

The Eye as an Optical Instrument

Pablo Artal

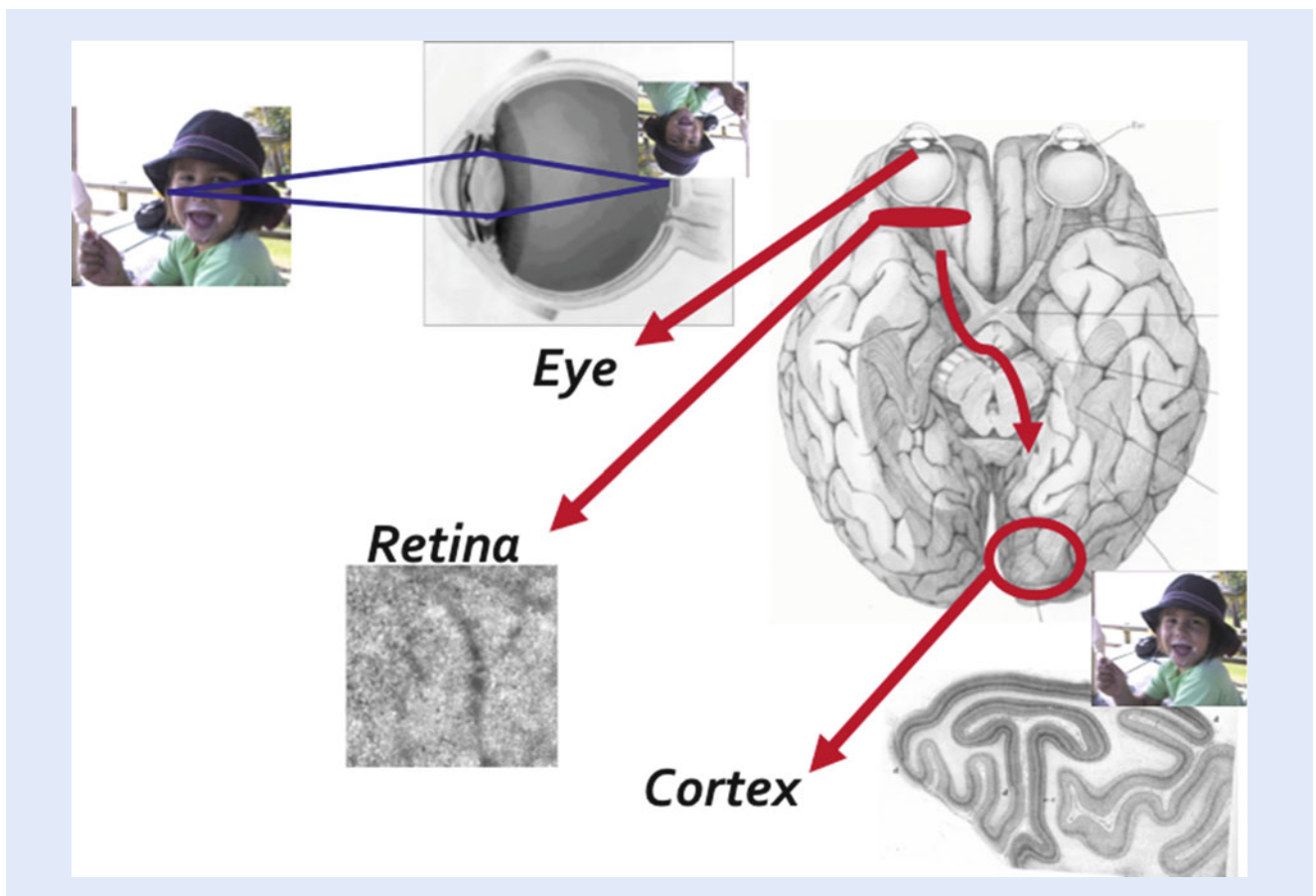
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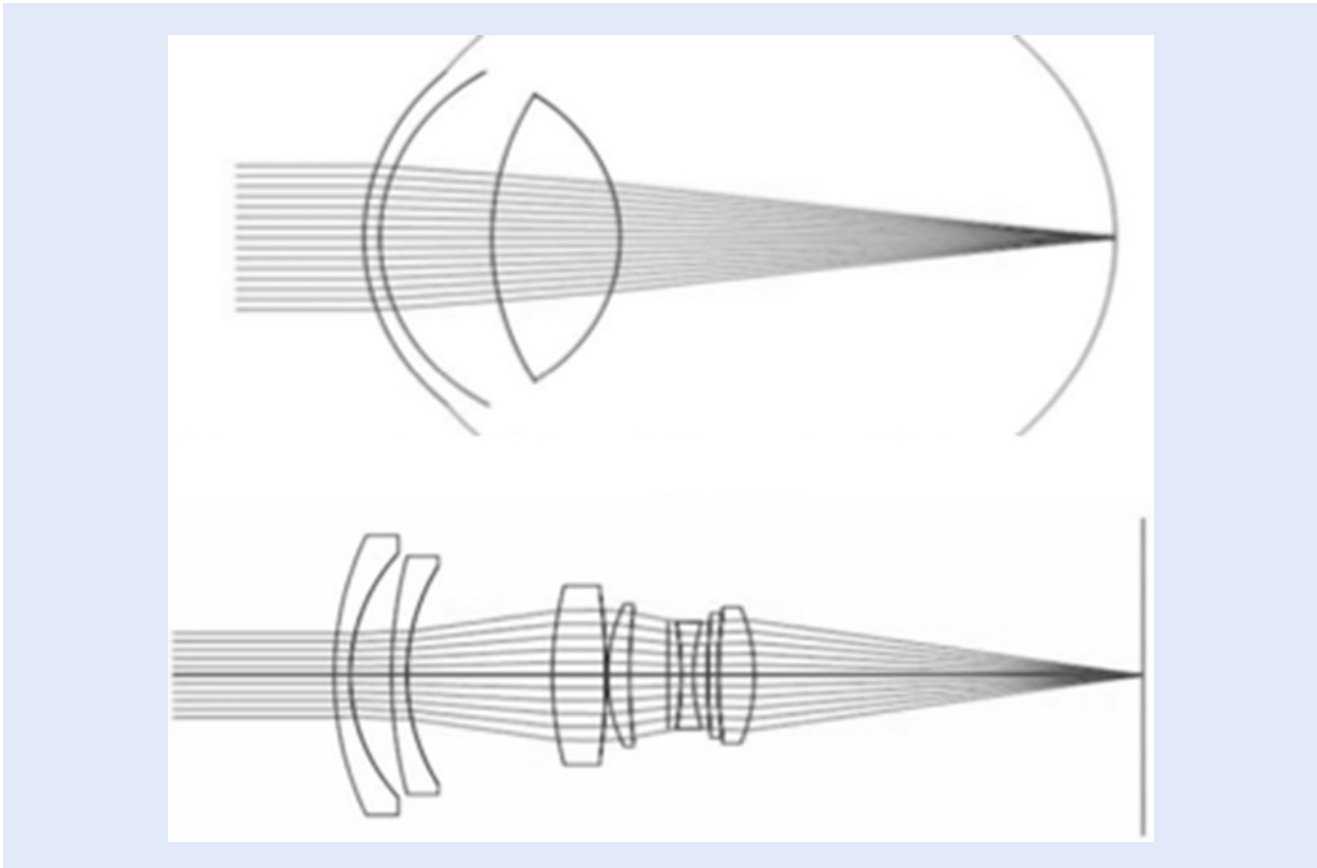
12.1 Introduction

For us, humans, vision is probably the most precious of senses. Although our visual system is a remarkably sophisticated part of our brain, the process is initiated by a modest optical element: the eye. ■ Figure 12.1 shows a schematic and simplified example of the visual process. The eye forms images of the visual world onto the retina. There, light is absorbed in the photoreceptors and the signal transmitted to the visual cortex for further processing. The eye, the first element in the system, is a simple optical instrument. It is composed of only two positive lenses, the cornea and the crystalline lens, that project images into the retina to initiate the visual process. In terms of optical design complexity and compared with artificial optical systems, often formed by many lenses, the eye is much simpler. However, despite this simplicity and the relative poor imaging capabilities, the eye is adapted to the requirements of the visual system. ■ Figure 12.2 shows a schematic illustration of the eye as compared to a photographic objective that is composed of many lenses.

Optical systems use transparent materials as glass or plastics with refractive index selected to bend the light rays to form images. In the case of the human visual system, our eyes have to form images of a large field of view for objects placed at different distances with high resolution at least at a central area of the retina. And these tasks have to be accomplished using living tissues.



■ Fig. 12.1 Schematics of the visual system. The eye forms images of the world on the retina. There, optical images are sampled by the photoreceptors, converted into electrical signals and transferred to the visual cortex for further processing. The eye, although is the simplest part, since it is placed first in the visual cascade may impose fundamental limits

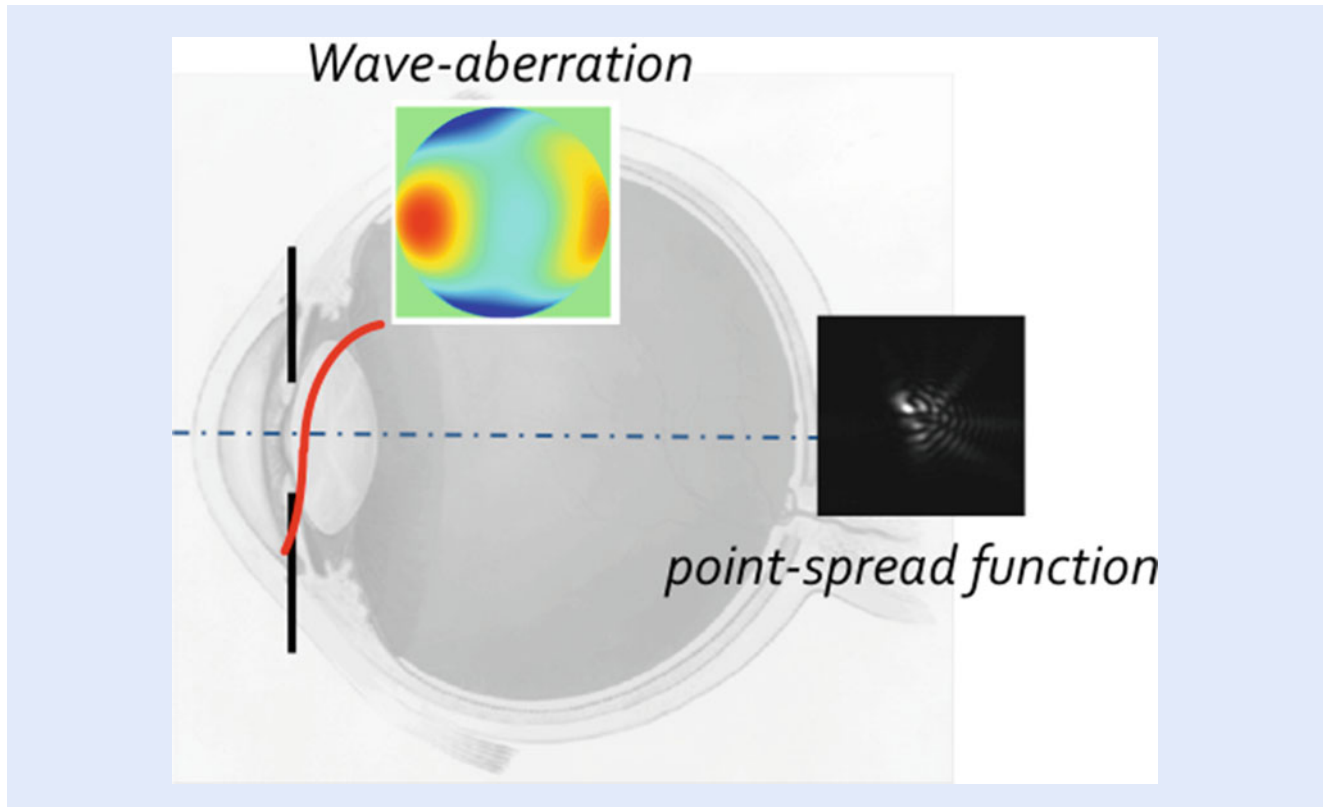


■ **Fig. 12.2** The eye is only composed of two lenses, cornea and crystalline lens, as compared with artificial systems, such as camera objective that may have many single lenses

The eye as an optical instrument is extremely important because our vision is only good when the images formed on the retina are of sufficient quality. If the retinal images are too blurred, the visual system will not work properly. The opposite situation is not true since there are retinal and neural diseases that may impair vision even when the eye forms good quality retinal images.

The intrinsic nature of the light is somehow responsible for some of the characteristics of the eye. Or equivalently, the eye is adapted to transmit visible light and form images on the retina. The sensitivity of the retina is also optimized in the central part of visible spectrum and is similar to the solar emission spectrum. Light may be considered as a transverse electromagnetic wave. Monochromatic light waves have electric fields with sinusoidal oscillation perpendicular to the traveling path. Visible light has wavelengths ranging from approximately blue (400 nm) to red (700 nm), what is a small fraction of the electromagnetic spectrum. A simpler geometrical description of the light as rays pointing along the direction of wave propagation is often used to describe some of the image properties of the eye.

It is interesting to note that also the particle nature of light may have a role in vision under particular conditions. Absorption of light by matter only can be interpreted if the light is considered as a particle, called a photon. Photon absorptions occur in the photoreceptors following the rules of a random process, discontinuously in discrete quanta. Specifically, the light intensity reaching each photoreceptor only determines the probability of a photon being absorbed. This imposes another fundamental limit to vision related to the photon statistics. However, this is restricted to very low luminance conditions after dark adaptation.



■ **Fig. 12.3** The main functions describing the optical quality of the eye. The wave-aberration on the pupil plane represents the deviation in phase compared with a perfect optical system. The point-spread function (PSF) is the image of a point source formed in the retina. A good eye will form compact and symmetrical images, while in an aberrated eye the PSF will be more extended and asymmetric

Under most normal viewing conditions, the quality of the retinal images is governed by the wave-like nature of the light. The functions used to describe the quality of any optical instrument are shown in ■ Fig. 12.3. The wave-aberration function is defined as the difference between the perfect (spherical) and the real wave-front for every point over the pupil. It is commonly represented as a two-dimensional map, where color level represents the amount of wave-aberration, expressed either in microns. The image of a point source is called the point-spread function, PSF. An eye without aberrations has a constant, or null, wave-aberration and forms a perfect retinal image of a point source that depends only on the pupil diameter. By performing a convolution operation, it is possible to predict the retinal images of any object. This can be easily understood as placing a weighted PSF onto each point of the geometrical image. Readers interested in more information on the nature of light and/or the functions describing image quality could read some general optics references [1–3].

12.2 The Anatomy of the Eye

The human eye can be described as a fluid-filled quasi-spherical structure. Anatomically consists essentially of three tissue layers: an outer fibrous layer (the sclera and cornea), an inner layer consisting largely of the retina, but including also parts of the ciliary body and iris, and an intermediate vascular layer made up of the choroid and portions of the ciliary body and iris. The eye in adult humans is approximately a sphere of around 24 mm in diameter. It is made up of a variety of cellular and non-cellular components derived from ectodermal and mesodermal

germinal sources. Externally it is covered by a resistant and flexible tissue called the sclera, except in the anterior part where the transparent cornea allows the light to pass into the eye. Internal to the sclera are two other layers: the choroid to provide nutrients and the retina, where the light is absorbed by the photoreceptors after image formation. The eye moves due to the action of six external muscles permitting fixation and the scanning of the visual environment. The light reaching the eye is first refracted by the cornea, a thin transparent layer free of blood vessels of about 12 mm in diameter and around 0.55 mm thickness in the central part. An aqueous tear film on the cornea assures that the first optical surface is smooth to provide the best image quality. After the cornea, the anterior chamber is filled with the aqueous humor, a water-like substance. The iris, two sets of muscles with a central hole whose size depends on its contraction, acts as a diaphragm with characteristic color depending on the amount and distribution of pigments. The aperture is the opening in the center of the iris, and limits the amount of light passing into the eye. The entrance pupil is the image of the iris through the cornea and the exit pupil the image of the aperture through the lens. The aperture size changes with the ambient light, from less than 2 mm in diameter in bright light to more than 8 mm in the dark. The pupil controls retinal illumination and limits the rays entering the eye affecting the retinal image quality. After the iris, the crystalline lens, in combination with the cornea, form the images on the retina. The crystalline lens is an active optical element. It changes its shape modifying its optical power. The lens is surrounded by an elastic capsule and attached by ligaments called zonules to the ciliary body. The action of the muscles in the ciliary body permits the lens to increase or decrease power.

The retina has a central area, the fovea, where photoreceptors are densely packed to provide the highest resolution. The eyes move continuously to fixate the desired details into the fovea. The peripheral parts of the retina render lower resolution but specialize in movement and object detection in the visual field. The typical field covered by the eye is quite large as compared with most artificial optical system, at least $160 \times 130^\circ$.

The cornea is approximately a spherical section with an anterior radius of curvature of 7.8 mm, posterior radius of curvature of 6.5 mm, and refractive index of 1.3771. Since the largest difference in refractive index occurs from the air to the cornea (actually the tear film), this accounts for most of the refractive power of the eye, on average over 70 %. The lens is a biconvex lens with radii of curvature of 10.2 and -6.0 mm for the anterior and posterior surfaces. The internal structure of the lens is layered, which produces a non-homogeneous refractive index, higher in the center than in the periphery and with an equivalent value of 1.42. The refractive indexes of the aqueous and vitreous humors are 1.3374 and 1.336, respectively. More detailed information on different aspects of the eye's geometry and its optical properties can be found in references [4–6].

An average eye with these distances: 3.05, 4, and 16.6 mm for the anterior chamber, lens, and posterior chamber, respectively, will have a total axial length of 24.2 mm and will image objects placed far from the eye precisely in focus into the retina. This situation is called emmetropia. However, most eyes are affected by refractive errors since they do not have the adequate optical properties or the dimensions required for perfect focus. Refractive errors are classified as myopia, when the images of distant object are focused in front of the retina, and hypermetropia, when distant objects are focused behind the retina. In addition, the eye is not rotationally symmetric, being a common manifestation the presence of astigmatism: the retinal image of a point source consists of two perpendicular lines at different focal distances. ■ Figure 12.4 shows an example of a myopic eye and the degradation found in its retinal image.

The ocular media filter the wavelengths reaching the retina. There are a good matching between transmission and photoreceptor sensitivity. The cornea and the

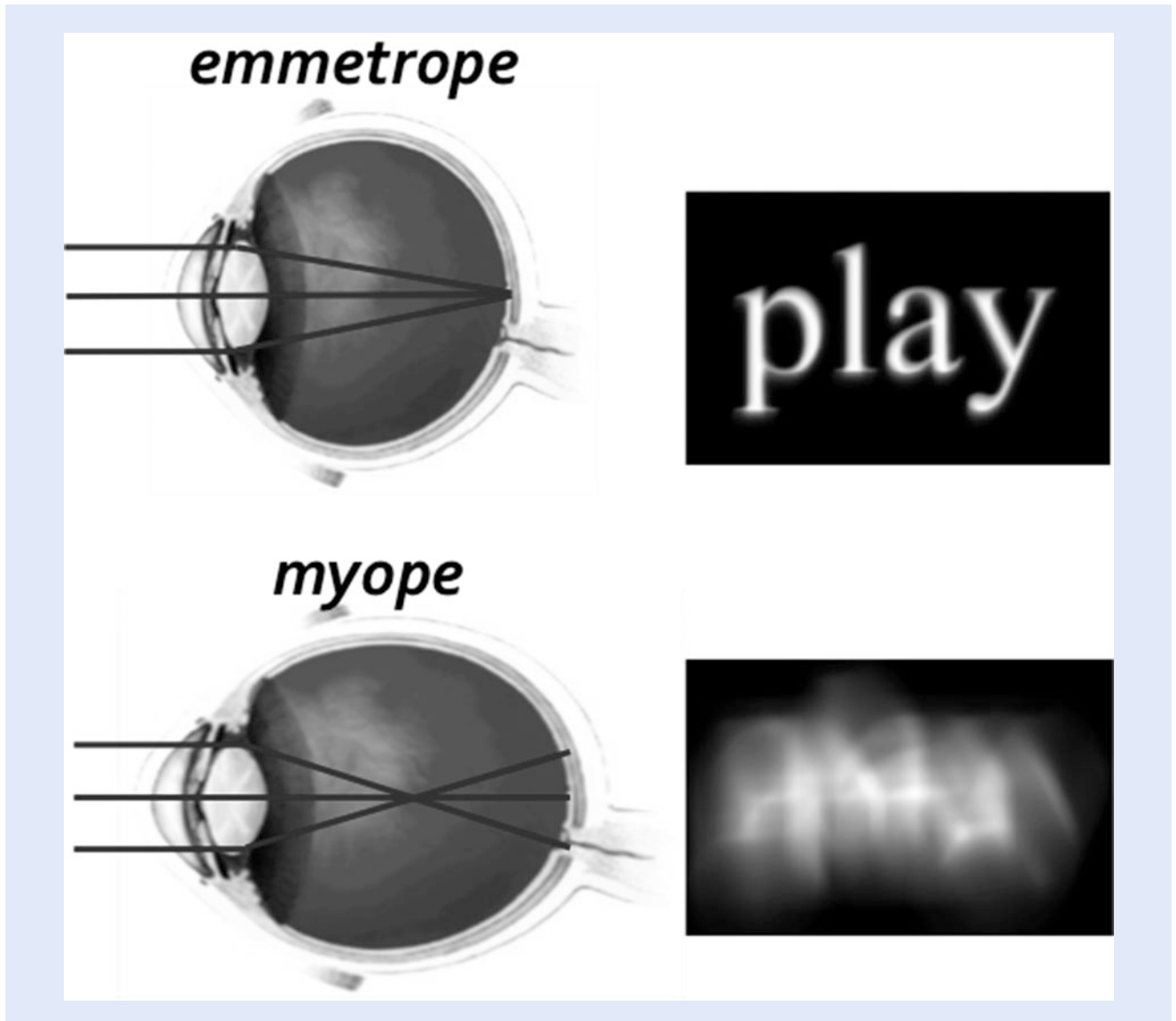


Fig. 12.4 Examples of an emmetrope and a myopic eye and the image formed in the retina of the word “play.” In myopes, the image is formed behind the retina and the images are blurred

vitreous have bandwidths that exceed the visible spectrum, but the lens absorbs light in the short wavelength (blue) part of the spectrum. The retina has also pigments that filter the light reaching the photoreceptors. The main filter in the retina is the yellow macular pigment located within the macular region near the fovea. It has been suggested that the macular pigment may protect the retina from degenerative diseases and also improve vision by removing blue light.

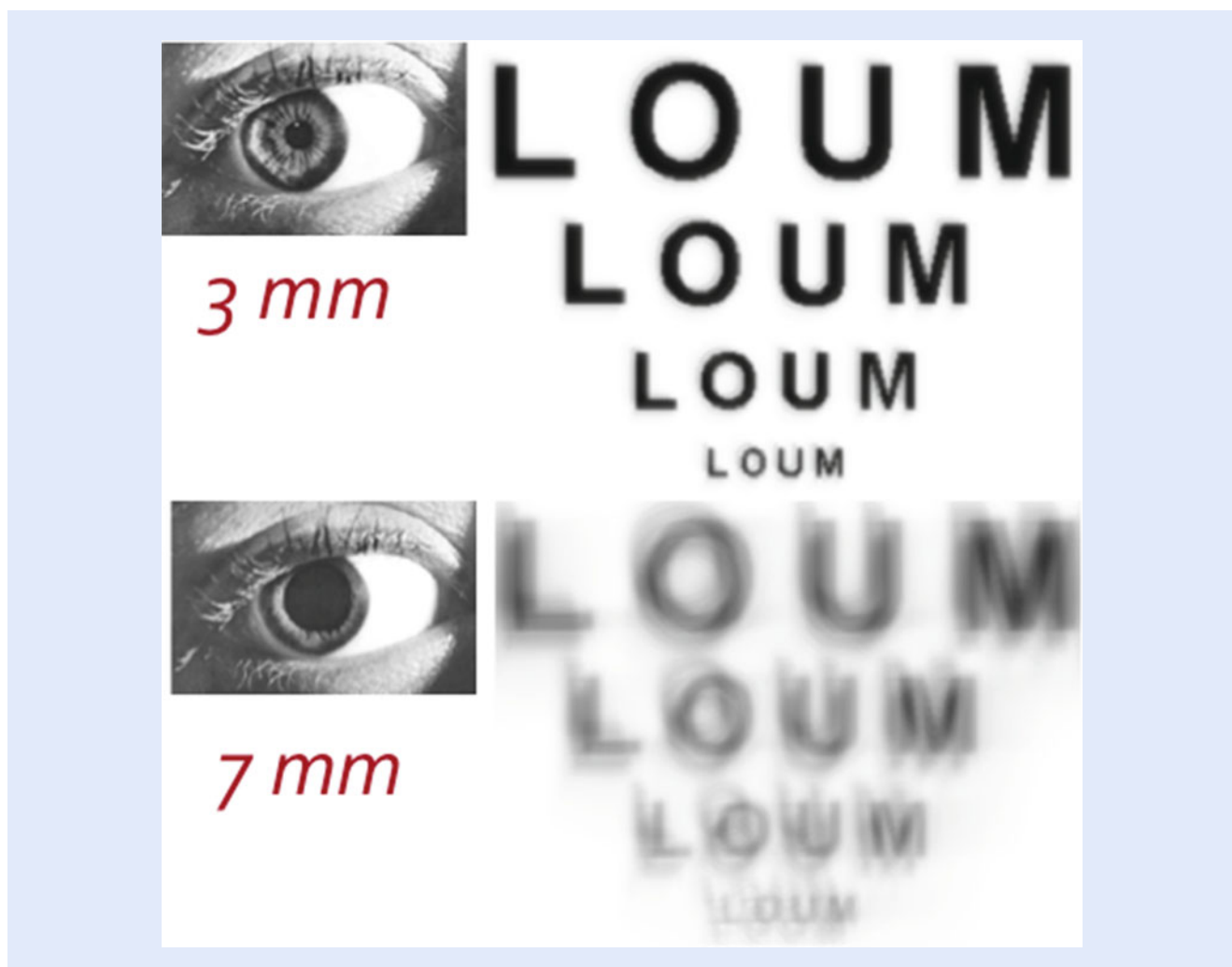
12.3 The Quality of the Retinal Image

Even when the eyes are at perfect focus, as in the case of an emmetrope, they do not produce completely perfect images. This means that the retinal image of a point source is not another point, but an extended distribution of light. Several factors are responsible for the degradation of the retinal images: diffraction of the light in

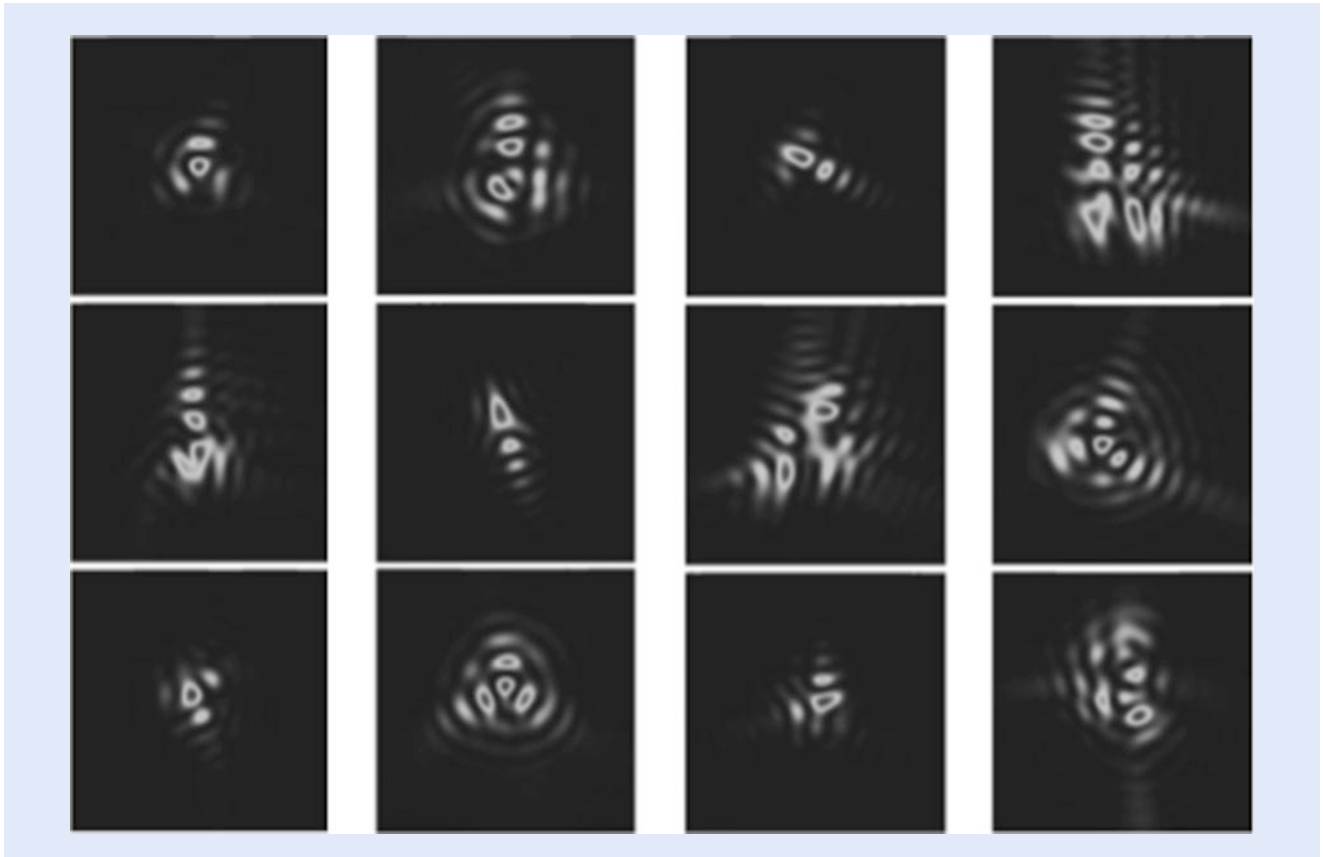
the eye's pupil, optical aberrations, and intraocular scattering. Diffraction blurs the images formed through instruments with a limited aperture due to the wave nature of the light. The effect of diffraction is usually small and only can be noticed with small pupils. The impact of the ocular aberrations in the eye's image quality is more significant for larger pupil diameters. The pupil of the eye varies diameter from around 2–8 mm in diameter. This corresponds approximately to an aperture range from $f/8$ to $f/2$, values which can be compared with the typical values in a camera objective. ■ Figure 12.5 shows an example of realistic retinal images of letters for the same eye for small (3 mm) and a larger (7 mm) pupil. Note how aberration degrades the image for larger pupils.

The amount of aberrations for a normal eye with about 5 mm pupil diameter ($f/4$ aperture) is approximately equivalent to less than 0.25 D of defocus, a small error typically not corrected when dealing in the clinic with refractive errors.

The particular shapes of the eye's lenses, refractive index distribution, and particular geometry are responsible for the limited optical quality of the eye compared with artificial optical systems. A normal eye has at least six times lower quality than a good (diffraction-limited) artificial optical system. Each eye produces a peculiar retinal image depending on the optical aberrations present. This can be demonstrated by how a point source is projected in the retina. For example, the shape of stars would depend on our image quality. ■ Figure 12.6



■ Fig. 12.5 Example of the effect of the pupil diameter in the retinal image quality. Aberrations affect more with larger pupils

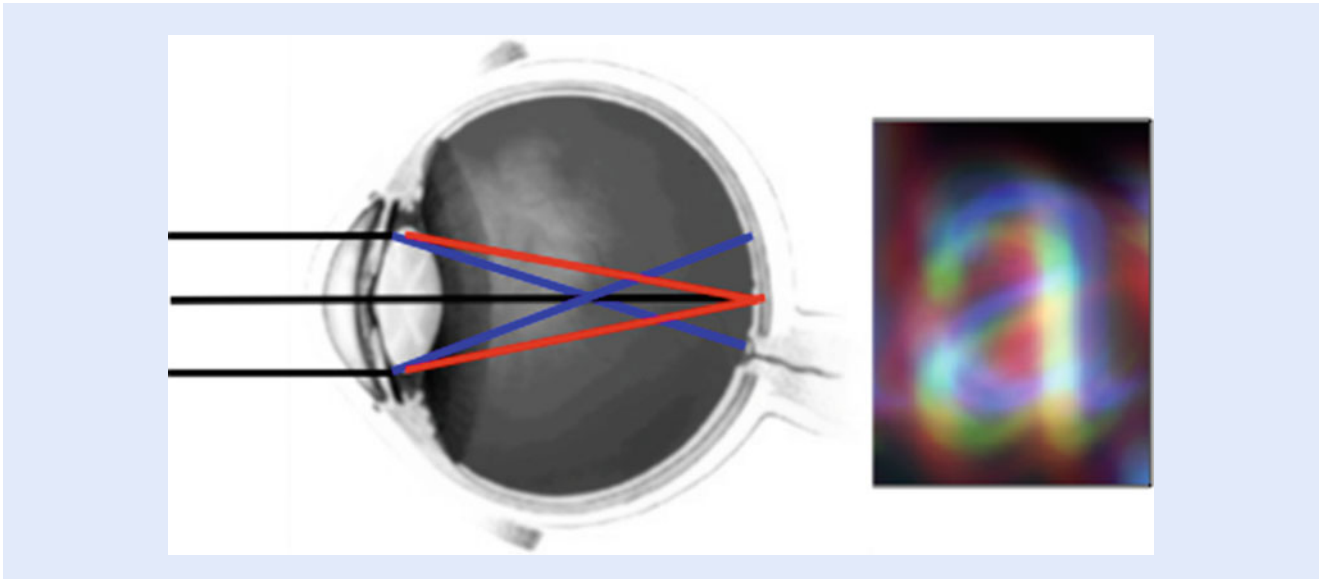


■ **Fig. 12.6** Retinal PSFs measured in a group of normal young subjects. Each eye has particular optical characteristics that produce a unique PSF. It can be understood as if each one of us sees point objects (for instance, stars or distant lights) differently

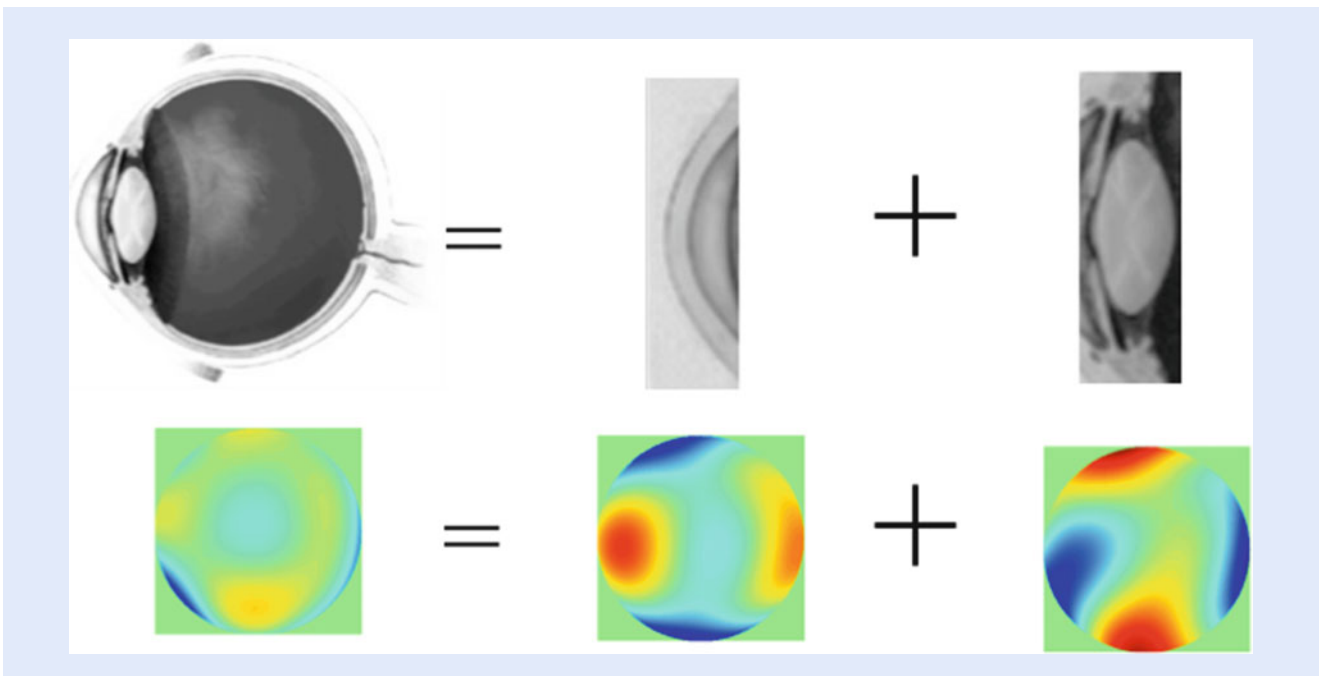
shows PSFs for a group of normal eyes. This could be understood as how every subject sees an individual star. All are different in shape and size, so our experience of point objects is quite personal.

In addition, chromatic effects also contribute to reduce the retinal image quality since real scenes are usually polychromatic (in white light). This is due to the dependence of refractive index on wavelength that produces changes of the power of the eye with wavelength [7]. The chromatic difference in defocus for the eye from red to blue is large: around 2 diopters. This can be understood as if when you see simultaneously two letters, one red and one blue, and when the red is in perfect focus, the other would be defocus by nearly 2D in your retina. However, your perception of color images is not like that since the real impact of chromatic aberration is smaller than the equivalent of 2D defocus blur. The reason is that the visual system has mechanisms to minimize the impact. The relative larger filtering of blue light in the lens and the macular pigment, together with the spectral sensitivity of the retina, reduce the contribution of the most defocused bluish colors. ■ Figure 12.7 shows an example of the appearance on the retina of a white letter a in a normal eye. It is important to note that due to retinal and neural factors, the actual impact of this chromatic blur is reduced and our perception less affected.

A question that attracted the interest of many scholars was how the cornea and lens contributed to the eye's optical quality. Early in the nineteenth century, Thomas Young neutralized the cornea by immersing his own eye in water and found that astigmatism persisted. This suggested that the crystalline lens itself have some degree of astigmatism. Recent experiments have also shown that the lens

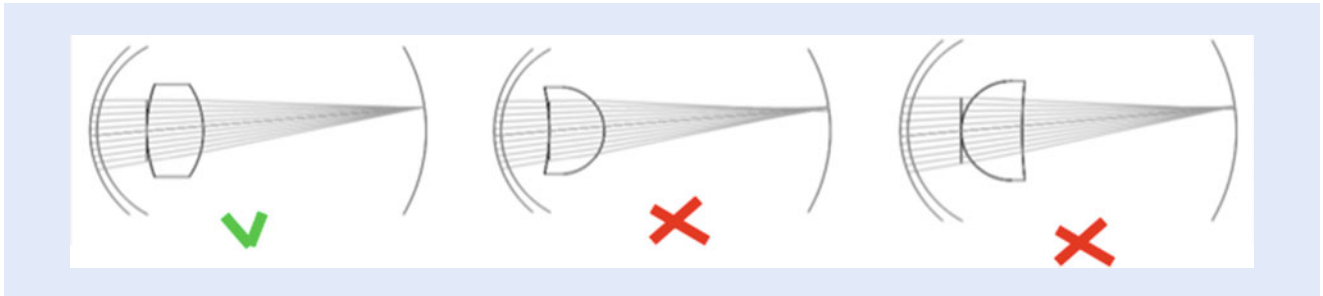


■ **Fig. 12.7** Chromatic aberration in the eye. Due to the chromatic dispersion of the ocular media, if an eye is perfectly focused for red light, it will be myopic (up to 2 diopters) for blue light. This affects the quality of white light images, as the realistic simulation of an image of letter “a” shows (on the right)



■ **Fig. 12.8** The cornea and lens in young eyes have similar aberrations but with opposite signs rendering the whole eye with better quality than each component isolated. The eye behaves like an aplanatic optical system with partial correction of spherical aberration and coma

compensates not only for some moderate amounts of corneal astigmatism, but also spherical aberration and coma. ■ Figure 12.8 shows as an example the aberrations for one author’s eye for the anterior cornea, internal optics (mostly the lens), and the complete eye. The aberrations of the cornea and the lens are somehow opposite rendering an eye with improved optics. The eye as an optical system presents an aplanatic design of the eye, with partial correction of the spherical aberration and coma [8, 9]. This may help to maintain a rather stable optical quality independent of some alignment ocular variables. The reason for this compensation is found in



■ **Fig. 12.9** The particular biconvex shape of the lens is an optimized design. Other possible options (as those on the right of the figure) would produce eyes with the same power but with worst image quality



■ **Fig. 12.10** The center of the visual field (fovea) has the highest resolution and declines with retinal eccentricity. This figure shows a practical example. When fixating at the smallest letter at the left when placing this page at 30 cm distance, the larger letters should appear visible at the corresponding eccentricities. This shows the degradation in acuity with eccentricity

the particular shape of the cornea and lens. They have form factors (a relation between their curvature radii) of opposite sign. This means that their shape is optimized by evolution. ■ Figure 12.9 shows an example. Although the three schematic eyes have the same power, so could be considered as plausible solutions in a design, the optimum one is the biconvex lens that actually present in our eyes.

However, this optimized design is only present in younger eyes. During normal aging, the eye's aberrations tend to increase due to a partial disruption in this coupling between cornea and lens [10]. There is another compensatory mechanism: smaller pupil diameters in older eyes tend to compensate for this increase in aberrations.

12.4 Peripheral Optics

The central visual field (the fovea) has the highest spatial resolution; however, the periphery of the retina also plays a crucial role in our visual system. We use the peripheral parts of the visual field to detect objects of interest that we may bring to our fovea more detailed information. Ocular movements change fixation accordingly.

The optics of the eye has a different behavior when the images are formed eccentrically. The oblique incidence of light on the eye produces off-axis aberrations. The ability to discriminate small objects decreases severely with eccentricity. For example, while the normal resolution in the fovea is 1 min of arc, it will increase to 2.5, 5, and 10 at 10, 20, and 30° of eccentricity, respectively.

■ Figure 12.10 shows an example. When fixating to the smallest letter with the



■ **Fig. 12.11** Retinal images of a letter “E” in a normal eye for different angles at the retina, fovea, 10, 20, 30, and 40°. At larger eccentricities, the off-axis aberrations further degrade the quality of the retinal images

fovea placing the book, or the screen, at around 30 cm, the larger letters at the different eccentricity have the correct size to be still legible.

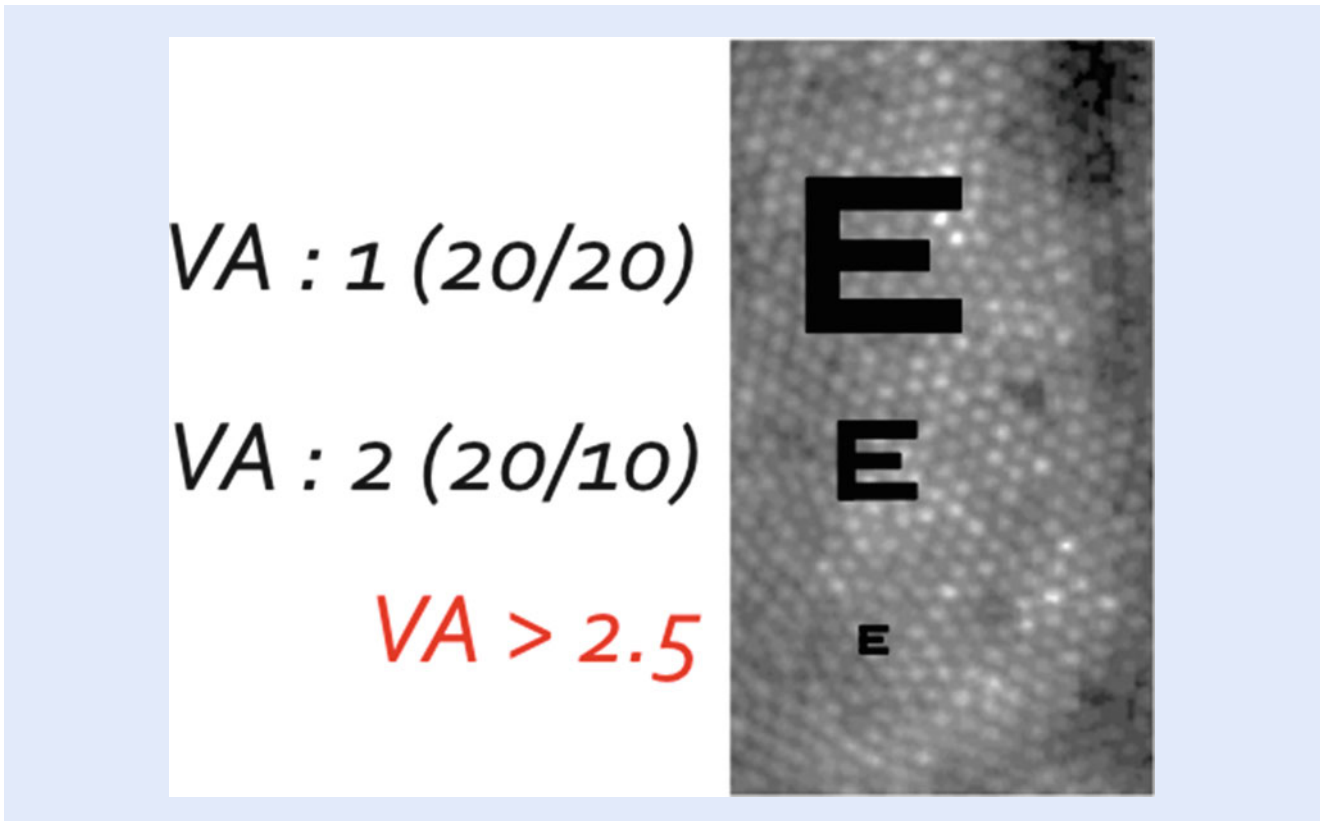
This resolution reduction is due to both optical and neural factors: the eccentric angular incidence induces optical aberrations, which lower the contrast of the retinal images, and the density of cones and ganglion cells also decline with eccentricity, resulting in sparse sampling of the image. In the fovea (central vision) the optics is in many cases the main limiting factor for vision, in the periphery vision is limited by neural factors. The optics is degraded for eccentric angles by distortion, field curvature, astigmatism, and coma [11]. Field curvature is a defocus for off-axis objects and implies that the best image is not formed on a plane but on a parabolic surface. In the eye, the screen is the retina, which has a spherical shape constitutes a curved image plane that in most cases compensates for field curvature. Astigmatism off-axis induces a significant optical degradation in the periphery.

■ Figure 12.11 shows examples of retinal images of a letter for different eccentricities. Despite the poor optics, visual acuity in the periphery cannot be improved with optical corrections. However, it is interesting to know that our peripheral optics is also optimized by the gradient index structure of the crystalline lens. This was demonstrated by comparing the peripheral image quality in the eyes of a group of patients with one eye implanted with an artificial intraocular lens and the fellow eye still with the natural pre-cataract lens. The eyes implanted had more astigmatism in the periphery than the normal eyes. This result suggests that the crystalline lens provides a beneficial effect also to partially compensate peripheral optics.

12.5 Conclusions

The eye is a simple and robust optical instrument that is fully adapted to serve our visual system. Although the optical quality is not as good in the eye as in the best artificial optical systems, it matches what is required by most of the visual capabilities. There are also a number of compensating mechanisms in the visual system that renders some of the potential optical limitations as invisible. For instance, the large potential deleterious effect of chromatic defocus is limited by proper color filters and the band-pass spectral sensitivity.

An interesting discussion in the last decades has been the possibility to correct for the aberrations of the eye using adaptive optics [12]. This is now technically possible in the laboratory and also, although partially, with correcting devices such



■ **Fig. 12.12** The sampling of the images the retina by the photoreceptors imposes the second limit to vision after the optics. Images of letters corresponding to decimal visual acuity 1, 2, and larger than 2.5 are represented. At the limit, a very small letter even if well projected into the retina would cover one single receptor. Then, the details of the letter will not be detectable. This suggests that even if the optics were perfect, visual acuity would not be improved

as intraocular lenses. The correction of the eye's aberrations may improve vision in some subjects but there are fundamental limitations that cannot be surpassed. The first is the sampling of the retinal images by the photoreceptors. Even if sharp images are projected into the retina, the smallest letter to be perceived will require several photoreceptors across to be properly interpreted. ■ Figure 12.12 shows this schematically at a correct scale. Images of letters smaller than those corresponding visual acuity (decimal) two will not be discriminated even if the letter is resolved by the eye's optics.

However, as was pointed out, the main cases for optical degradation are not higher order aberrations, but defocus and astigmatism. In that context, the manipulation of the eye's optics by different devices has been a successful technological development since the correction of defocus in the thirteenth century to the use of cylindrical lenses to correct astigmatism in the nineteenth century. Today, it is also possible to correct and induce also higher order aberrations in contact lenses, intraocular lenses, or laser refractive surgery procedures.

The future of correcting the eye's optics is both exciting and promising. And photonics and light technology will surely play a key role. The use of advanced optoelectronics would allow new prostheses to restore accommodation in the presbyopic eye. Two-photon interaction in the cornea by using femtosecond lasers may offer the possibility of changing the optical properties without the need to remove tissue, as is the case in the current ablation-based procedures. Optical technology is also fundamental in new diagnosis instrument. New swept-source optical coherence tomography allows full three-dimensional imaging in real time

of the eye in an unprecedented manner. And ophthalmoscopes equipped with adaptive optics obtain high-resolution images of the retinal structures in vivo. Optics and photonics are now, more than ever, at service to help our eyes to see well.

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