spherical surfaces, the marginal rays will come to a focus in front of the paraxial rays. In geometrical optics, because only spherical surfaces are typically considered, the term 'spherical aberration' is used to describe the effective increase in power that occurs as a function of distance away from the optical axis. However, in visual optics, where optical surfaces are often not spherical, the term 'spherical aberration' is employed to refer to any zone-dependent change in refracting power. With aspherical optical systems, it is possible to have greater refracting power in the paraxial region of the optical system than in the marginal zones and as a result the paraxial rays may come to a focus before the marginal rays. To discriminate between these two situations, when the marginal rays come to a focus in front of the paraxial rays, it is called **under-corrected** or **positive** spherical aberration (Figure 8.1). When the paraxial rays come to a focus in front of the marginal rays, it is referred to as **over-corrected** or **negative** spherical aberration (Figure 8.2).

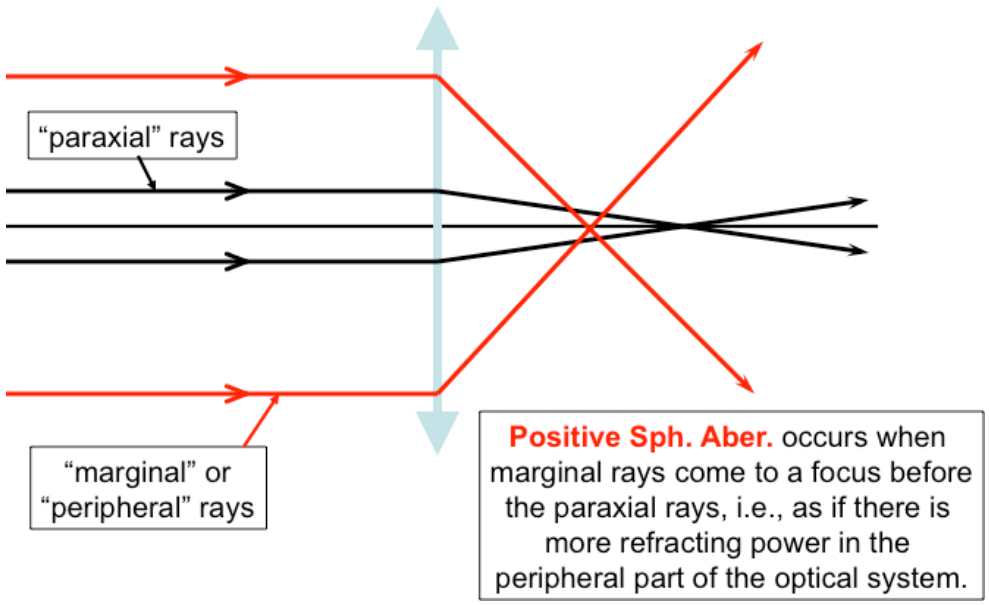


Figure 8.1: *Spherical aberration – positive or undercorrected*

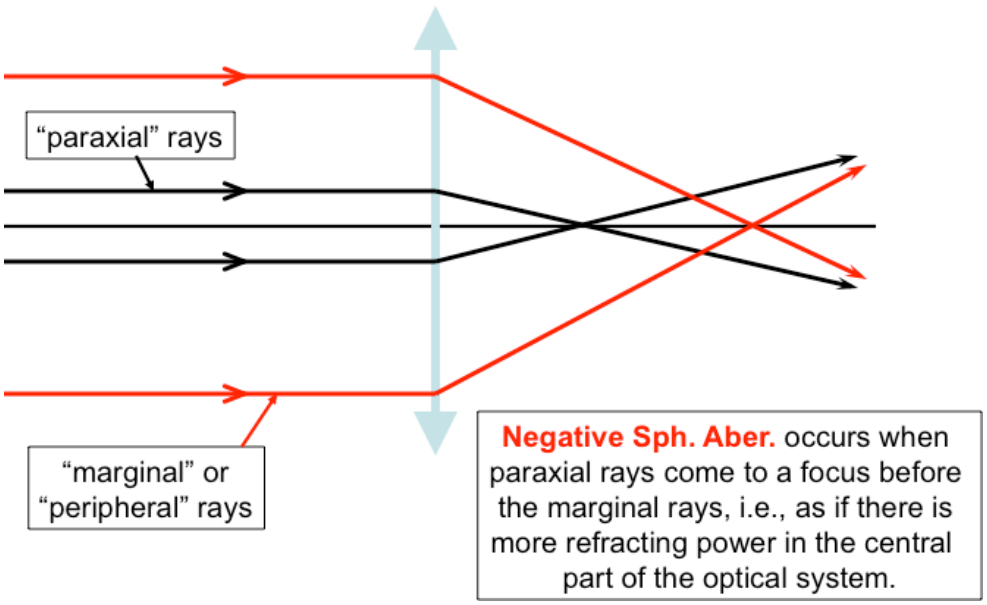


Figure 8.2 Spherical aberration – negative or over corrected

The extent or magnitude of spherical aberration can be expressed in one of two ways (Figure 8.3). **Longitudinal** spherical aberration refers to the dioptric distance between the points where the marginal and paraxial rays come to a focus (i.e. the difference in refractive power between the marginal and paraxial regions of the optical system.). For a point object, **lateral** spherical aberration denotes the radius of the patch of light produced by the marginal rays in the plane of the paraxial focus. In addition to depending on the differences in refractive power between the marginal and axial portions of the optical system, lateral spherical aberration is dependent upon the size of the limiting aperture. It is typically more informative and convenient to specify the amount of spherical aberration that a given optical system has in terms of longitudinal spherical aberration.

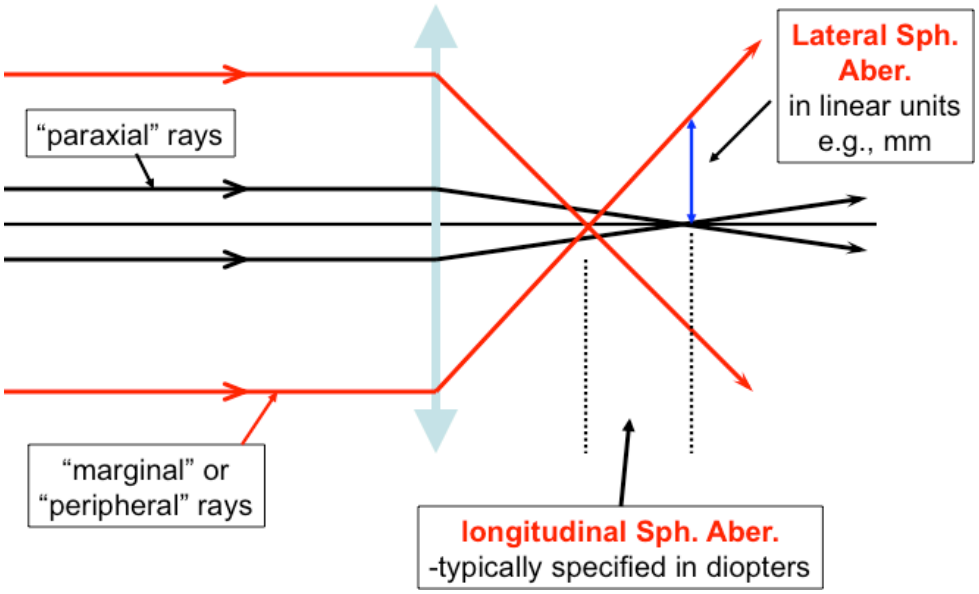
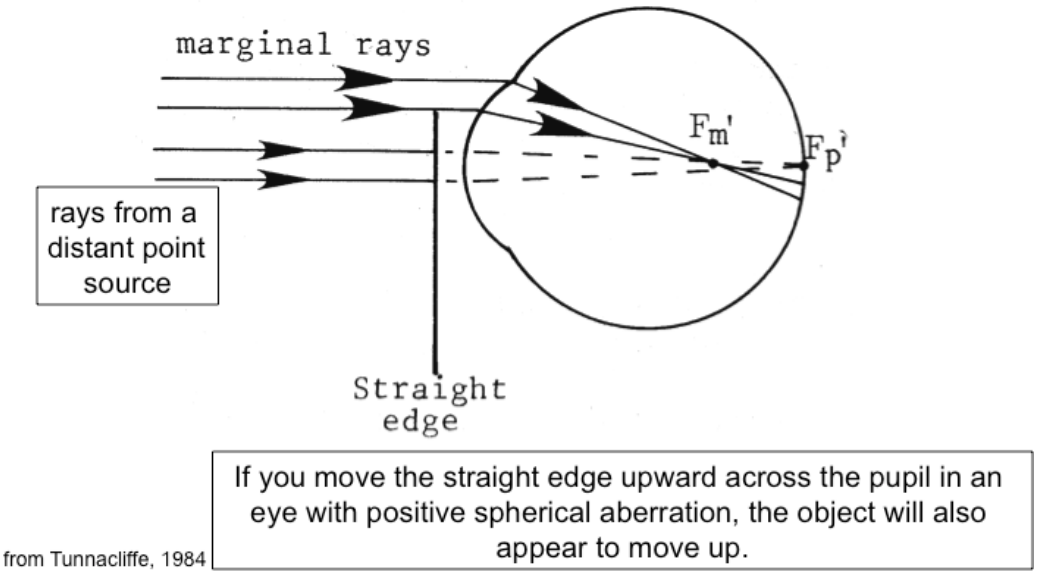


Figure 8.3: *Longitudinal and lateral spherical aberration*

The unaccommodated eye usually suffers from positive spherical aberration. The nature of the eye's spherical aberration can be demonstrated by moving a straight edge in front of the eye while viewing a distant object. As the straight edge approaches the margin of the pupil, the distant object will appear to move a small amount in the same direction as the straight edge. Figure 8.4 illustrates why the object appears to move as the straight edge occludes the pupil. Because the paraxial rays will typically be focused on the fovea (the paraxial rays are typically brighter and the eye prefers to focus for the paraxial rays), the marginal rays (i.e. the rays that enter the eye near the margins of the pupil) will come to a focus in the vitreous at a point closer to the cornea. Therefore, as illustrated in Figure 8.4, the rays that enter the eye near the top of the pupil will strike the retina below the fovea. As the straight edge is moved across the pupil, it will first block off the marginal rays through the lower part of the pupil. Since the paraxial rays are being used to fixate the object, its apparent position will not be affected. However, as the straight edge occludes the paraxial rays, leaving only the marginal rays through the upper portion of the pupil, the object will appear to move up because the image of the object formed by these marginal rays are below the fovea.



from Tunnacliffe, 1984

Figure 8.4: *Spherical aberration causes apparent movement of objects when a straight edge is moved across the pupil*

Interestingly, if you fixate a near object (e.g. an object about 15 cm away), and pass a straight edge across the pupil, typically the fixated object will appear to move in the opposite direction as the straight edge (i.e. if you move the edge up across your pupil, the fixation point will appear to move down – to appreciate this phenomenon it sometimes helps to oscillate the edge up and down near the margins of the pupil). The reversal in the perceived direction of movement demonstrates that the nature of the eye's spherical aberration is not the same in the accommodated and unaccommodated states. If the eye's level of accommodation exceeds about 2.0 D, the eye typically demonstrates negative or overcorrected spherical aberration.

It is difficult to specify in simple terms the magnitude of spherical aberration in the eye. As indicated above, the nature of spherical aberration is influenced by the level of accommodation. Moreover, the amount of spherical aberration that the eye demonstrates varies substantially, not only from individual to individual, but for a given individual, the amount of spherical aberration varies from one meridian to another. And along any given meridian, the exact amount of spherical aberration will change as a function of distance away from the eye's optical axis. Most cursory expositions on spherical aberration indicate that the average eye has about 0.5 to 1.0 D of positive spherical aberration.

Ivanoff is credited with providing one of the most complete descriptions of the amount of spherical aberration in the 'average eye'. He performed a very straightforward experiment; he measured the refractive power of the eye as a function of position across the horizontal meridian of the pupil. His results for the average eye are summarized in Figure 8.5. The amount of longitudinal spherical aberration is plotted on the ordinate as a function of position across the pupil (i.e. the amount of spherical aberration is expressed as the difference in refractive power found at the pupillary axis and that measured at different points away from the center of the pupil). Results are shown for 3 different levels of accommodation.

There are several points to consider about Figure 8.5. First in the unaccommodated state, the amount of positive spherical aberration increases rapidly over the first 1-2 mm from the center of the pupil and then levels off to a value slightly below about 1.0 D. Most of the total spherical aberration within the central 1-2 mm of the center of the pupil is thought to be caused primarily by the crystalline lens. However, in comparison to the amount of spherical aberration that would be expected for a system that had spherical refracting surfaces (the solid line in Figure 8.5 indicates the amount of spherical aberration calculated for a typical schematic eye), the absolute levels of spherical aberration demonstrated by the human eye are relatively low. There are several physiological characteristics of the eye that help reduce the amount of spherical aberration in the unaccommodated state. First, the cornea and the lens both have aspherical surfaces. Both the cornea and the lens get progressively flatter in the periphery which results in a relative decrease in power in the periphery of these refracting structures. Second, there is a progressive increase in the refractive index of the lens from its surface to its center; i.e. the core of the crystalline lens has a higher index of refraction than that of the lens cortex. As a result, light rays passing through the center of the lens will encounter a higher effective refractive index and refracting power than rays that pass through the periphery of the lens. Both of these factors tend to counteract the positive spherical aberration that would be expected in an equivalent optical system.

A second point that should be extracted from Figure 8.5 is that when the eye accommodates between about 1.0 and 2.0 D, there is very little spherical aberration of any kind. At greater levels of accommodation the eye demonstrates approximately 1.0 D of negative spherical aberration at about 2-3 mm away from the center of the pupil. These changes in the nature and magnitude of spherical aberration can be attributed to the asymmetrical changes in the surfaces of the lens that occur during positive accommodation. Remember because of the differences in the thickness of the lens capsule, the changes in the lens' surfaces during accommodation are not symmetrical. Instead, the central portion of the lens undergoes a greater increase in curvature than the peripheral portion of the lens. These differential changes in curvature result in a greater increase in refractive power in the center of the lens than in the periphery. The differences are great enough to move the focal point for paraxial rays in front of those for marginal rays (i.e. the type of spherical aberration changes from positive to negative.).

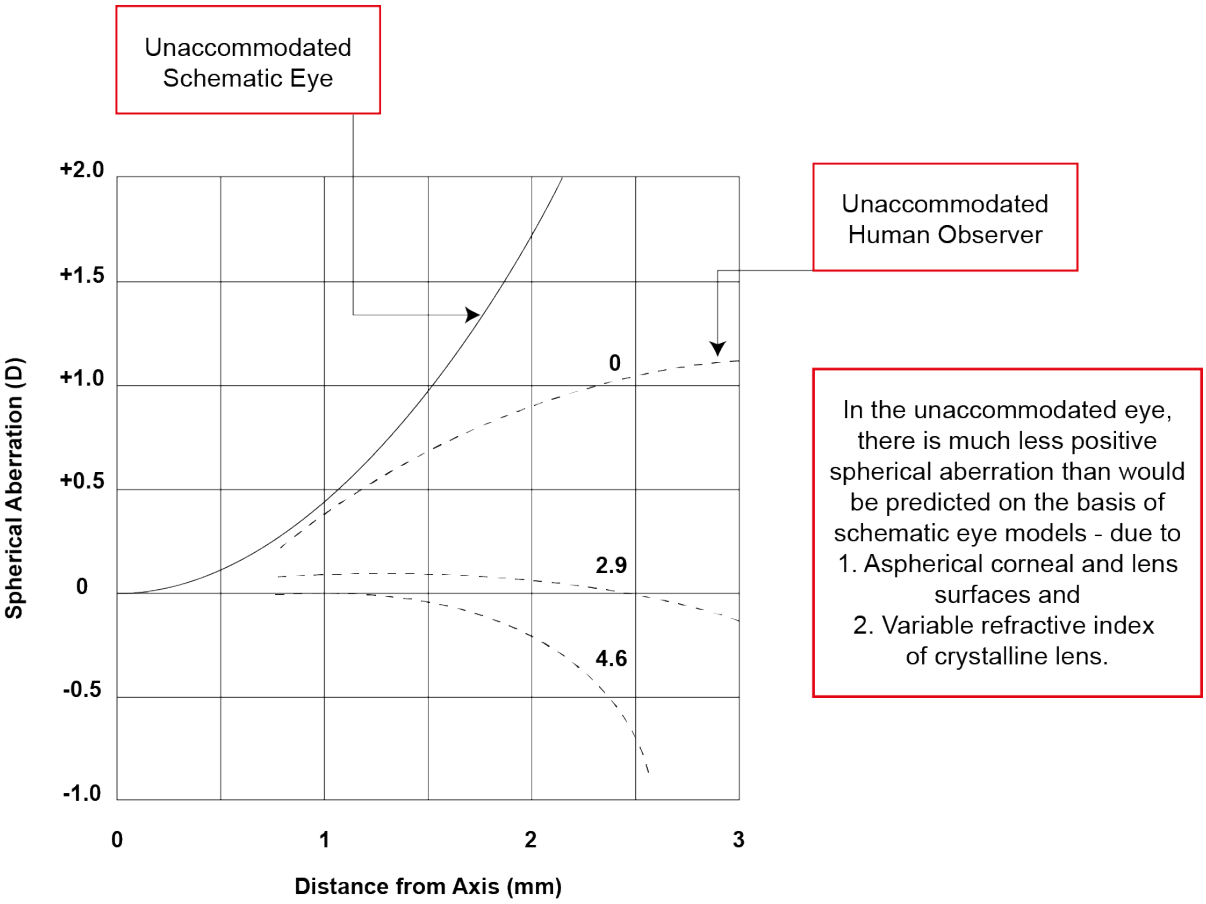
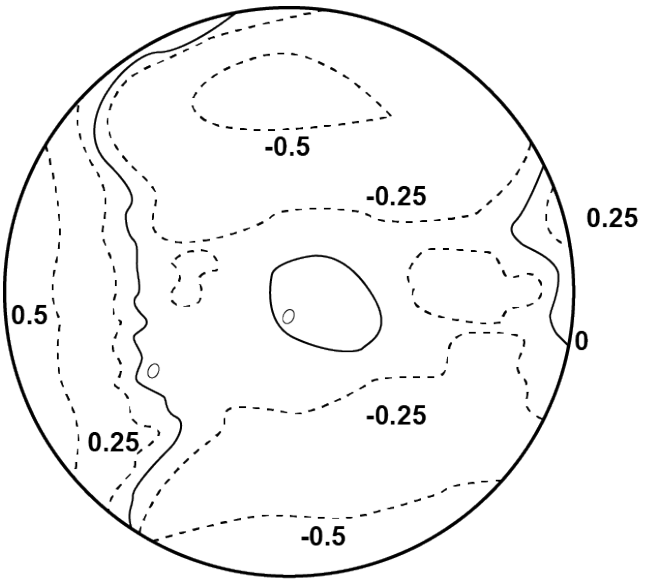


Figure 8.5: *Spherical aberration in the average eye varies with the distance from the axis and with accommodation (inspired by Bennett and Rabbetts, Clinical Visual Optics, Butterworths, London and Boston, 1989)*

As mentioned above, there can be a substantial amount of variability in spherical aberration across the plane of the pupil. Ivanoff's (1953) data provide a description of the amount and character of spherical aberration across the horizontal meridian of the average eye. Figure 8.6 is a plot of iso-power zones in the plane of the pupil for one subject. It illustrates the nature of the variability of spherical aberration in the eye. In this case, the vertical meridian demonstrates negative spherical aberration whereas the horizontal meridian exhibits positive spherical aberration.



Pupil diameter 7mm

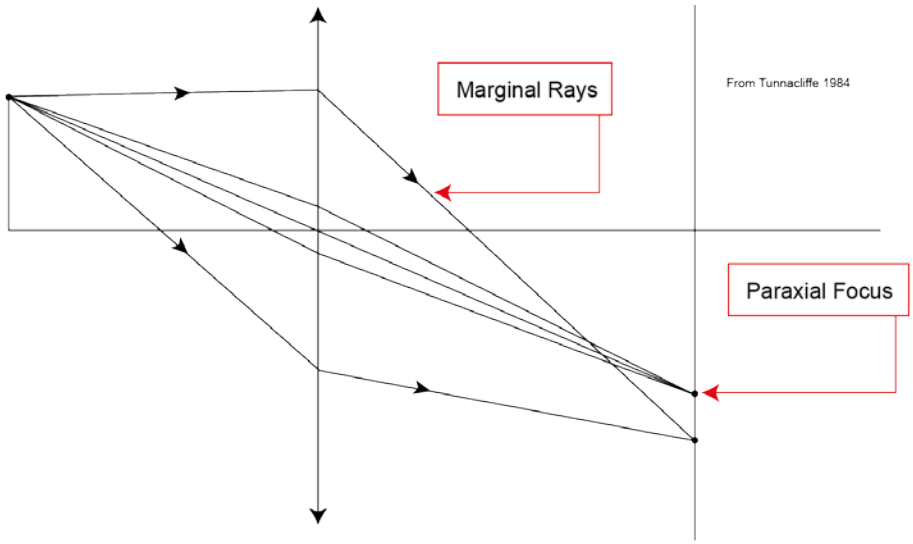
Iso-refractive error zones for an individual with a relatively small amount of spherical aberration.

The degree and sign of spherical aberration can vary from one meridian to the next.

Figure 8.6: *Aniso-refractive error map of spherical aberration in one individual's eye*

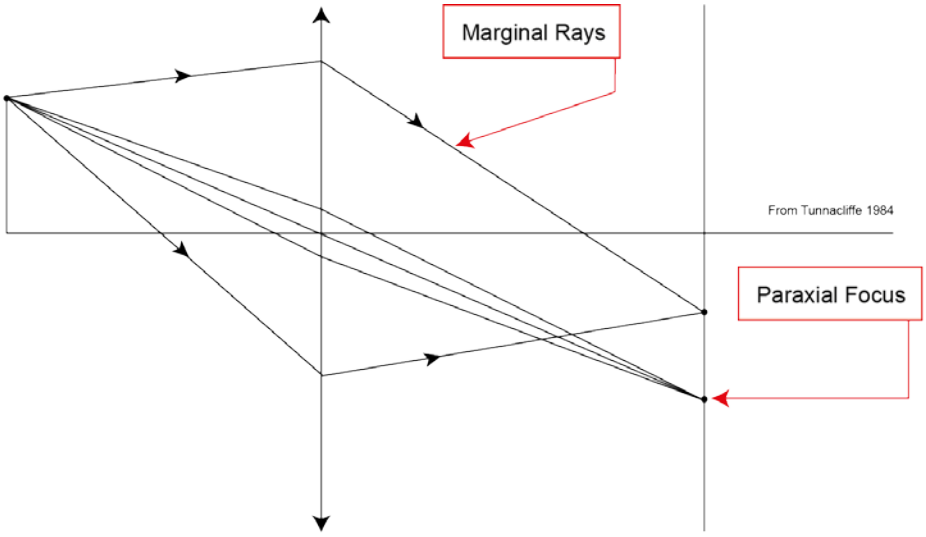
COMA

Coma affects the clarity of images formed for 'off-axis' objects. Coma occurs when rays from a point source come to focus in the same image plane, but they fail to come to focus at the same point in that plane. Variations in linear magnification across the plane of a lens cause coma. Because coma results in an asymmetry in the image of a point, coma can, in some cases, have a greater impact on an optical image than any other monochromatic aberration. The two basic forms of coma are illustrated in Figure 8.7 and 8.8. When the rays through the paraxial region of the optical system (e.g. the chief ray) come to focus closer to the optical axis within the image plane, the condition is referred to as **positive** coma. When the marginal rays focus closer to the optical axis than the paraxial rays, the condition is called **negative** coma.



Positive Coma - Paraxial rays come to a focus closer to the optical axis than the marginal rays through the periphery of the lens. The head of the 'comet' is directed toward the optical axis.

Figure 8.7: *Ray diagram showing positive coma*



Negative Coma - Marginal rays come to a focus closer to the optical axis than the paraxial rays. The head of the 'comet' is directed away from the optical axis.

Figure 8.8: *Ray diagram showing negative coma*

When an optical system has spherical aberration (i.e. like the unaccommodated eye), the type of coma that exists is dependent on the position of the limiting aperture. Figure 8.9 demonstrates how the nature of coma is affected by the position of the limiting stop. When the aperture is at the position labeled 1, B will be the chief ray and the marginal rays (e.g. ray A) will come to a focus closer to the optical axis resulting in negative coma. When the aperture is at position 2, the peripheral rays are blocked by the aperture and this plus lens system suffers from spherical aberration but not coma. Finally, when the aperture is at position 3, the chief ray (D in this case) will come to focus closer to the optical axis than the more peripheral rays (e.g. ray E) producing positive coma.

In the eye there are two plus lenses (i.e. the cornea and the crystalline lens) with a limiting aperture between them. In this situation, the cornea-pupil combination contributes positive coma, but the crystalline lens-pupil combination

contributes negative coma. The opposite forms of coma produced by these two structures tend to cancel each other and, thus, limit the impact that coma has on the quality of the retinal image. Even when the retinal image suffers from coma, it does not significantly affect the functional capacity of the eye. Keep in mind that coma only affects the clarity of 'off-axis' retinal images. However, the visual acuity of the eye decreases in a rapid fashion with increasing eccentricities. Since the peripheral retina has relatively poor visual acuity, the residual amount of coma that exists probably does not interfere with vision.

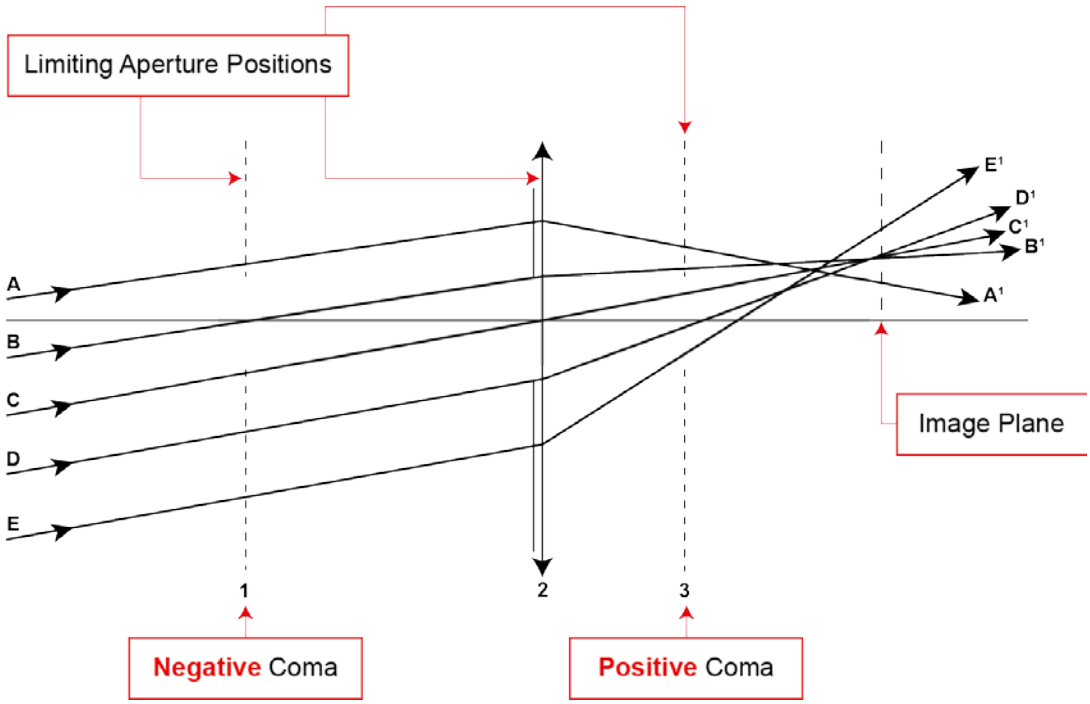
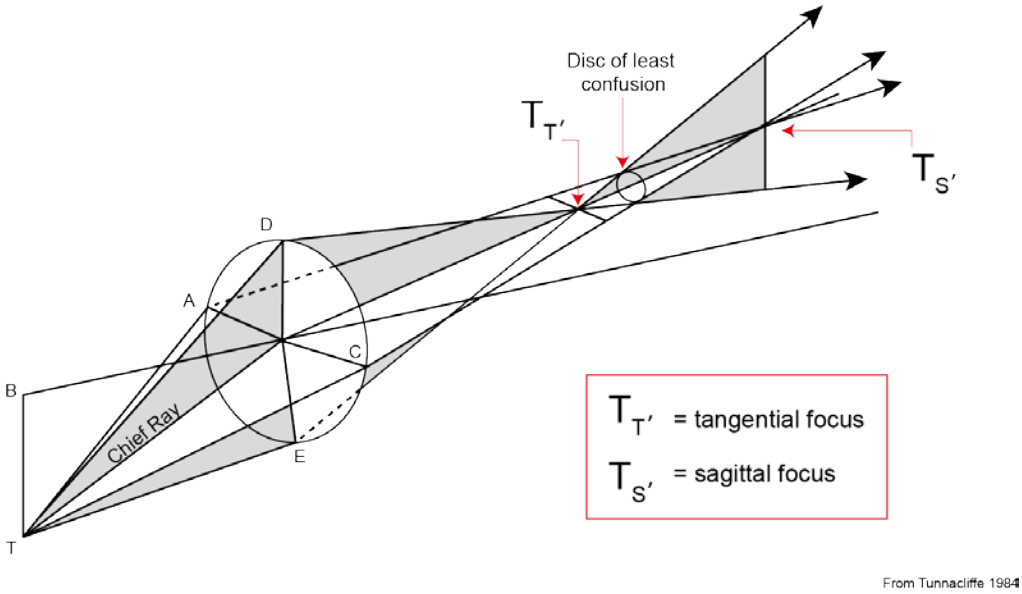


Figure 8.9: *The type of coma aberration is dependent on the position of the limiting aperture*

OBLIQUE OR RADIAL ASTIGMATISM

Oblique or radial astigmatism is similar in nature to astigmatism produced by a toroidal refracting surface for an axial object. Oblique astigmatism is produced by a spherical lens that is tilted with respect to the object in question (i.e. when the object in question is not located on the optical axis – an 'off-axis' object).

Oblique astigmatism is illustrated in Figure 8.10. For a point source that is below the optical axis (point T in Figure 8.10), the rays that are refracted through the tangential plane of the lens (DE) come to a focus at point T_t, forming a horizontal line focus. The rays from point T that are refracted in the sagittal plane of the lens (AC) form a vertical line focus at point T_s. The astigmatic images formed for a series of point objects that are positioned farther and farther from the optical axis form two curved image shells (i.e. the tangential and sagittal image shells) that become more separated as the eccentricity of the object points increase.



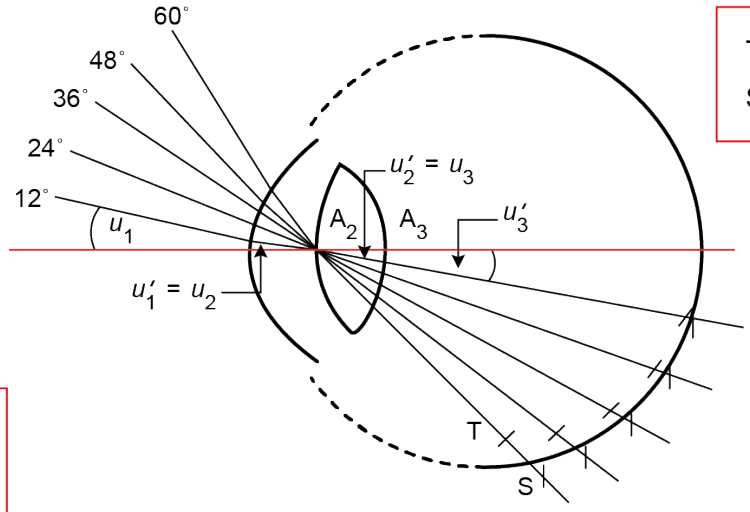
Oblique Astigmatism - is produced by a spherical surface that is tilted with respect to an object, i.e. when an object is not on the optical axis.

Figure 8.10: *Oblique astigmatism*

Although the eye suffers from oblique astigmatism, the impact of this aberration on the quality of the retinal image is minimized by the curvature of the retina. If you calculated the curvatures of the tangential and sagittal image shells for Gullstrand's exact schematic eye, it can be shown that the tangential shell has a shorter radius of curvature than the retina, but that the sagittal image shell has a longer radius than the retina (see Figure 8.11). As a result, the circle of least confusion associated with the astigmatic interval produced by oblique astigmatism (i.e. the image position that contains the best representation of the point object) would lie between the two image shells very close to the retina. Because of the curvature of the retina and the decrease in visual acuity that occurs as a function of eccentricity, the eye is reasonably well-corrected for oblique astigmatism. In fact, the quality of the retinal image is better in an eye that is not corrected for oblique astigmatism than one that is corrected for this aberration. When an optical system is corrected for oblique astigmatism, a single point image is formed for each object point. These point images are formed in a concave (at least for a converging lens system) image shell called **Petzval's surface** (see Figure 8.12). The calculated radius of curvature for the Petzval's surface of Gullstrand's schematic eye is substantially longer than the true radius of curvature of the retina (17.4 mm vs 12 mm). More importantly, because Petzval's surface is flatter than the retina, the size of the blur circles that would be produced on the retina if the eye was corrected for oblique astigmatism would be larger than the circles of least confusion that are normally imaged near the retina as a result of uncorrected oblique astigmatism.

Chief rays from eccentric point objects.

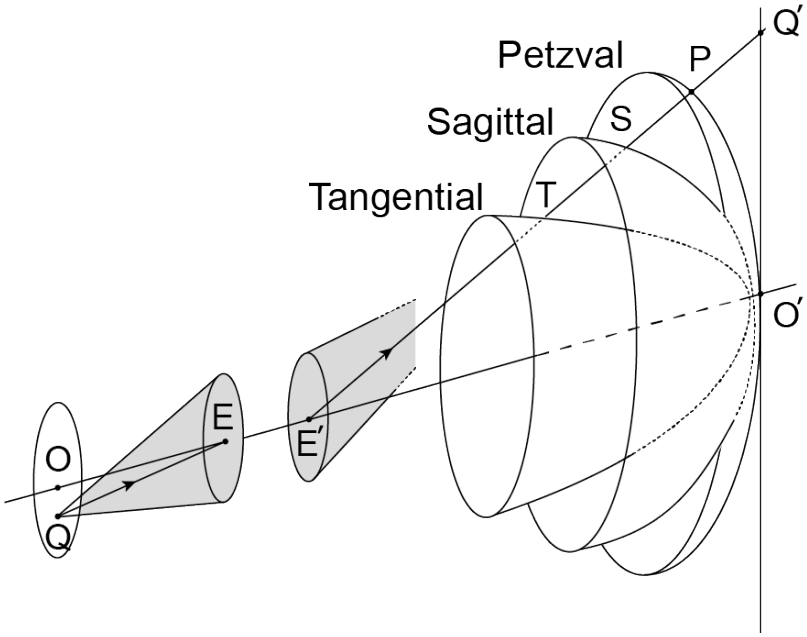
T = tangential focus
S = sagittal focus



Calculated positions of the tangential and sagittal image shells for Gullstrand's schematic eye.

From Bennet & Rabbetts, 1989

Figure 8.11: *Tangential and sagittal image shells in oblique astigmatism*



E = Entrance Pupil
E′= Exit Pupil

From Smith & Atchison, 1997

The calculated Petzal's surface for Gullstrand's schematic eye is flatter than either the sagittal or tangential image shells (and the retina).

Figure 8.12: *Petzval's surface when an optical system is corrected for oblique astigmatism*

CURVATURE OF FIELD

Curvature of field affects the shape of the image produced by an extended object (i.e. an object that includes 'off-axis' points). Curvature of field is very closely related to oblique astigmatism. In a positive refracting system, curvature of field results in an image that is concave with respect to object space. In a system that is corrected for oblique astigmatism, the image curvature will correspond to that for Petzval's surface. In a system that is not corrected for oblique astigmatism, the curved image plane associated with curvature of field can be considered to correspond to the image shell that would contain the circles of least confusion produced by oblique astigmatism. But as noted above, the retina is also concave with respect to object space and as a result, curvature of field is not a troublesome aberration in the eye.

DISTORTION

Distortion is produced by unequal linear magnification across the image plane. It is produced any time there is a limiting aperture near a refracting lens. But like coma, the type of distortion that is produced depends on the refractive nature of the lens (i.e. plus or minus) and the position of the aperture. When the limiting aperture is in front of a plus lens, the image will suffer from '**barrel**' distortion (i.e. see Figure 8.13; magnification will be greater in the paraxial region of the image than in the peripheral zones). On the other hand, if the limiting aperture is behind the plus lens (i.e. in image space), the image will suffer from '**pincushion**' distortion (i.e.see Figure 8.14, greater magnification in the marginal areas compared to the paraxial image areas).

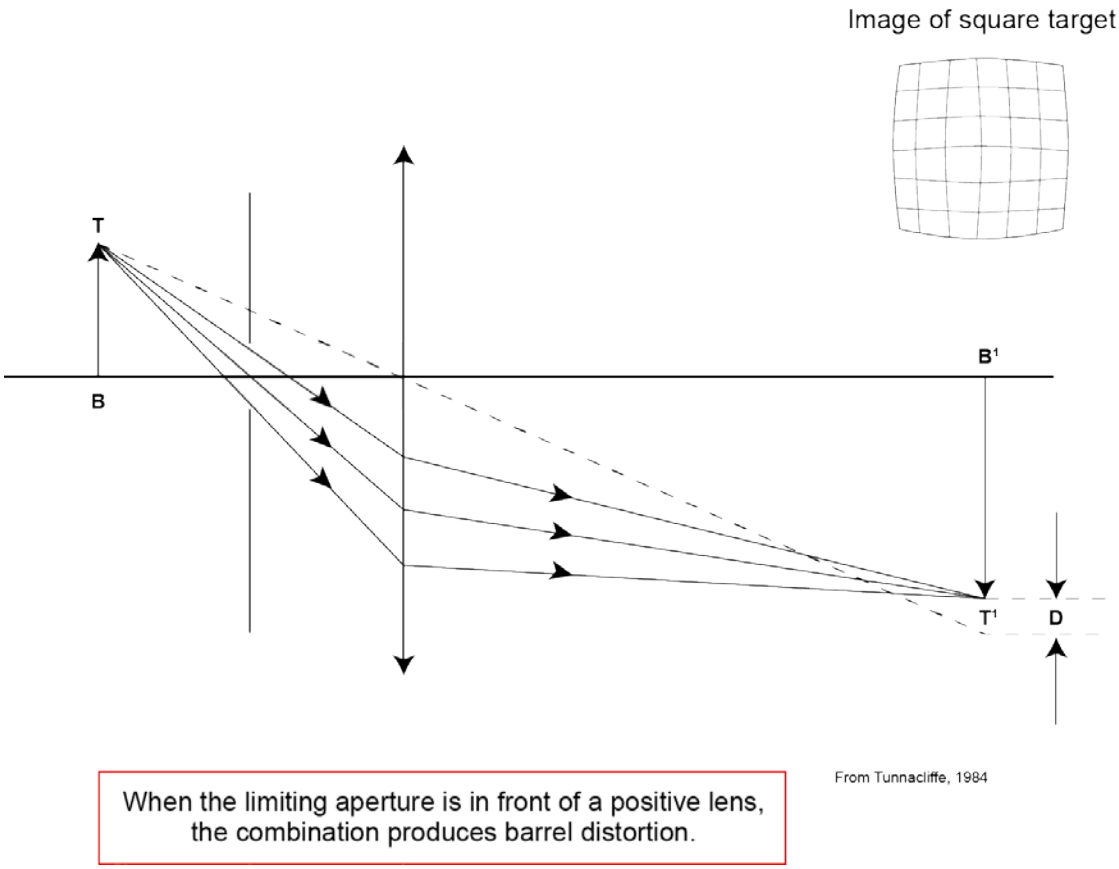


Figure 8.13: *Barrel distortion*

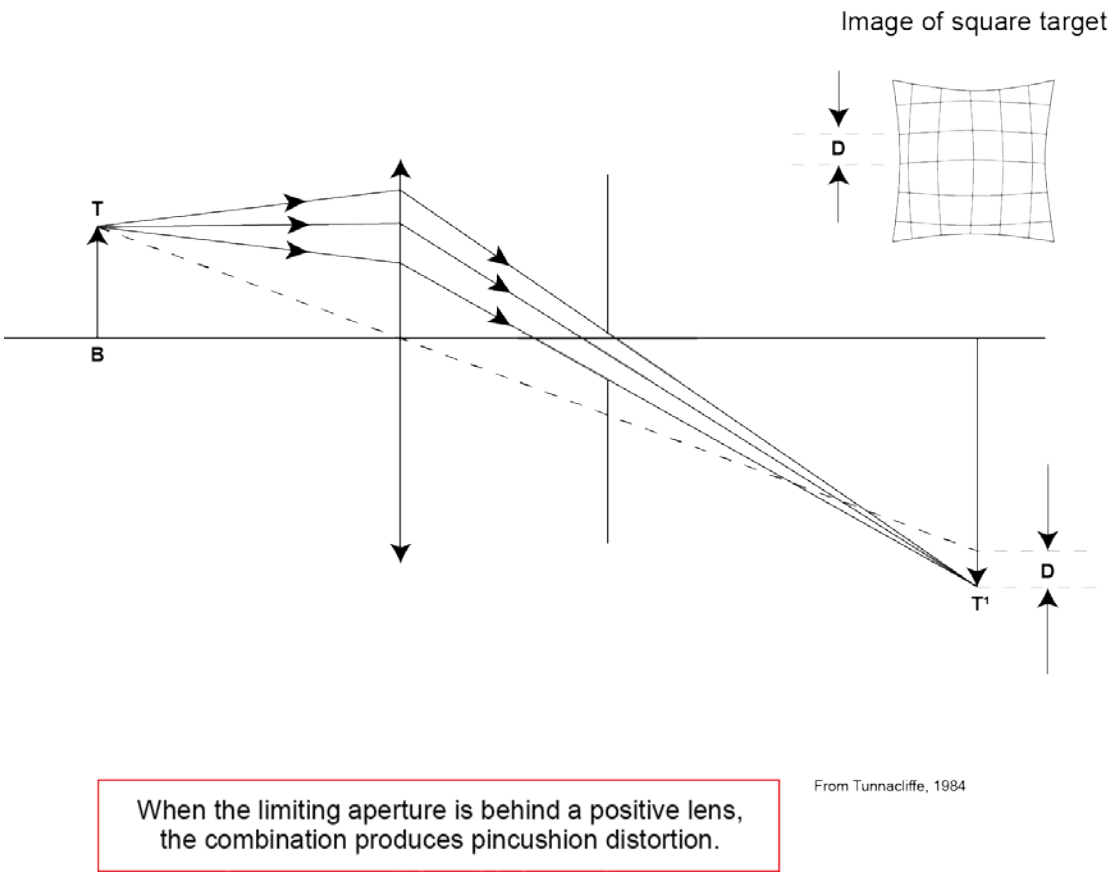


Figure 8.14: *Pincushion distortion*

As in the case of coma, the position of the pupil is optimal to minimize the impact of this aberration on the quality of the retinal image. The cornea-pupil combination results in a pincushion type of distortion, whereas the crystalline lens-pupil combination produces the barrel type of distortion. As a result, the distortion patterns produced by the cornea and lens, respectively, tend to cancel each other so that in most cases the eye does not suffer from a significant degree of distortion.

About the only time that distortion has an effect on the quality of the retinal image is in the case of aphakia. In an aphakic eye, the normal balance between the types of distortion produced by the cornea and lens is disrupted by the removal of the crystalline lens so that the retinal image suffers from pincushion distortion. The magnitude of the pincushion distortion is compounded if the aphakic refractive error is corrected with spectacle lenses. In this situation, both the correcting lens and the cornea will produce the pincushion type of distortion.

CHROMATIC ABERRATION

Chromatic aberration exists because the index of refraction for a given media varies as a function of the wavelength of light. The refractive index for a given media is the ratio of the velocity of light in a vacuum compared to the velocity of light in the given media. In the vacuum, all the wavelengths of the light travel at the same velocity. However, in a denser medium (e.g. spectacle glass or the media of the eye), the velocity of light is inversely proportional to the frequency of light or, since wavelength is reciprocally related to frequency, directly proportional to the wavelength of light. Therefore, short wavelengths travel slower in a given media than long wavelengths and, hence, the refractive index of a given media will be relatively higher for short wavelengths of light (e.g. blue; 450 nm light) than for long wavelengths of light (e.g. red; 650 nm light). As a consequence, the total refracting power of an optical system or eye will depend on the wavelength of light employed to measure the system's power. The shorter the wavelength of the light, the greater is the total refracting power.

The effects of chromatic aberration on the formation of the retinal image are illustrated schematically in Figure 8.15. Assume that the eye is emmetropic for yellow light (e.g. wavelengths about 575 nm) and that it is viewing a distant

point source of white light. Because the eye has a higher refractive index and, thus, higher refractive power for light with wavelengths shorter than the yellow focused on the retina, the eye will be myopic for blue light. On the other hand, the eye's refractive power will be lower for longer wavelengths and, thus, the eye will be hyperopic for wavelengths longer than the yellow focused on the retina.

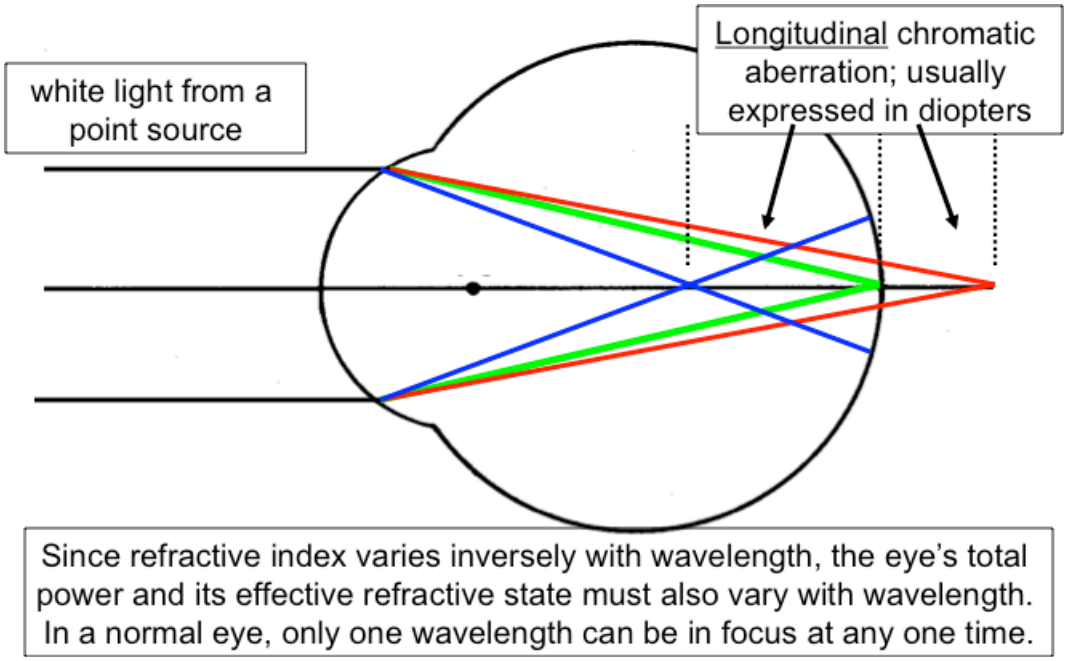


Figure 8.15: *The effects of chromatic aberration on the formation of the retinal image*

MAGNITUDE OF OCULAR CHROMATIC ABERRATION

The amount of **longitudinal** chromatic aberration, like longitudinal spherical aberration, is specified in terms of refractive diopters. Typically, the amount of longitudinal chromatic aberration for a given optical system is expressed as the difference in the system's refractive power for two specific points in the visible spectrum, the C and F Fraunhofer lines. The Fraunhofer C- and F-lines correspond to wavelengths of 656 nm and 486 nm, respectively. Ivanoff (1953) determined the amount of chromatic aberration for the average eye. He found a difference of about 0.9 D between the focal points for the red light from the C-line and the blue light from the F-line.

Note: Fraunhofer lines are actually dark lines seen against the continuous spectrum of the light from the sun. The dark lines are caused by the selective absorption of light at these specific wavelengths by gasses that surround the sun.

It is important to keep in mind that although the amount of chromatic aberration is traditionally defined with respect to the C and F Fraunhofer lines, the visible spectrum includes wavelengths shorter than the F-line and wavelengths longer than the C-line. Most authorities consider the visible spectrum (i.e. that portion of the electromagnetic spectrum that can stimulate the retina and produce a visual sensation under normal viewing conditions) to extend from about 380 nm to about 760 nm. The amount of longitudinal chromatic aberration across the entire visible spectrum is considerably larger than that between the C- and F-lines. There is about a 2.6-2.8 D difference in the refractive power of the eye for light from the short and long wavelength ends of the spectrum (i.e. the refractive status of the unaccommodated eye measured with light from the two extremes of the visible spectrum would vary by almost 3.0 D). The average dispersion of the human eye is just slightly greater than that for distilled water (i.e. the eye has about as much chromatic aberration as an equal volume of distilled water).

CHROMATIC ABERRATION AND CLINICAL PROCEDURES

Unlike the monochromatic aberrations, the amount of chromatic aberration does not vary much between individuals. That makes sense because the monochromatic aberrations are dependent on the shape or form of an optical system and it is obvious that the exact shape of the eye (e.g. corneal curvature, anterior chamber depth, lens curvature, etc.) varies substantially between individuals. In contrast, chromatic aberration is dependent on the refractive indices of the ocular media and there is very little inter-subject variability in the refractive indices of healthy eyes (keep in mind that it is thought that some systemic diseases, e.g. diabetes, can produce changes in the refractive indices of the ocular media). Because chromatic aberration is an extremely consistent effect and because different wavelengths of light produce different color sensations under normal viewing conditions, clinicians have historically employed procedures to measure the eye's refractive status that are based on the eye's chromatic aberration.

COBALT FILTER

One of the earliest attempts to employ chromatic aberration to determine the refractive status of the eye involved the use of **Cobalt filters**. Cobalt filters transmit light primarily from the red and blue ends of the spectrum, but absorb light in the middle of the spectrum (i.e. greens and yellows). As a result, extended white light sources typically appear purple in color when viewed through a cobalt filter.

Figure 8.16 shows how cobalt filters could be used to help the clinician determine the location of the secondary focal points for blue and red light relative to the retina. Assume that a 5.0 D uncorrected, unaccommodated myope is viewing a distant white point source of light through a cobalt filter. The blue and red light that is transmitted by the filter is refracted by the eye's optics and comes to a focus in the vitreous. Because the power of the eye is greater for blue light than for red light, the blue light will come to a focus closer to the cornea. Since the eye is uncorrected, the blue and red light will form blur circles on the retina. However, since the focal point for the red light is closer to the retina, the size of the red blur circle will be substantially smaller than that for the blue light. As a result, if asked to describe the appearance of the distant source of light, the myope will typically indicate that it looks like a red spot surrounded by a blue fringe.

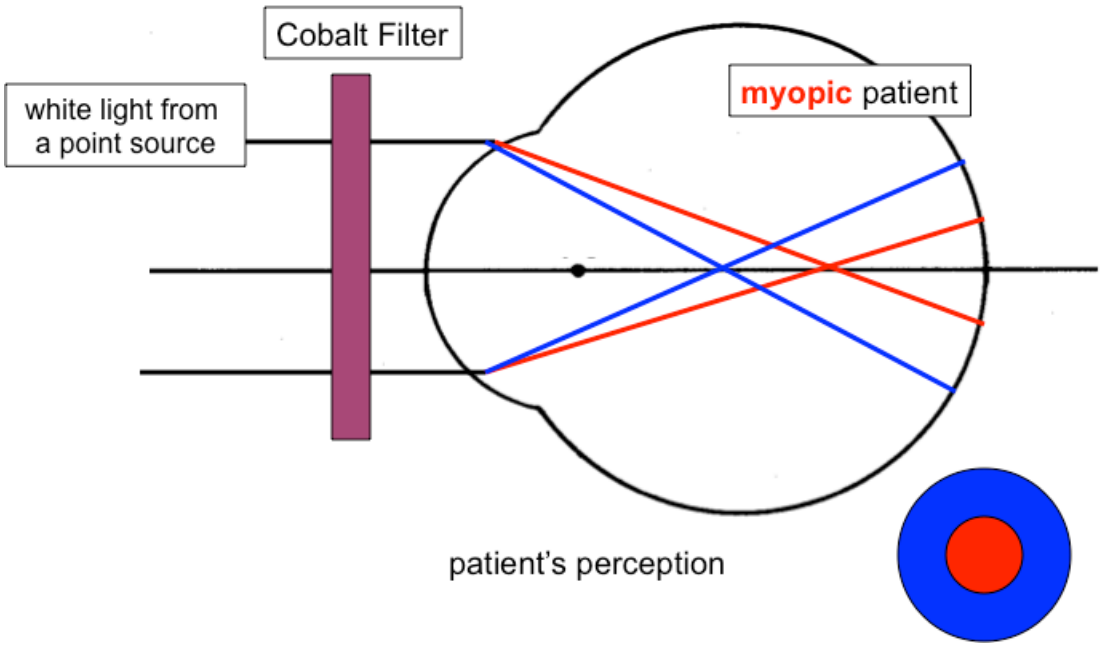


Figure 8.16: *Cobalt filters can be used to help the clinician determine the location of the secondary focal points for blue and red light relative to the retina*

If the patient in the above example was a hyperope, or if the myope in the above example viewed a white point source that was located closer to the eye than the myope's near point, the appearance of the light source would be quite different. In these cases, both the red and blue focal points would be located behind the retina. But since the blue focal point would be closer to the retina than the red focal point, the light source would appear as a blue spot surrounded by a red fringe.

How can a cobalt filter be used to determine a patient's refractive status? To determine a patient's refractive status, the lens power in the phoropter is usually adjusted so that the patient reports that the distant white point source viewed through the cobalt filter appears uniform purple in color. In order for the light source to appear uniform purple, the red focus must be behind the retina while the blue focal point must be an equivalent distance in front of the retina. In this situation, the retinal blur circles for red and blue will be equal in size as well as superimposed resulting in a uniform purple image. The lens power that produces this effect is considered to be the appropriate spectacle correction.

It is unfortunate that the refractive corrections obtained with this procedure do not always agree with the subjective findings found using more traditional procedures. It is believed that the primary reason for this discrepancy is related to the observation that the eye prefers to have specific wavelengths of light focused on the retina when it is viewing a distant object. Implicit in the cobalt filter procedure is the assumption that the eye wants to have a wavelength of light that is between blue and red focused on the retina in the unaccommodated state. The peak of the photopic luminosity function is at about 550 nm and its focal point is located approximately between the focal points for red and blue. Since the eye is most sensitive to green light with a wavelength of about 550 nm, it seems reasonable to assume that the eye would select to have 550 nm light focused on the retina and that the end-point for the cobalt filter procedure described above would be adequate. However, direct measurements of the wavelength of light that is focused on the retina in the unaccommodated state indicate that the eye typically prefers to have long wavelength light, i.e. red light, focused on the retina when the eye is fixating a distant object.

Note: The **photopic luminosity function** reflects the relative brightness-producing capacity of different wavelengths of light under photopic or light-adapted conditions. In essence, the photopic luminosity function (i.e. the photopic spectral sensitivity function obtained for certain test conditions) specifies the relative sensitivity of the eye for different wavelengths of light. The peak of the function is at about 550 nm; i.e. the eye is most sensitive to light with a 550 nm wavelength.

FOCUSING WAVELENGTH OF THE VISUAL SYSTEM

As indicated above, when the eye is fixating a distant object, and given the opportunity, the visual system of most individuals will select to have red light with a wavelength of about 680 nm focused on the retina. Interestingly, as the eye focuses on nearer objects, i.e. as the accommodative demand is increased, the wavelength that the eye prefers to have focused on its retina changes in a systematic fashion. The wavelength that the eye prefers to have focused on the retina can be plotted as a function of the accommodative demand. It is important to note that although there is a systematic decrease in the selected wavelength as the accommodative demand increases, the function levels off at about 550 nm. Even for high accommodative demands, the eye does not usually focus for wavelengths shorter than about 500 nm.

The failure of the visual system to use the entire chromatic interval is probably due to the relatively poor spatial, temporal, and luminance processing capacity of visual system neurons that signal short wavelength information. In comparison to the neural elements that process information for green, yellow, and red wavelengths, the elements that process information for blue light (i.e. short wavelengths) have a relatively low spatial and temporal resolving capacity (i.e. in a sense, lower visual acuity and poor sensitivity for flickering lights) and they do not appear to contribute substantially to the perception of brightness.

The reason for selectively focusing on relatively shorter wavelengths at near should be obvious. The shorter the wavelength of the light, the greater is the total dioptric power of the eye. So by focusing for long wavelengths for distance, but shorter wavelengths at near, the eye does not have to change the power of the crystalline lens as much as it would if it focused for the same wavelength at distance and near. In this regard, the visual system saves accommodative energy by taking advantage of its chromatic interval. For example, assume that an eye was focused for 600 nm light when it fixated a distant target. If fixation was shifted to a point 40 cm in front of the principal plane, the eye would have to increase its power by +2.5 D in order to have red light (600 nm) from the near object focused on the retina. By focusing for a slightly shorter wavelength at near (e.g. 550 nm), the eye may only have to accommodate 2.00-2.25 D in order to see clearly. The other required 0.25-0.50 D of power would come from chromatic aberration (i.e. the eye has a higher total dioptric power for 550 nm than for 680 nm light).

Note: Some recent studies have suggested that the wavelength that is conjugate to the retina in the unaccommodated state is shorter than that typically specified in text books (600 nm or shorter instead of 680 nm) and that there is a substantial amount of inter-subject variability. Nevertheless, these recent studies have confirmed the tendency of the eye to select relatively shorter wavelengths for viewing near objects.

When assessing the eye's refractive status, you must be conscious of the wavelength of light that you are using to evaluate the eye's optics and the wavelength of light that the visual system prefers to have focused on the retina. The ‘lag of accommodation’ that is often observed during near retinoscopy is a good example of the consequence of a mismatch between the wavelength of light that is focused on the retina and that employed to assess the eye's optical system. During near retinoscopy the patient, viewing through the **distance spectacle correction** in the phoropter, is instructed to fixate your retinoscope at a 50 cm working distance (typically a letter target attached to the scope is employed as a fixation target). If the patient has accommodated an amount equivalent to the 2.0 D demand associated with the 50 cm working distance, you would expect that the retinoscopy reflex would be neutral (i.e. the sight hole of your retinoscope would be conjugate to the patient's retina). However, in most instances you will observe ‘with motion’ and will have to add about 0.75 D more plus power to the distance Rx in order to achieve a ‘neutral’ reflex.

At first glance, it would seem that the patient simply did not accommodate for your working distance (the amount of plus required to produce a neutral reflex is often called the ‘lag of accommodation’) and, therefore, before the plus was added to the distance Rx, the fixation target on your retinoscope should have been blurred to your patient. But, if asked, the patient will report that the fixation target was ‘clear’. Why then did you have to add plus lenses to get a neutral reflex? This apparent discrepancy stems from the fact that the dominant wavelength observed in a retinoscope reflex is about 600 nm (i.e. with a retinoscope you are refracting the eye with red light). However, at the 50 cm fixation distance most patients will prefer to have a shorter wavelength of light focused on their retina. As a consequence, the patient's eye will appear to be under accommodated for red light. You can neutralize the apparent hyperopia observed in near retinoscopy by adding plus lenses over the BVA lens. In essence, you are reducing the accommodative demand until the patient chooses to have red light focused on the retina.

Note: If the dominant wavelength of the retinoscopy reflex was not red, your retinoscopy findings would usually not agree with your subjective BVA. In this regard, it is fortunate that the eye prefers to have red light focused on the retina at infinity. You can alter the dominant wavelength of the retinoscopy reflex by placing a ‘color’ filter in front the scope's light source (i.e. chromoretinoscopy). If, for example, you placed a green filter in your retinoscope, you would find that your retinoscopy finding would be more minus/less plus than your subjective BVA.

The ability to use the chromatic interval to reduce the amount of accommodative effort required for fixating a near target appears to be a ‘learned’ phenomenon. Unlike adult subjects, children under about 3.5 years of age do not show the wavelength preference pattern that adults exhibit. In children this young, it is not possible, for any accommodative demand, to predict which wavelength will be focused on the retina. Between about 3.5 and 5.0 years, children begin to prefer to have long wavelengths focused on their retina when viewing distant targets. However, children in this age bracket do not usually select to have short wavelengths focused on their retinas at near (i.e. they do not take advantage of their chromatic interval). After about 6 years of age, most children exhibit the typical adult wavelength preference pattern (i.e. red wavelengths for distance, shorter wavelengths for near). It appears, however, that some individuals, for whatever reason, never learn to use their chromatic intervals to their advantage. These patients may show an unusual ‘lead of accommodation’ during near retinoscopy.

THE RED-GREEN TEST

The most common clinical procedure that relies on chromatic aberration is the Red-Green test (i.e.bichrome or duochrome test). In the R-G test, approximately 0.5 D of plus is added to the BVA and the patient is instructed to attend to a bi-partite red/green display at optical infinity in an otherwise dark room. The patient is requested to indicate the color of the background that is perceived to have the darkest/blackest letters/targets. Typically, since both the red and green foci will be located in the vitreous with the red focal point closer to the retina, the patient will indicate that letters on the red side are 'darker' (see Figure 8.17). The amount of plus power in the phoropter is then reduced (in essence moving the entire chromatic interval back toward the retina) until the patient reports that letters in the red and green fields are equally dark (i.e. the red focus is behind the retina but the green focus is an equivalent distance in front of the retina) or that the letters on the green side are slightly darker (i.e. the green focus in closer to the retina). Since the chromatic interval between the green and red colors employed in most projector charts is about 0.36 D, it typically takes about 0.5 D to go from the red side being darker to the green side being darker.

Note: The red-green test takes advantage of the eye's chromatic aberration to locate the position of the secondary focal point with respect to the retina. It is dependent primarily on the dispersive characteristics of the patient's eye. The test is not dependent on the patient's ability to discriminate different colors. Even if your patient is 'color blind', the R-G test can be used. In this case you would simply change the instructions and ask the patient to identify the side (not the color) of the display (i.e. the right or left) that contained the darkest targets.

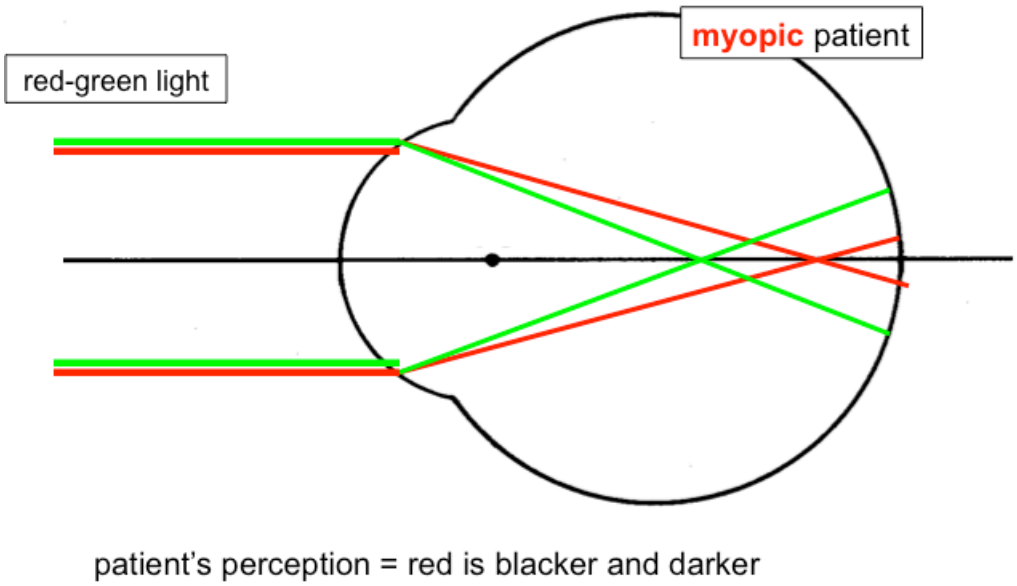


Figure 8.17: *The red green 'duochrome' test relies on chromatic aberration*

Some individuals do not respond in a typical manner during the red-green test. In some cases, the patient will report that the letters on the red side always appear darker. Even if you increase the minus/decrease the plus power in the phoropter by a substantial amount. It is likely that these individuals have a very strong tendency to have long wavelengths of light focused on their retinas when they are viewing a distant target. In these individuals the R-G test does not work because, as you reduce the plus power in the phoropter, these patients accommodate to keep the red wavelengths focused on the retina. The R-G test is conducted in a dark room in order to reduce the number of cues concerning the distance of the red/green target so that most patients will allow non-red wavelengths to be focused on their retinas. Therefore, one reason the test is conducted in a dark room is to mask (in a sense) the true position of the screen and, thus, minimize the tendency that most adults have for selectively focusing on red light for distant targets.

EFFECTS OF CHROMATIC ABERRATION ON VISUAL FUNCTION

For a given viewing distance only one wavelength of light from an object will be focused on the retina at any one time; all other wavelengths of light from the object will be out of focus and, thus, produce a series of blur circles on the retina. Since the quality of the retinal image would certainly be improved by eliminating the blur circles produced by the wavelengths that are not focused on the retina, it seems logical that visual acuity would also improve if only one wavelength of light was employed to illuminate an acuity chart. Interestingly, if you employ monochromatic light to illuminate an acuity chart (making sure that it was as bright with the monochromatic light as it was for white light), the measured acuity values would not be affected appreciably. Contrast sensitivity for moderate and high spatial frequencies would be increased, but the ability to detect high spatial frequencies (Snellen acuity is an estimate of the high spatial frequency resolution of the eye) would not be affected very much. In fact, even if the amount of chromatic aberration in the eye is doubled artificially, the high-spatial resolving capacity of the eye is not substantially affected.

It is believed that the deleterious effects of chromatic aberration on the functional capacity of the eye are minimized by the following factors.

1. **Pupil size:** The pupil minimizes the effect of chromatic aberration by limiting the size of the blur circles for the wavelengths that are not focused on the retina.
2. **Selective absorption by ocular media:** Some of the effects of chromatic aberration are reduced by the selective absorption of certain wavelengths of light. Specifically, the macular pigment and, in older individuals, the crystalline lens preferentially absorb short wavelength light and, thus, reduce the impact of the blur circles associated with blue light.
3. **Retinal neural mechanisms:** The majority of neurons in the primate retina respond selectively to a limited range of stimulus wavelengths. As a result, a neuron that is selective for red light will not be affected to a significant degree by an out of focus blue light.
4. **Foveal Optics:** There is a substantial change in refractive index at the interface between the retina and the vitreous (the retina having a significantly higher index of refraction). Therefore, the vitreal-retinal interface can function as a minus refracting surface – particularly the foveal pit. It has been calculated that the chromatic aberration associated with the vitreal-retinal interface can cancel some of the chromatic aberration associated with the positive refracting elements is the eye.

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