Chapter 4

Optics and the Eye

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In Chapter 4, we leave the province of psychophysics and enter the province of optics, one of the classical branches of physics. Our topic also includes physiological optics – the optics of eyes built by biological systems. Students with backgrounds in physics and biology, of course, will be more comfortable with these topics than they were with psychophysics, whereas students with backgrounds in perception will be less so. Hard core neuroscientists will have to wait their turn!

In Chapter 1 we raised the question of spatial resolution: what limits grating acuity? We laid out four possibilities: the optics of the eye; the photoreceptor matrix; the spatial convergence of signals within the retina; and other factors at higher levels of the visual system. In the present chapter we return to the first of these options. The goal of the present chapter is to fill in the background we need, in order to evaluate the possibility that the optics of the eye are the major factor that limits grating acuity.

To begin, we first define the units used to specify the spatial frequency of square wave gratings, both in physical and in quasi-physical terms. We then introduce the basic properties of light, including its dual nature as both waves and quanta. We outline four ways that light interacts with matter – reflection, refraction, diffraction, and absorption. We expand on the property of refraction in order to explain how lenses make images, and on the property of diffraction because of the remarkable role that interference fringes produced by diffraction patterns play in defining optical quality (discussed in Chapter 5).

We then turn to physiological optics, and examine the human eye as an optical system. The optical elements of the eye – the cornea, pupil and lens – form an image of the physical world
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Figure 4.1: Physical specification of a square wave grating. The sketches show variations in luminance across spatial position. One cycle of a grating consists of one high-luminance and one low-luminance region. The spatial frequency of each grating is specified by the number of cycles per centimeter (cy/cm). Not to scale.

inside the eyeball, at the back, on the sheet of neural tissue called the retina. We spell out the consequences for vision of optical errors within the eye. We describe the possible sources of information loss within the human optical system, and outline how to specify its quality. Finally, we introduce adaptive optics, a technique with which, remarkably, it is possible to improve the quality of the retinal image within the living human eye.

In sum, the eye is a remarkable physical and physiological structure. It captures a bundle of rays of light coming from the three-dimensional world, and focuses the rays to make the retinal image. The retina in turn provides the initial encoding of the information contained in the retinal image, that eventually allows us to judge the shapes, colors, motions, and distances of physical objects. But how much do the eyes optics affect the information available in the retinal image? The background provided in this chapter will allow us to attack this question again at greater depth in Chapter 5, in which psychophysical, optical, and neural themes combine.

4.1 Square wave gratings

We begin with a digression on the question of units. In Chapter 1, we specified the acuity gratings in Figure 1.2 only by letters: A, B, C, and so forth. Obviously we need to adopt more formal units. Vision scientists specify gratings in two different kinds of units – one physical, and the other quasi-physical.

4.1.1 Physical specification: Spatial frequency in cycles per centimeter

Figure 4.1 shows luminance profiles of three square wave gratings, corresponding to three of the seven gratings from Figure 1.2. Each white stripe of the grating gives a relatively high luminance,
4.1. SQUARE WAVE GRATINGS

Figure 4.2: Quasi-physical specification of a square wave grating. The spatial frequency of the grating is specified in units of the angle subtended by one cycle at the eye. The two gratings pictured differ in spatial frequency, specified in cy/cm. However, the 1/2 cy/cm grating is twice as far from the eye as the 1 cy/cm grating, such that a single cycle of each grating occupies the same angular size at the eye. At their respective distances, these two gratings produce nearly identical retinal images of the same spatial frequency when specified in cycles per degree.

and each black stripe gives a relatively low luminance. The name square wave grating comes about because the transitions between black and white are abrupt, or “square”.

Physically, these gratings alternate between black and white stripes at regular intervals across space. Such cyclical patterns can be specified in terms of the number of cycles per unit distance. By this convention, one black and one white stripe of the grating constitute a cycle. The number of cycles per unit distance is called the spatial frequency of the grating (we will refine this definition later). Thus, the gratings in Figures 1.2 and 4.1 can be specified in terms of cycles per centimeter on the page.

4.1.2 Quasi-physical specification: Spatial frequency in cycles per degree

But second, as we saw in the case of luminance, vision scientists often develop quasi-physical units; that is, special units that specify the properties of the physical stimulus in terms of its probable effectiveness for human vision. Figure 4.2 shows another schematic view of a human eyeball. As stated previously, the eye forms an optical image of the physical objects in the visual field. For an object of a fixed size at a fixed distance, we can estimate the size of the image to a first approximation by drawing lines from the edges of the object, crossing (as it turns out) just behind the lens, and diverging again to hit the retina. For a fixed distance, the larger the physical object, the higher the spatial frequency.

1Specifying the grating in cycles per unit distance yields units that are counterintuitive for some people, since coarser stripes are designated by smaller numbers. Just remember – the finer the stripes, the more of them will fit in a unit distance – so the higher the spatial frequency.
the larger the retinal image. Similarly, the higher the spatial frequency of a physical grating, the higher the spatial frequency in its retinal image.

Things become more complicated when we vary the distance of the object. For an object of a fixed size, if we double the distance we will cut the image size in half; or, to keep the image the same size, we will have to double the size of the object. Similarly, for a square wave grating with a fixed spatial frequency, if we double the distance we will cut the width of each stripe in half, and so double the number of stripes per unit distance. To keep the same spatial frequency in the retinal image, as we double the distance we will have to double the widths of the stripes in the grating (decrease its spatial frequency).

How do we derive quasi-physical units for the sizes or spatial frequencies of objects in retinal image terms? We can think of the eye as occupying the center of a 360° (degree) circle. So, we can specify a stimulus in units of its angular size at the eye; that is, in terms of the visual angle it occupies (subtends). For example, if three cycles of a grating fit into a single degree of visual angle, it is a three cycles/degree (cy/deg) grating. (Other common abbreviations for cycles per degree are c/deg and c/°.)

There are two rules of thumb that will give you a better intuitive feel for specifying stimuli in terms of visual angle. The first is wonderfully literal: your thumbnail at arm’s length subtends about 1° of visual angle. The second is that the sun and the moon, at their respective distances, each subtend about 1/2°. You can check that these two rules of thumb are consistent by measuring the angular size of the moon (do not try this with the sun!) with your thumbnail held at arm’s length. You will find that in terms of visual angle, the moon is about half as large as your thumbnail at arm’s length.

Quasi-physical units are useful in specifying spatial resolution, for both empirical and theoretical reasons. Empirically you already have evidence, from viewing Figure 1.2 at different distances, that the physical grating you could just barely resolve varied with distance. When the grating is specified in physical units, every doubling of distance requires approximately a halving of spatial frequency for resolution. But specified in quasi-physical units, spatial resolution turns out to be virtually constant across changes in the distance of the grating, allowing us to separate the parameters of spatial resolution and distance.

More theoretically, it makes sense to guess that the spatial resolution capacities of the retina will be related to size or spatial frequency in the retinal image rather than in the world. A retinal image of a fixed spatial frequency will always make the same pattern on a fixed patch of retina. This pattern will be processed by the same patch of photoreceptors, interneurons, and ganglion cells both times, and it makes sense to assume that the same retinal image will be processed the same way each time. Thus, from this point on, gratings will always be specified in terms of cy/deg.

4.1.3 How good is grating acuity?

Armed with units of measurement, we can now ask, how good is grating acuity? The answer is that under the best conditions, in the best young eyes, grating acuity is just about 60 cy/cm. Alternatively, since there are 60 minutes of arc in one degree, the best visual acuity can also be stated as about 1 cycle per minute of arc. That is, the finest grating you can resolve (if you have excellent eyes) contains about 60 black and 60 white stripes across your thumbnail, at arm’s length. In Figure 1.2, this is the approximate spatial frequency of grating E at 4 meters, grating F at 2 meters, or grating G at 1 meter. Use Figure 1.2 to recheck your visual acuity with these numbers.
in mind. We will come back to these numbers several times in the next few chapters. Grating acuity of 60 cy/deg joins the scotopic and photopic spectral sensitivity curves as system properties in search of explanations.

4.2 Light

4.2.1 The electromagnetic spectrum and the visible spectrum

Electromagnetic energy (also called radiant energy) is one of the basic forms of energy in the universe. Electromagnetic energy varies in its wavelength. As shown in Figure 4.3, the electromagnetic spectrum encompasses many orders of magnitude of variation in wavelength.

But what is light? The term light is used to refer to the part of the electromagnetic spectrum to which human eyes are sensitive. As you already learned in Chapter 2 and 3, the visible spectrum covers a range of wavelengths of just less than a factor of two, from about 400 to about 700 nm. These limits are not absolute, but represent practical extremes based on the rapid fall-off of the eye’s sensitivity at the ends of this range (as shown, for example, in Figure 3.5B).

Notice that even psychophysical measurements such as those involved in defining the spectral sensitivity curves you saw in Chapter 2 and 3 enter into the fundamental definition of the concept of light. In fact, the distinction between electromagnetic energy and light provides the quintessential example of quasi-physical specification. If it’s a wavelength humans can see, it’s light; if not, it isn’t.

The other immediately striking thing about light is that at photopic levels, the different wavelengths of light take on characteristic colors, as we saw in the color naming experiment in Chapter 3. This fact is so universally appreciated that expectations about the perceived colors of lights of different wavelengths are often included in diagrams like that in Figure 4.3A. Vision scientists, however, usually avoid this practice, in order to avoid conflating physical with perceptual entities. Instead, we reserve one set of terms (say, wavelength) to describe the physical characteristics of the stimulus, and another set (say, color names) to describe the perceptual characteristics of the stimulus.

There are two important reasons for making such terminological distinctions. First, if we are initially clear in separating physical and perceptual realms, we are set up to ask how one realm maps to the other, without any initial presumptions. And second, the mapping between physical and perceptual realms is often complex, and (as we will see) many factors other than wavelength influence perceived colors. Figure 4.3B is separated from Figure 4.3A in order to make a clear distinction between perceived colors and the wavelength of light.

In terms of design, why is the visible range restricted to between 400 and 700 nm? Part of the answer is that it makes evolutionary sense to match the visual system to the wavelengths that are available at the earth’s surface and are therefore available to our eyes in our natural environment. Electromagnetic radiation at the long wavelength end of the visible spectrum, toward the infrared, gets increasingly absorbed in the earth’s atmosphere; and electromagnetic radiation toward the short end, in the ultraviolet, gets increasingly scattered by the atmosphere. The remaining radiation is the radiation available to our eyes for seeing.

On this view it is not surprising that different animals have different spectral ranges for vision, depending on their environments. Different species of fishes, for example, tend to match their spectral sensitivity curves to the wavelength composition of the light that penetrates water to the particular depth at which they live.
Figure 4.3: The electromagnetic spectrum and the visible spectrum. A. The electromagnetic spectrum, with wavelength specified in meters. The visible portion of the electromagnetic spectrum, which we call light, occupies only a narrow range of wavelengths, from about 400 to about 700 nanometers (nm; 1 nm = 10^{-9} meters). B. A typical mapping between wavelengths of light and perceived colors, based on psychophysical studies. In photopic vision, different wavelength ranges are typically perceived as different colors (V = violets, B = blues, G = greens, Y = yellows, O = oranges, R = reds; shaded areas show intermediate colors). In scotopic vision, all wavelengths of light look whitish, and no colors are seen. [A. Modified from Levine and Shefner (1991, Fig. 4.1, p. 66). B. DT]
A second part of the answer is that vision in either the ultraviolet or the infrared has practical disadvantages. Ultraviolet light can destroy biological structures in the eye – remember what it can do to the skin! Ultraviolet radiation also encourages the yellowing of the lens and the formation of cataracts; and there is some evidence that it can even damage the short-wavelength-sensitive photoreceptors – the cells that capture short wavelengths of light within the retina.

Infrared wavelengths, at the opposite end of the spectrum, are similar to our bodily radiations due to heat. Snakes can sense infrared radiation, to help them locate prey. But for us, seeing our own body heat within our own eyes would add noise that would tend to mask the images of objects in the real world. Detection of our own body heat would be especially deleterious at absolute threshold, where every bit of energy in the visible range counts.

In support of this latter argument, it can be shown that our absolute threshold varies as body temperature changes over the course of the day. At night, when the human body temperature is low, due to normal circadian fluctuations, absolute threshold is low too. When body temperature rises during the day, so does the absolute threshold\(^3\).

### 4.2.2 Quanta vs. waves

Electromagnetic energy sometimes behaves like waves and sometimes behaves like particles, or discrete packets of energy. For a long time physicists argued about whether electromagnetic energy was “really” waves or “really” particles. We now know that both the wave-like and the particle-like properties of light, or any electromagnetic radiation, can be fully and consistently described mathematically. For the non-mathematician, the conceptual problem is that there is no single entity at the level of things we can observe directly that has both kinds of properties, so it’s hard to imagine light as having them both. The way around this conceptual blockade is to be willing to use different analogies to elucidate different properties of light. We will do this below.

In fact, the wave-like and particle-like properties of light manifest themselves under different conditions. Light behaves like waves when traveling through air or another transparent substance (medium) – for example, from the sun to the earth, or from a physical object to your eye, or within the eyeball. It behaves like particles of energy when interacting with matter – for example, when it is absorbed by a physical object, or by your retinal cells to start the visual process. Both the particle-like and the wave-like properties of light are important to understanding vision, and vision scientists use the two different concepts interchangeably at different times, depending on what the light is doing.

Physicists use the term *quantum* (plural *quanta*) to refer to a particle of light when its particle-like properties are being emphasized. Quanta of light (within the visible range) are sometimes called *photons*. However, in other contexts the terms quantum and photon are used interchangeably.

\(^3\)DT has a friend who was interested in the influence of body temperature on absolute thresholds. His lab was in an old house, so he happened to have a bathtub in the lab. He sat in a very hot bath while he dark adapted for an hour or so. He then wrapped himself up in a sleeping bag and measured his absolute threshold (we’re not sure how he got from the bathtub to the apparatus), and showed that his absolute threshold was elevated while his body temperature was elevated. We suggested that he put the bathtub outside in the winter and see if he could lower his absolute thresholds, but he declined. There’s a limit to what even he would do for science!
4.2.3 Quantal fluctuations

When considered as particles, light has another important property for vision. It turns out that the emission of a quantum is a probabilistic occurrence. Thus, the output of any given source of light is not precisely constant in terms of quanta/sec, but varies over time. Moreover, the quantal fluctuations increase (the magnitude of the noise increases) as the intensity of the light increases. Thus, the physical variability of the light source itself is one of the major factors that limits detection thresholds in human vision. This topic is elegantly discussed in Cornsweet (1970).

In Chapter 2, in the context of signal detection theory, we introduced the idea that a threshold can be considered as a signal/noise discrimination. We can now add to that discussion by noting that quantal fluctuations are a classic example of noise. In this case, the source of the noise is external to the observer, or extrinsic. Intrinsic noise – noise generated within the observer – will also influence visual thresholds.

4.3 Optics

4.3.1 Interactions of light with matter

A beam of light is traveling along as a wave on a straight path through the universe, minding its own business, when suddenly it encounters a bit of matter. What happens? There are four possibilities, as shown in Figure 4.4. First, reflection occurs when light, acting briefly in its particle mode, bounces off the surface of the matter. The wave now changes its direction of travel in a precise way. A useful analogy for reflection is a billiard ball bouncing off the side of the table. The angle at which the light hits the edge of the table (the angle of incidence) determines the angle at which it bounces off (the angle of reflection). In fact, all things being equal (e.g., no spin on the ball) the angle of reflection will be exactly equal to the angle of incidence.

The second possibility is refraction. Refraction occurs when light enters (but is not absorbed by) a new medium – for example, in passing from air to glass. If the medium is more dense (has a higher index of refraction) the wave is slowed down. As a result, it changes its direction of travel. A useful analogy here is a heavy vehicle going from asphalt to gravel at an angle (the asphalt is the air, and the gravel is the glass). As the first wheel (say the right front wheel) hits the gravel, it is slowed down, and the vehicle tends to turn toward a line normal (perpendicular) to the boundary, changing its direction of travel. As it goes from gravel to asphalt again, the right front wheel hits the asphalt first, and speeds up again, and the vehicle turns the opposite way, once more changing its direction of travel. Any skier has experienced a similar phenomenon when going from ice to snow or vice versa. Note that by manipulating the boundaries between various transparent materials, we can manipulate the direction of travel of a beam of light. [What would happen in Figure 4.4B (refraction) if the pane of glass were triangular in cross-section?]

The third possibility is diffraction. Diffraction occurs when a ray of light passes very close to the edge of a piece of matter. The ray is bent in proportion to how close it is to the edge – the closer, the more bent. Think of water in a fast-moving stream as it courses around a rock. The bits of the stream that are close to the rock bend around it, while those sufficiently far away are not affected. Analogously, when light passes through a very small hole, it is bent outward in all directions at the edge of the hole, and it will make a blurry spot (not a sharp one) on a piece of paper placed on the far side of the hole. As the hole gets larger, only the rays very near the edge are bent, so the light will make a concentrated spot with only a slightly blurry edge. Another
Figure 4.4: Four ways that light can interact with matter. A. reflection; B. refraction; C. diffraction, and D. absorption.
reasonable analogy is an adjustable hose nozzle. With a small opening you’ll get a spray, but with
a larger one you’ll get a stream.

The final possibility is absorption. Acting as particles, individual quanta of light are absorbed
by the individual molecules that make up the absorbing substance. They then cease to exist as
electromagnetic energy, and become part of the energy state of the molecules that absorb them.

4.3.2 Lenses and image formation

The formation of an optical image by a lens depends upon the property of refraction. As shown in
Figure 4.5A, light rays leaving a point on an object (or a point source of light) diverge from that
point in straight lines in all directions. Suppose that a cone-shaped group of those rays encounters
a glass lens. As the light passes from the air to the lens, it bends; and the greater the angle at
which it strikes the air-glass interface, the more it will bend.

If we design the lens cleverly, with a surface that varies in curvature, we can bend each ray by
a different amount; say, so that all of the rays are parallel to each other within the lens. If the
second surface of the lens is equally cleverly shaped, we can bend each ray again, say just enough
so that all of the original rays will converge to a single point on the far side of the lens. Rays from
neighboring points on the object will converge at neighboring points in the image, and voila! – an
optical image of the object. As shown in Figure 4.5B, the farther the source is from the lens, the
closer to the lens the image will be.

The power of a lens is defined by its focal length. Rays from one point on a very distant object
(say, a point on the surface of the sun) arrive at the lens virtually parallel to each other. This case
is illustrated in Figure 4.5C. When these parallel rays pass through the lens, they will converge at
a point on the far side of the lens. The distance from the lens at which the parallel rays converge
is called the focal length, \( f \), of the lens. The shorter the focal length, the greater the power of the
lens. We express power in diopters, which are units of one over the focal length \( 1/f \), where \( f \)
is in meters. So, if \( f = 1 \) meter, the power of the lens is 1 diopter. If \( f = 1/2 \) meter, the power is 2
diopters, and so on.

The lenses shown in Figure 4.5A-C are all convex, or positive, lenses – they converge the
incoming rays of light and form an image. Concave, or negative, lenses, on the other hand, diverge
the light and do not form images. The more the divergence, the higher the power of the lens. A
negative lens is shown in Figure 4.5D. Both positive and negative lenses are used in fitting glasses
to correct focusing errors of the eye, as will be discussed below.

4.3.3 Interference

The phenomenon of interference is illustrated in Figure 4.6. Interference patterns are a manifesta-
tion of the property of diffraction. If beams of light from the same source pass through two small
neighboring slits in, say, a metal plate, each of the slits will diffract the light. The two diffracted
beams will spread out, and can overlap beyond the slits. If the two overlapping beams then fall
on a screen, they will form a set of fuzzy light and dark stripes called interference fringes. The
analogy here is to the overlapping ripple patterns produced when you drop two stones into a pool.

\[\text{The term optical infinity is used to refer to a distance beyond which further variations in distance have only negligible effects. For most purposes, objects more than 30 feet or so away are considered to be at optical infinity, and the rays from a point on an object at 30 feet or more are considered functionally parallel.}\]
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The farther the source is from the lens, the closer to the lens the image will be. When the source is at optical infinity, the rays from the source are parallel. The image is formed at a distance $f$ behind the lens. The distance $f$ is the focal length of the lens.

Figure 4.5: Lenses and image formation. A. A convex, or positive lens, forming an image of a point source. B. The farther the source is from the lens, the closer to the lens the image will be. C. When the source is at optical infinity, the rays from the source are parallel. The image is formed at a distance $f$ behind the lens. The distance $f$ is the focal length of the lens. D. A concave, or negative, lens diverges the light. [Modified from Cornsweet (1970, Fig. 3.9, p. 37).]
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Figure 4.6: Interference. Light from a single source is diffracted by a slit in plate H, and diffracted again by a pair of slits in plate P. The interference patterns made by the two slits in P overlap, and produce an interference pattern on the screen J. [Modified from Wandell (1995, Fig. 3.8, p. 55).]

of water – each set of waves produces high and low points, and where they overlap, the highs add to produce super highs and the lows add to produce super lows.

Here’s a puzzle that illustrates the paradoxical nature of light. Suppose that you set up a double slit experiment. You shine a light from a laser onto the two slits, but you make the light so dim that on average, only one quantum per day will reach the two slits. Since a quantum is indivisible, one might think it would have to go through only one of the slits; and since interference is a property of the two beams together, one might think that no interference fringes could be made. Now you put a sensitive photographic film where the screen was, and go away for a year. The question is, when you come back and develop the film, will you see interference fringes? The answer is yes.

4.4 Physiological optics: The eye as an optical system

How do the properties of light and optics manifest themselves in the human eye? All of the interactions that light can have with matter are of importance to vision. Reflection is important in that some of the light reaching the front surface of the eye is reflected, never enters the eye, and therefore cannot contribute to vision. Refraction is important because the eye contains an optical system, and forms the retinal image. Diffraction is important because the pupil of the eye is a small hole, and all of the light that reaches the retina must pass through it. When the pupil is very small, many of the rays will be diffracted and will not reach the proper point on the retina. And, of course, absorption is critical, because the absorption of light by the photoreceptors within the
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The optics of the human eye are shown in Figure 4.7. The light entering the eye passes through the transparent window, the cornea, which forms the external surface of the eye. It then passes through a thin liquid called the aqueous humor; then through the pupil, a small hole in the iris (the colored part of the eye); then through the lens; and finally through a viscous material called the vitreous humor and on to the retinal surface, where it passes through the inner retinal layers before being absorbed by the photoreceptors (see Figure 1.4).

The cornea and lens together serve to form an image of the physical world on the retina. Every time light encounters a change of refractive index, it changes its direction of travel. Interestingly, since the largest change in refractive index occurs between the air and the cornea, most of the focusing or bending of light rays is actually done by the cornea, and not by the lens. Then the lens fine tunes the focus onto the retina. The total refractive power of the eye is about 60 to 70 diopters; of the total, about 40 diopters is due to the cornea, and 20 to 30 diopters to the lens (see below).

You can demonstrate to yourself the importance of the cornea for focusing by opening your eyes underwater. The cornea’s index of refraction is very close to that of water. Thus, if the light travels from water to the cornea, it will not be bent much at all, and the cornea is essentially ineffective. You can’t change focus enough with the lens to compensate, so your vision is vastly degraded. However, if you put on a pair of goggles or a dive mask, vision is restored because you
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Figure 4.8: Optical density of the eye’s optics as a function of wavelength and age. Notice that the density of the optics varies a great deal with wavelength. Most of the absorption of light is done by the lens. At 400 nm for a 21-year-old, the optical density is about 0.4. This means about 1/4th of the light is absorbed by the optics. This amount increases with age. The lens “yellows” with age, absorbing more and more of the short wavelength light. [Modified from Ruddock (1972, Fig. 3, p. 458). Original data from Said and Weale (1959).]

have provided the air interface required by the cornea.

4.4.2 Spectral transmissivity of the eye’s optics

The optical elements of the eye do not transmit all wavelengths of light equally well. The most important contributor to this effect is the lens, which absorbs light more strongly at short than at middle or long wavelengths. The differential absorption of different wavelengths by the lens is shown in Figure 4.8\(^5\). A second entity, the macular pigment, also absorbs at short wavelengths. So the optics of the eye act as a yellowish filter, letting through middle and long wavelengths but reducing the radiance of the light at short wavelengths. [Why might the optics be designed this way?] The density of the lens pigmentation increases with age, causing older people to lose more and more of the incoming short wavelength light.

\(^5\)The absorption of light by a filter (or other medium, such as the lens) is specified quantitatively in terms of optical density, \(D\). Optical density is defined as log base 10 of the ratio of incident light \(I\) to transmitted light \(T\). That is, \(D = \log_{10}(I/T)\). A filter with a density of 1 transmits 1/10 of the incident light; with a density of 2, 1/100\(^{th}\) of the light; and so on. Optical density is plotted on the ordinate of Figure 4.8.
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4.4.3 Accommodation

A glass lens such as that shown in Figure 4.5A-C has a fixed focal length. However, the lens of the eye can change its focal length in order to focus objects at different distances on the retina at different times. Changes in the focal length of the lens are called accommodation. To demonstrate accommodation, hold a finger as close to your eye as you can and still keep it in focus. Now concentrate on the finger and notice the blur of distant objects. Now reverse the process – look at the distant object and notice the blur of the finger.

Accommodation is shown schematically in Figure 4.9. These changes in focal distance are brought about by changes in the shape of the lens. For far away objects a thin, flat lens is sufficient to bring the image to focus on the retina; whereas for near objects a thicker, more curved lens will be required. When you focus at a near distance, special muscles within your eye (the ciliary muscles) contract to make your lens thick – increase its power. When you relax your accommodation to focus far away, these muscles relax and allow your lens to become thin again – decrease its power.

A young person with normal optics has a range of accommodation – the range of distances that can be brought into focus by accommodation – that covers 10 or more diopters, and goes from about optical infinity to within a few cm of the nose. [How close can you bring your finger to your nose and still keep it in focus?]

4.4.4 Common optical problems and their corrections

The human eye is susceptible to a variety of focusing problems, known collectively as refractive errors. An eye with a normal range of focus and no other optical problems is called emmetropic. Common refractive errors include myopia, or nearsightedness, hyperopia, or farsightedness, and presbyopia, or “old eyes”. Myopia, hyperopia, and presbyopia involve changes in the range of accommodation away from the normal range typical of emmetropia. These four types of eyes are illustrated in Figure 4.10, in terms of a set of distances important to a child (not to scale).

*Myopia* occurs when the whole accommodative range is moved in toward the eyeball. In consequence, close objects can still be focused readily, but distant objects cannot be brought into focus; the myopic child can’t see the blackboard in class. Myopia often appears in adolescence and may be the result of long periods of focusing at near, or of continued growth of the eyeball while the eye socket (orbit) slows in its growth. This mismatch results in an eye that is too long for the available focusing power – the lens can’t be made thin enough to focus objects at far distances. Myopia can be corrected by putting negative lenses – glasses or contact lenses – in front of the eyes. The negative lens diverges the incoming light, moving the accommodative range away from the eyes and back toward the normal range. (For example, a glasses prescription of -5.25 indicates that the myope needs a -5.25 diopter lens to move her accommodative range back to normal.)

*Hyperopia*, in contrast, results when the accommodative range is moved too far away from the eyeball, usually because the accommodative power of the lens is too limited. A person with hyperopia can focus far away objects fine, but cannot make his lens thick enough to focus close objects. A hyperopic child often has difficulty learning to read because she can’t focus the type on the book page on her retina. Like myopia, hyperopia can be corrected with a properly chosen external lens. In this case a positive lens is needed to bring the accommodative range in closer to the eye. (For example, a prescription of +5 indicates the need for a 5 diopter positive lens to bring the hyperope’s accommodative range back to normal.)

*Presbyopia* (“old eyes”) refers to a condition that most people encounter after about age 40.
Figure 4.9: Accommodation in the normal (emmetropic) eye. A. A parallel beam of light is coming from a distant source. The lens is relaxed and thin, and the beam is focused on the retina. B. If we bring the source closer but keep the lens thin, the image will fall “behind” the retina, and will be out of focus on the retina. C. The solution: Increase the curvature of the lens surfaces. This increases the power of the lens, bringing the source back into focus on the retina.
Figure 4.10: A normal eye and three common optical problems. The top row shows a child’s view of the world—a set of important distances, from the end of his nose to the outfield in a baseball diamond (not to scale). The lines A-D show the accommodative ranges of eyes of various types. A. An emmetrope (person with normal eyes) can focus at all of these distances. B. A myope (nearsighted person) has a range of accommodation restricted to near distances. C. A hyperope (farsighted person) has a range of accommodation restricted to far distances. D. A presbyope (a person with “old eyes”) has only a very narrow range of accommodation. The diagram shows three different presbyopes with different residual ranges of accommodation.
Throughout the lifespan, from childhood on, the lens continues to grow, adding layers to its structure like an onion. As the lens grows it becomes less flexible, and harder for the muscle that controls accommodation to change its shape. So starting at about age 17, the range of accommodation narrows, and the near point of accommodation gradually moves out away from the nose. [Can you still focus as close as you used to?]

As humans age we compensate for a receding near point of accommodation by holding our books farther from our noses, playing the trombone to put the book in focus. The trend finally catches up with us at about age 40, when the near point of accommodation becomes farther away than the length of our arms, and the print is too small to resolve at that distance anyway! When this happens we get bifocals or “granny glasses” to provide artificial accommodation for reading and viewing close objects. The glasses prescription for bifocals has two parts – one for optical infinity and one for reading distance. But bifocals still give us only two distances at which objects are in focus, and are a poor and frustrating substitute for our natural accommodation. Eventually the lens becomes virtually rigid, and we are left with our accommodation frozen permanently at a single distance. The person who figures out a solution to this problem will be a millionaire.

Astigmatism is another common refractive problem. People with astigmatism have an optical system that has one power for focusing lines or gratings at one orientation (say vertical) and a different power at the opposite orientation (say horizontal). In consequence lines at one orientation will be in focus with one level of accommodation, while lines at the opposite orientation will be in focus with a different level of accommodation. The astigmat can’t ever focus both orientations in the visual scene at once, and always sees images with one kind of blur or the other. Astigmatism can be corrected by fitting the patient with an astigmatic (cylindrical) lens that compensates for the differential focusing power of the eye in the two orientations. (A prescription that looks like -5.25 +1.00 x 180 describes the correction needed by a myope who is also astigmatic. The first number gives the spherical correction; the second, the additional cylindrical correction to counter the astigmatism; and the third, the angle at which the cylinder axis is to be placed.)

Still other optical problems have to do with losses of transparency of the eye’s optics. Cataracts are opacities in the lens which can greatly interfere with vision. They become increasingly common in old age. In addition, the lens develops more and more of the yellow pigment that gives it its selective absorption of light at short wavelengths.

Relatively routine surgical procedures have been developed to remove the cataractous lens and replace it with a plastic lens. Unfortunately, no plastic zoom lens is available. However, a person who was so myopic that he wore “coke bottles” all his life can have a myopic correction built into the implanted lens, and be left delighted with needing only light weight bifocals. Also, a person who has just had a cataractous lens removed will often marvel at how the colors of things are restored – the blues look like they used to before the aging lens began to steal the short wavelengths of light away.

4.5 Optical information loss

Imperfections in the eye’s optics limit the flow of information from the physical world to the visual neurons. Imperfections arise not only from refractive errors and opacities (discussed above), but also from additional factors we have yet to consider. How much degradation is there, what are the reasons for it, and how can we quantify it?
4.5.1 Why can’t retinal images be perfect?

Even when the eye is in perfect focus, retinal images are not perfect, because the optics of the eye degrade the retinal image in several more complex ways. The cornea and lens refract the incoming light to form the retinal image. Insofar as their surfaces are not perfectly shaped, they will make blur circles instead of point images, leading to degradation of the overall image. The pupil, when it is very small, can degrade the image by diffraction. The vitreous too plays a role in image quality because it is not completely clear; the vitreous can contain imperfections including floaters: pieces of cellular debris that make a wash of scattered light and degrade the contrast of the image. Finally, internal reflections from various structures within the eye scatter the incoming light and further degrade the image. In the following sections we treat some of these problems in greater detail.

The refractive system of the cornea and lens produces four kinds of complex distortions: chromatic, monochromatic, spherical and higher order aberrations. Chromatic aberration occurs because different wavelengths of light are refracted differently as they pass from one medium into another. When light passes through a traditional lens system the shorter wavelengths are bent more than the longer ones. The result is that if the long wavelengths are focused on the retina, the short wavelengths will be focused in front of the retina, and out of focus at the retina. Conversely, if the short wavelengths are focused on the retina, the long wavelengths will be aimed at a focus behind the retina, and out of focus at the retina. In short, it is impossible for the optical system of the eye to focus all wavelengths of light at the same time. In the laboratory, we often eliminate chromatic aberrations by using light of a single wavelength (monochromatic light).

Monochromatic aberrations occur because the surfaces of lenses are not perfect. If the curvature of a lens (or the surfaces of a lens system) do not bend each ray of light by exactly the right amount, the image will not be perfect – it will be spread out due to the inaccuracies or irregularities in the lens surfaces. In spherical aberration, the center of the lens has one focal length and the periphery of the lens has another. With a large pupil both are used together, making a fuzzy image. More idiosyncratic irregularities in the lens and cornea can also produce higher order aberrations that contribute to the imperfection of the image.

What pupil size makes the sharpest image?

The diameter of the human pupil ranges from about 1.5 mm to about 8 mm, as the person moves from bright to dim light. In general, optical quality degrades slightly from the center to the periphery of the lens. In addition, the power of the lens changes slightly from center to periphery, so optical degradation is worst overall when the pupil is largest and the whole lens contributes to the image. One might conjecture, then, that the way to optimize the image is to make the pupil small. But when the pupil is small, diffraction can make a significant contribution to imperfections in the image. How should one balance these two opposing demands? Given high light levels, is there an optimal pupil size?

4.6 Line-spread functions

How can the quality of the human retinal image be measured? Conceptually, one would want to form an image of a simple target – say, a point or a line – on the retina, with optimal focus. Then one would measure the diameter of the blur circle produced by the point, or the width of the image of the line, on the retina. These measurements would yield quantitative values for how far the image of the point or line was spread across the retina, due to optical errors of all kinds. That is,
we could measure the point spread function or line spread function of the eye.

The classical measurements of the line spread function were made by Campbell and Gubisch in 1966. They used a special optical system similar to the system used in an ophthalmoscope—an instrument that allows another person to peer into your eye and examine your retina. This approach is known as the double pass technique, for reasons that will be clear below. The essential elements of their apparatus are shown in Figure 4.11. (Notice that the subject makes no judgments in this experiment. The measurements are entirely physical, not psychophysical. The subject need only to hold still and fixate a fixation point.)

First, Campbell and Gubisch used drugs to paralyze the subject’s pupillary and accommodative systems temporarily—the pupil was dilated to its largest possible diameter, and the lens flattened to be focused at optical infinity. They set up a light source to project a line of light onto a subject’s retina, to form the retinal image. The light was monochromatic in order to avoid the problem of chromatic aberration. Then they captured the light reflected back from the retina out of the eye, to make a second image (an image of the retinal image) in physical space outside the eye. Finally they optimized focus by placing glass lenses in front of the subject’s eye until they produced the sharpest possible line spread function in the second image.

Campbell and Gubisch next scanned the second image with a photocell to quantify its luminance across space. They repeated the experiment with a series of artificial pupils—small holes in thin metal plates placed just in front of the eye—of different diameters, to simulate variations in pupil size. Of course the second image has passed through the optics twice, not once as it would for normal vision. Campbell and Gubisch overcame this problem by factoring out the double pass mathematically. The calculations produced an estimate of the line spread function in the retinal image.

Figure 4.12 shows both theoretical predictions and empirical measurements from Campbell and Gubisch’s experiment. The dotted lines show the theoretical predictions based on diffraction alone. If diffraction were the only source of light dispersion in the retinal image, the line spread functions should follow these predictions. As expected, the image produced by diffraction varies with pupil diameter—the larger the pupil, the narrower the diffraction limited image. For large pupils the predictions based on diffraction have a width at half height of only about 0.2 minutes of arc—about five times narrower than the diffraction limit for small pupils.

The solid lines in Figure 4.12 show the measured line spread functions. For small pupils (1.5 to 2 mm), the data come quite close to the limit set by diffraction. The width of the distribution at half height is about 1.3 minutes of arc. Thus, for small pupils, the optical quality of the retinal image is said to be diffraction limited, and not further degraded by the optics of the eye. Since diffraction is an absolute limit imposed by the laws of physics, the optics of our eyes do remarkably well in matching the physiological limit to the physical limit. The measured line spread function is actually narrowest at a pupil diameter of 2 to 2.4 mm. The distribution at its best is very tight—the width at half height is only about 1 minute of arc, and the central part of the distribution still approaches the diffraction limit. So for small and intermediate pupil sizes, what we have is just about as good as it gets.

But for large pupils, the observed line spread functions are much broader than the predictions based on diffraction, with a width at half height of about 2 minutes of arc. That is, for large pupils the quality of the retinal image is about ten times worse than the diffraction limit. When the pupil is large, other aspects of optical quality—spherical and higher order aberrations, and scattered light—take over to limit the quality of the retinal image.
4.6. LINE-SPREAD FUNCTIONS

Figure 4.11: Double-pass method for measuring line spread functions. Light from the source (the light bulb at left) is imaged by a lens onto a slit. The slit makes the line that will be imaged on the retina. Light leaves the slit and passes through a beam splitter. The light reflected by the beam splitter is lost to the experiment at the light absorber at the top. The light transmitted by the beam splitter passes through another lens, enters the eye and is imaged on the retina (the first or retinal image). Some of the light from the retinal image is reflected back out of the eye. The returning light is again divided by the beam splitter, and the light transmitted is lost to the experiment. The light reflected by the beam splitter passes through another lens, is reflected by a mirror, and forms a second image in space. The second image is scanned by a photodetector, and the amount of light in the second image is plotted as a function of spatial position. The experimenter back calculates from the second image to estimate the line spread function in the first (retinal) image. B. The distribution of light in the retinal image can be characterized by its width at half height. [After Wandell (1995, Fig. 2.3, p. 16).]
Figure 4.12: Campbell and Gubisch’s results. The numbers beside each distribution show the diameter of the artificial pupil. The dotted lines show the diffraction limits for each pupil size. The larger the pupil, the narrower the distribution predicted from diffraction. The solid lines show the measured line spread functions. The measured distributions approach their respective diffraction limits for small and midsize pupils, but not for large pupils. [After Wandell (1995, Fig. 2.11, p. 29).]
In short, given the properties of diffraction, the line spread function is potentially narrowest with a large pupil. For a large pupil, a more perfect optical system – one without such marked spherical and higher order aberrations – could in principle yield a retinal image with a much narrower line spread function than we in fact have. But our visual systems do not take advantage of this opportunity. Viewed from this perspective, the optics of the human eye are remarkably poor. And it’s interesting to wonder why better optics haven’t evolved for the human eye. We will return to this question in Chapter 5.

4.7 Adaptive optics: Improving on nature

Meantime, science is improving on nature. In the late 1990s an exciting new chapter was added to the story of optical quality: the use of adaptive optics. An adaptive optical system is one in which measurements of the optical quality of an individual eye can be made, and then fed back to correct the path of each ray in the incoming bundle of light rays, in such a way as to improve the quality of the retinal image for that particular eye. The system consists of two parts: a wave front sensor that allows measurement of the optical aberrations of a given eye, and a deformable mirror that allows correction of these aberrations.

In 1997, Liang and Williams (Liang and Williams, 1997; Liang, Williams, and Miller, 1997) built the first successful adaptive optical system for use with the human eye. Simplified optical diagrams of the system are shown in Figure 4.13 and 4.14. The first part of the adaptive optical system, the wave front sensor, is shown in Figure 4.13A. First, in a double-pass optical design similar to that used by Campbell and Gubisch, light from a laser (with its radiance carefully controlled so as not to do damage) is shined into the eye, and forms a tiny spot of light on the retina. Light from this spot is reflected back, and a cone of light – a wave front – emerges from the pupil. The trick is that different subparts of the wave front have passed through different parts of the eye’s optics – different locations within the pupil, corresponding to different parts of the cornea and lens. By analyzing this beam of light region by region, we can evaluate the eye’s optics region by region as well.

The light emerging from the eye eventually falls on a tightly packed array of 217 tiny lenses (lenslets). Each lenslet makes an individual image of the retinal spot, so the output of the device is an array of 217 tiny dots of light. But the different dots have been processed by different regions of the optics. As it happens, any irregularity in one region of the optics will shift the corresponding dot out of its place in the matrix of dots. The matrix of dots falls on a charge coupled device (CCD), which creates a record of the location of each dot in the matrix and passes it on to a computer for the next step. By analyzing the spatial irregularities in the whole pattern of dots, a description of the overall irregularities in the optics can be derived.

Two dot matrices produced by the wave front sensor with a 3 mm artificial pupil are shown in Figure 4.13B. The first matrix was made by analyzing an “ideal” eye rather than a real one, and the regularity of the matrix is apparent. The second matrix was made by analyzing a real eye (subject DRW). When the pupil is small, as it is in this case, the matrix of dots remains regular – as we said earlier, the retinal image is usually diffraction limited for this pupil size, and spherical and other aberrations have little effect. In contrast, two dot matrices produced with 7.3 mm pupils are shown in Figure 4.13C. In this case, there are obvious irregularities in the matrices of dots, showing again that spherical and higher order aberrations degrade the retinal image when the pupil is large.
Figure 4.13: Adaptive optics: the wave front sensor. A. A tiny dot of light from the laser is imaged on the retina, and reflected back to the lenslet array. The lenslet array makes a matrix of tiny images of the retinal image. Irregularities in this matrix indicate aberrations in the optics of the eye. B. For a 3 mm pupil, the matrix of images is regular, both for an ideal eye (left) and for a real eye (right). C. For a 7.3 mm pupil, the matrix at the left shows a closer spacing of the dots at the edge of the array, indicating the presence of spherical aberration. The matrix at the right shows a set of irregular aberrations in the region where the eyelid normally rests against the cornea. [From Liang and Williams (1997, Fig. 1, p. 2874, Fig. 2, p. 2875 and Fig. 3, p. 2876).]
Figure 4.14: Adaptive optics: the complete optical system. In this figure the wave front sensor, including both the laser source and the array of lenslets, has been folded up into the box at the lower right. The parts of the wave front sensor closest to the eye have been spread apart by adding lenses, so that the light from the laser can be bounced off the deformable mirror on the way to and from the eye. The deformable mirror is mounted on a set of tiny pistons. The surface of the mirror can be deformed by advancing some of the pistons and retracting others, in order to compensate for the particular aberrations of the eye being studied. [Adapted from Liang et al. (1997, Fig. 2, p. 2885).]
The complete adaptive optics system, including the deformable mirror, is shown in Figure 4.14. How does it work? A subject and his eye are aligned in the apparatus. Starting with the deformable mirror set to be flat, the apparatus is activated, and a matrix of dots is made by the lenslets. The spacing of the matrix of dots is analyzed by a computer. The computer makes an educated guess as to how the mirror should be deformed to make the matrix of dots more nearly regular. This guess is implemented by deforming the mirror. New measurements are then taken, and a new deformation is tried. After 10 to 20 iterations, a highly regular matrix is usually produced. The deformations required to produce the regular matrix provide a description of the aberrations introduced by the particular eye being studied.

To what accuracy can the eye be corrected with adaptive optics? As of the late 1990s, with the pupil fully dilated, line spread functions could be made about a factor of two narrower than the best line spread function Campbell and Goldberg saw with a 3 mm pupil. The ultimate goal is to use a large pupil, for which the line spread function is potentially narrowest, and to reduce the line spread function to the diffraction limit calculated for the large pupil. If that goal were achieved, gratings of frequencies much higher than 60 cy/deg could be imaged on our retinas! [But could we see them? Think about it. We return to this question in Chapter 5]

Adaptive optics have generated much excitement, because they can be applied in at least three important ways. First, some people have major optical aberrations that are not readily corrected with currently available glasses and contact lenses. Adaptive optics may eventually allow optometrists and ophthalmologists to analyze the optical aberrations in these eyes, and fit patients with specialized contact lenses designed to correct them. Second, by creating higher quality retinal images in normal eyes, adaptive optics can be useful for laboratory studies of the post-optical limits of acuity and spatial sensitivity.

And third, adaptive optics can also be used to look into the eye. Currently, when an ophthalmologist or optometrist dilates your pupil and looks into your eye, she looks in through your imperfect optics. If adaptive optics could be incorporated into ophthalmic instruments, she could see your retina more clearly. Moreover, clearer picture of the retina could be taken, for both basic science and clinical purposes. We will return to these applications in later chapters.

4.8 Summary: Optical properties of the eye

We began this chapter by returning to square wave gratings, and introducing the specification of spatial frequency in both physical and quasi-physical units. We continued with a brief review of the nature of light and the properties of physical optical systems.

We then examined the properties of the human eye as a physiological optical system. The eye has two major optical components: the cornea and the lens. The cornea has about 40 diopters of optical power, and the lens a variable power between about 20 and 30 diopters. The variable power of the lens – accommodation – allows us to focus objects at different distances on the retina. Many common clinical vision problems, including myopia, hyperopia, presbyopia, and astigmatism, are due to problems in focusing, and can be corrected or ameliorated by placing lenses (glasses or contact lenses) in front of the eye.

Beyond questions of focus, the optical quality of the eye is limited by two major factors: the diameter of the pupil (which diffracts the light substantially when the pupil is small), and optical aberrations (which result in poor image quality when the pupil is large).
We then introduced the double-pass method used by Campbell and Gubisch to make *in vivo* measurements of the optical quality of the human eye. They showed that the optimal pupil diameter is in the range of 2 to 2.5 mm. At that pupil diameter the line spread function has a width at half height of about 1 minute of arc. But spreading the lines of a 60 cy/deg grating this much should lead to a major loss of contrast in the retinal image. Thus, optical quality could indeed be the major factor that limits grating acuity to about 60 cy/deg. We return to this question in the next chapter.

Finally, we introduced a more recent development in studies of the optics of the eye: adaptive optics. With adaptive optics we can measure the specific pattern of aberrations present in an individual eye *in vivo*, and use external instrumentation to shape the incoming light, in order to improve the quality of the individual’s retinal image. Thus, we can potentially form images on the retina that are finer than those allowed by the eye’s optics; and the question is, what will we see?

In the next chapter, we look at an alternative method of specifying the quality of an optical system: the modulation transfer function, or MTF. We also consider the effects of discrete sampling of the retinal image by the photoreceptors, and reconsider the question of whether the optics of the human eye limit our acuity.