



FOUNDATIONS OF  
**SENSATION AND**  
PERCEPTION

Second edition

**SAMPLE**

**CHAPTER**

**George Mather**

# Foundations of Sensation and Perception

## Second Edition

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# Preface to the first edition

My primary aim in writing this book has been to provide a coherent, up-to-date introduction to the basic facts and theories concerning human sensory perception. A full appreciation of perception requires some understanding of relevant physical stimuli and a basic grasp of sensory physiology. Therefore, the physical and physiological aspects of each sensory modality are considered before its perceptual characteristics. Emphasis is placed on how perceptual experience relates to the physical properties of the world and to physiological constraints in the brain.

The first chapter introduces some of the techniques used to study perception, and some important general principles that apply equally to all the sensory systems. These principles are first applied to the minor senses in the following two chapters: smell and taste (Chapter 2), and touch and balance (Chapter 3). More space is devoted to hearing (Chapters 4 and 5), and yet more to vision (Chapters 7 to 12), reflecting the relative importance of the senses to humans. The final chapter considers individual differences in perception relating to age, sex, culture, and expertise.

The bulk of each chapter is devoted to fundamental material that all students should read. Each chapter also contains a tutorials section covering more advanced or controversial material, or newly developing areas, to offer an opportunity for further study and a bridge to more advanced texts. For example, tutorials in Chapters 4 and 8 introduce Fourier analysis; tutorials in Chapter 9 discuss Bayesian inference as well as the debate about active versus passive processing; a tutorial in Chapter 13 surveys recent research on sensory integration.

The manuscript has been improved significantly as a result of the critical comments offered by a number of people including Chris Darwin, Graham Hole, Ian Howard, Linda Murdoch, Romi Nijhawan, Daniel Osorio, and several anonymous reviewers. I am very grateful to them all for their valuable contributions, but any remaining errors are of course down to me. I would also like to thank Mike Forster, Ruben Hale, Mandy Collison, and everyone else at Psychology Press for all their encouragement during the protracted period of writing.

Finally I would like to dedicate the book to Anne, Laura, and Luke for their patience and support during the preparation of the manuscript and associated material. Laura was particularly helpful in the preparation of the indexes.

# Changes in the second edition

The publication of a full-color second edition gives me the opportunity to update the text and add new features that readers have suggested in their comments on the first edition (many thanks to all those who made suggestions). The most significant changes include:

- Revised and expanded coverage of taste processing and taste perception, touch perception, pitch perception, and receptive field modeling.
- New sections on word perception, the size after-effect, crowding, scene perception, and optic flow.
- A new chapter devoted to multisensory processing and synesthesia, with a new tutorial on attentional effects in perception (I am grateful to Jamie Ward for comments on this chapter).
- A new tutorial on visual dysfunction in artists.

An important goal of the text is to provide references to primary sources wherever possible, so that interested readers can delve deeper into the many fascinating aspects of modern perceptual research. Consequently a great many new references have been added in the second edition to reflect the changes in the text.

I hope you find the additions to the text worthwhile and, as always, comments from readers would be very much appreciated.

*George Mather  
January 2008*

# CHAPTER 6

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# The physics of vision—light and the eye

## INTRODUCTION

Before we can begin to understand visual perception, we must consider the basic properties of the physical stimulus, light. Answers to fundamental questions about vision, such as why we have a light sense and how our sense organs gather information from light, depend on understanding the nature of the physical stimulus.

The physical nature of light has puzzled philosophers and scientists throughout history, and is still not completely understood. The Ancient Greeks believed that vision was the result of a “fire” that is emitted by the eyes to strike objects and so reveal their shape. Plato distinguished three kinds of “fire”—daylight from the sun, fire of the same kind emitted by the eye, and fire streaming off objects to interact with the fire emitted from the eyes (see Gregory, 1981). We now know, of course, that the eye does not emit light (except as a reflection) but only receives it. Issues concerning the nature of light itself have taxed some of the greatest minds in the history of science, including Isaac Newton, Christian Huygens, Max Planck, and Albert Einstein.

## WHAT IS LIGHT?

Light is a form of radiant energy that is capable of stimulating receptors in the eye and evoking a visual sensation. The behavior of light can be described in three apparently incompatible ways: as rays, as particles, and as waves. One of the major successes of modern theoretical physics has been to resolve the apparent inconsistencies between these descriptions.

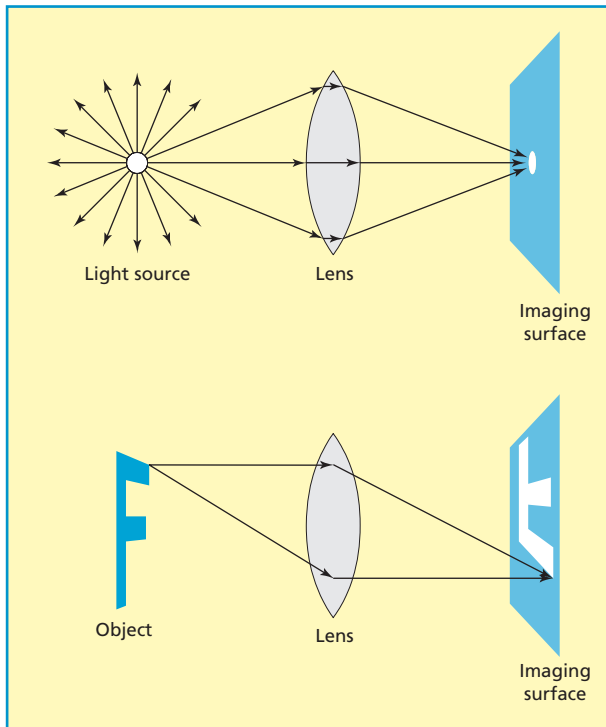
## LIGHT AS RAYS

Everyday experience tells us that light normally travels in straight lines or rays from a light source at such a high speed that it can be considered instantaneous. Light rays are emitted from a point on a source in all directions (see Figure 6.1). Opaque occluding objects in the path of the rays create well-defined shadows. Light rays are deflected (**refracted**), as they pass from one transmitting medium, such as air, into another, such as glass or water. This behavior is crucial to our understanding of how images can be formed by lenses and mirrors.

### KEY TERM

#### Refraction

The change in the direction of a light ray as it passes from one transmitting medium to another, caused by a change in the velocity of propagation.



**FIGURE 6.1**  
Image formation by lenses. Top: Light emanates from a point source in all directions. When some portion of the rays passes through a lens, refraction causes the rays to converge back to a point. An image of the point is created on an appropriately positioned imaging surface. Bottom: An extended object can be considered as a spatially distributed collection of points. The lens produces a spatially distributed image of the object on the imaging surface.

### KEY TERM

#### Interference pattern

The pattern formed when two sets of waves overlap, producing mutual reinforcement at some locations and cancelation at others.

## Lenses

A suitably shaped lens will refract incident rays emanating from a point so that they converge back to a point after they emerge from the lens. An image of the point on the source is created if an imaging surface is placed at the correct distance from the lens. If the source is a spatially distributed object comprising many points, then the lens will form a spatially distributed image of the object on the imaging surface.

The image will be inverted relative to the object, but it will preserve the topology of the object (the geometrical relations between individual points), as shown in Figure 6.1. The field of geometrical optics provides very precise descriptions of the ray behavior of light. The Tutorials section of this chapter provides a more detailed introduction to optics.

## LIGHT AS PARTICLES: ISAAC NEWTON

The question of what light rays contain was addressed by Isaac Newton (1642–1727). He believed that light rays were composed of a stream of particles or “corpuscles” that traveled in straight lines. He argued that reflections occurred when these particles bounced off an opaque surface. Refractions occurred as the particles entered a transparent medium at an oblique angle and were deflected in their path. Newton explained the spectrum of colors observed when sunlight is refracted through a prism by supposing that rays of different colors are “differently refrangible.”

## LIGHT AS WAVES

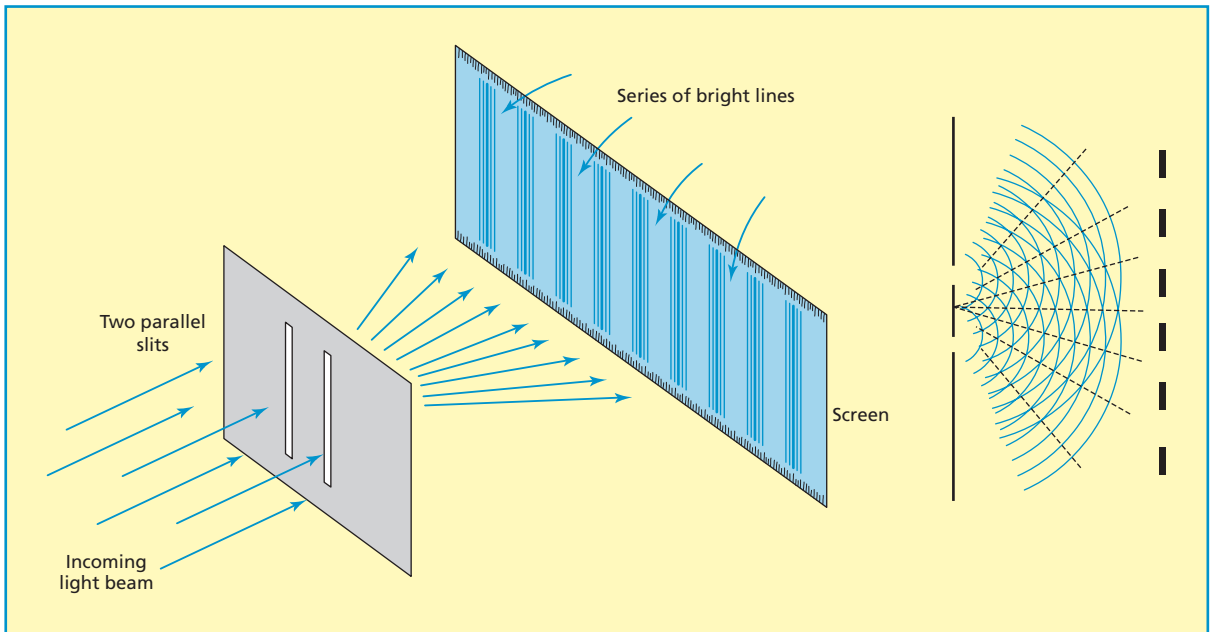
### Christian Huygens

Christian Huygens (1629–1695), who was a contemporary of Newton in the 1600s, proposed that light propagates from a source in waves similar to water waves. This wave theory was seen as a direct competitor to Newton’s particle theory.

### Thomas Young

The authority of Newton was such that Huygens’ wave theory received little attention until a critical experiment was published by Thomas Young in 1801. He passed light through two adjacent slits in an opaque screen, and observed the pattern created on a second screen (see Figure 6.2, left).

Young observed a pattern of alternating dark and light bands. It was clear that light added to light could result in darkness. He had observed the phenomenon now known as **interference**, which can be explained by supposing that light travels in waves. When two



**FIGURE 6.2**

Young's double-slit experiment. Left: When light is passed through two adjacent slits in a screen, the image formed behind the screen consists of alternating light and dark lines. Right: The lines are created by interference between the two wavefronts emanating from the slits. Where the peaks in the two wavefronts coincide (dotted lines on the right), bright bars are created on the screen. Young's experiment provided strong evidence for the wave properties of light. Copyright © 1982 John Wiley & Sons Limited. Reproduced with permission.

wavefronts cross, they can either augment each other or cancel each other out (see Figure 6.2, right), in the same way that water waves can interact to create a bigger wave or to cancel each other out. Notice from Figure 6.2 that as the original wavefront passes through each slit, it spreads laterally to create two new wavefronts. This effect is known as **diffraction**. The concentric circles emanating from each slit in Figure 6.2 (right) represent adjacent peaks in the advancing wavefronts. The radiating lines are drawn along directions in which peaks in the two wavefronts add together (constructive interference). Bright lines appear at locations where these lines strike the screen. In between the lines the waves tend to cancel each other out (destructive interference) because peaks in one wave meet troughs in the other wave.

## James Clerk Maxwell

What kind of waves make up light? This question was answered by James Clerk Maxwell's (1831–1879) famous electromagnetic field equations, according to which light waves can be described as transversely oscillating electrical and magnetic fields that propagate at finite speed. Maxwell described light as “an electromagnetic disturbance in the form of waves.”

The full **electromagnetic spectrum** of wavelengths extends from wavelengths as small as  $10^{-13}$  m ( $\gamma$ -rays) to wavelengths spanning several kilometers (radio waves), as shown in Figure 6.3. Wavelengths that can stimulate the receptors in the eye to produce a visual sensation occupy only a very narrow band of wavelengths in

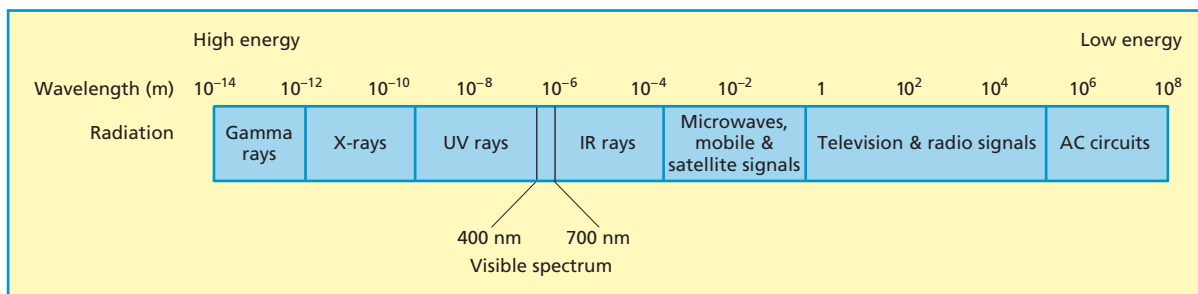
### KEY TERMS

#### Diffraction

The scattering or bending of a wave as it passes around an obstacle or through a narrow opening.

#### Electromagnetic spectrum

The full range of frequencies that characterizes electromagnetic radiation; only a tiny portion of it is visible as light.

**FIGURE 6.3**

The electromagnetic spectrum. The wavelength of electromagnetic radiation spans a huge range. The energy associated with the radiation co-varies with wavelength, so very short wavelength gamma rays have extremely high energy. The portion of the spectrum capable of producing a visual sensation occupies a narrow band of wavelengths, from 400 to 700 nm.

this spectrum (between 400 and 700 nm). As we shall see later, the wavelength of light is closely associated with visual sensations of color.

## THE DUALITY OF LIGHT

By the end of the 19th century, Newton's corpuscular theory had been eclipsed by the electromagnetic wave theory developed by Maxwell. However, a series of major empirical and theoretical developments in the first decade of the 20th century redefined views on the nature of light, and led to the development of quantum mechanics.

Planck's equation is one of the most famous in physics:

$$E = hf$$

Where  $E$  is the energy transferred by a quantum,  $f$  is the frequency of the quantum, and  $h$  is Planck's constant ( $6.63 \times 10^{-34}$  joules).

### Max Planck

At the turn of the century the German physicist Max Planck (1858–1947) was attempting to derive equations to describe the radiation emitted by a black body at different temperatures. He found that his equations worked only if he assumed that the radiation was emitted as a stream of discrete packets or **quanta** of energy. Planck proposed that each quantum vibrated at a specific frequency, giving quanta the wave-like properties observed by previous physicists. The energy of a quantum is proportional to its frequency, according to Planck's equation.

### Phillip Lenard

At about the same time another German physicist, Phillip Lenard (1862–1947), was making empirical observations that were entirely consistent with Planck's quantum theory and inconsistent with wave theory. He reported a phenomenon known as the *photoelectric effect*. He found that electrons can be released from a metal surface when it is struck by light. Observations of the kinetic energy measured in the released electrons did not agree with predictions of the wave theory of light. According to the theory, the energy of a light is proportional to its intensity. This would predict that the kinetic energy of electrons released in the photoelectric effect should be proportional to light intensity. Observations indicated that as light intensity increased more electrons were emitted, but the kinetic energy of each electron remained constant. Changing the frequency of the light, on the other hand, did produce a change in kinetic energy.

#### KEY TERM

##### Quantum

The smallest discrete unit of energy in which radiation may be emitted or absorbed.

## Albert Einstein

Albert Einstein (1879–1955) used Planck’s notion of quanta to explain the photoelectric effect in a major theoretical paper published in 1905. This paper laid the foundations of the theory of quantum mechanics, according to which light (and indeed all matter) can be considered to be both particles and waves.

Einstein published two other theoretical papers in 1905, while working as a clerk in the Swiss Patent Office in Bern. One paper concerned the random motion of small particles, and the other concerned the special theory of relativity. Einstein received a Nobel Prize for this work in 1921. Lenard and Planck also received Nobel Prizes for their work, in 1905 and 1918 respectively.

## Light is a wave *and* a particle

How can light be both a particle and a wave? The behavior of light is certainly consistent with both descriptions, since it propagates through space as a wave, yet behaves like particles during emission and absorption. It must be recognized that quanta of light are fundamentally different from the particles that we can see and touch in everyday experience, such as pebbles or grains of sand. Light quanta are submicroscopic units of energy that have no mass and do not even seem to have a discrete location. Light is both a ray, a wave, and a stream of particles. All three aspects of behavior are important for understanding visual perception:

1. Ray properties are especially useful when attempting to understand how images are formed by optical devices such as eyes.
2. Wave properties are important when considering the behavior of light at a much finer scale, such as when dealing with passage through small apertures (e.g., the pupil) or along very narrow waveguides (e.g., photoreceptors).
3. The quantal nature of light intrudes on visual perception when light intensity is so low that quantum absorptions can be counted individually.

Both wave and particle models of light can be related to the color sensations produced by light. According to wave theory, color depends on frequency (the frequency of violet light is about twice that of red light). According to particle theory, color depends on energy (violet quanta transfer twice as much energy as red quanta). The two models are related via Planck’s equation (see the box on the previous page). Discussions of color vision generally prefer to use the wave model.

Light quanta are also known as photons. This term was introduced by Lewis (1926).

## SOME IMPORTANT PROPERTIES OF LIGHT

### ABSORPTION, REFLECTION, TRANSMISSION

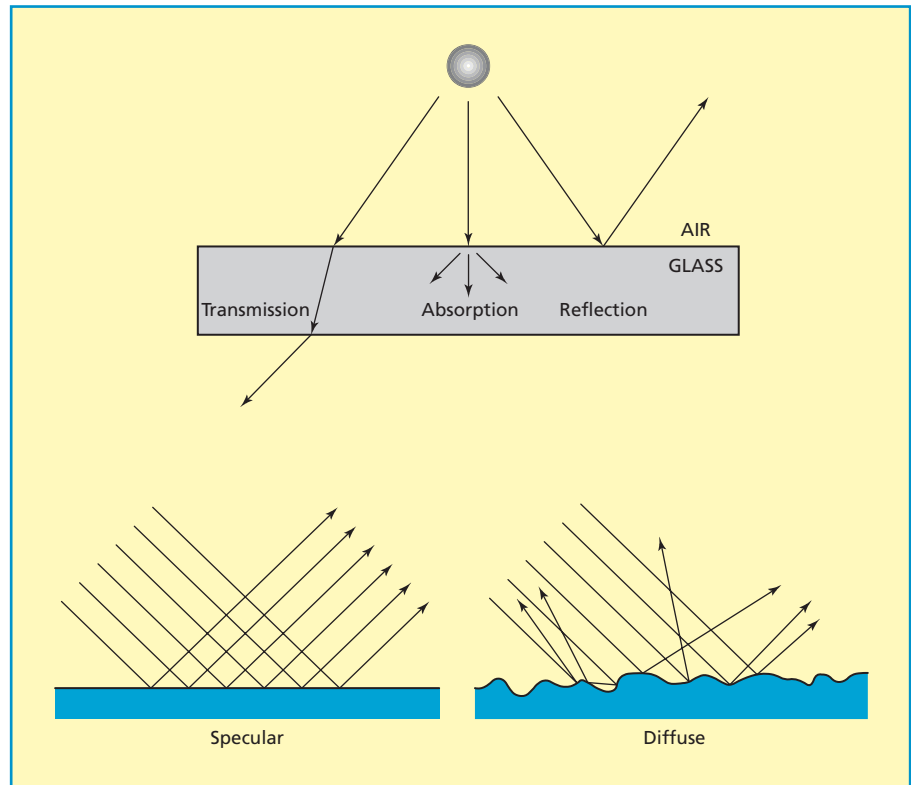
When light strikes the interface between two substances (e.g., between air and glass), it may be transmitted, absorbed, or reflected, as shown in Figure 6.4. All three properties are crucial for vision.

### Absorption

During absorption, light quanta are taken up by the substance and converted into thermal energy. Substances that absorb a high proportion of incident radiation,

**FIGURE 6.4**

How light interacts with surfaces. Top: When light strikes an interface between two media, such as air and glass, it may be transmitted, absorbed, or reflected. All three possible events are important for vision. Bottom: Reflections can be either specular (such as those seen in mirrors) or diffuse (such as those seen on rough surfaces like wood and fabric).



Heat is, of course, radiant energy that is re-emitted from the hot surface in the infrared region of the spectrum. In a greenhouse, or a car, longer wavelength sunlight heats up the interior, but the glass of the greenhouse or vehicle is opaque to the infrared heat waves, trapping the energy inside. A similar effect occurs when sunlight enters the earth's atmosphere and heats the surface of the earth—hence the “greenhouse effect.”

such as dark clothing and black-painted metal, heat up rapidly when exposed to sunlight.

Light must be absorbed to be seen. Photoreceptors in the eye must absorb light energy and convert it into electrical signals, otherwise the process of vision cannot begin.

## Reflection

During reflection, light rays are scattered backward at the interface. According to the first law of reflection, rays are reflected so that the angle of incidence equals the angle of reflection. Rays can be reflected in two ways (lower part of Figure 6.4):

- *Specular reflection* occurs when the surface is smooth (irregularities are small relative to the wavelength of light). Light rays are reflected regularly in a predictable direction.
- *Diffuse reflection* occurs when the surface contains larger irregularities. Each ray obeys the law of reflection, but rays are reflected in random directions.

Reflected light is crucial for vision, since it conveys information about the properties of surfaces present in the environment.

## Transmission

During transmission through a medium, quanta of certain wavelengths may be scattered by the molecules they hit. In low-density media such as air, light is

scattered laterally. Air molecules scatter light in the blue region of the spectrum, resulting in the bluish appearance of the sky. In dense, uniform media such as glass there is very little lateral scattering, because of destructive interference. Scattering occurs mostly in the forward direction. The interference between the original wave and waves produced by forward scattering results in a retardation of the wavefront as it passes through the medium.

### Refraction

An important consequence of the retardation of light during transmission through a medium is *refraction*, a change in the direction of the path of light rays as they enter a transmitting medium obliquely. The degree of change in direction depends on the extent to which the wavefront is retarded, and this in turn depends on the **refractive index** of the transmitting medium. Materials with higher indices retard light more, and consequently produce greater angles of refraction. Air has a refractive index close to 1.0, meaning that light is retarded very little during its transmission. Glass has a refractive index of approximately 1.5, so when light strikes an interface between air and glass it will change direction.

Refraction is a crucial property of light for vision, because it is the principle underlying the formation of images by lenses. Figure 6.5 shows two glass prisms receiving parallel light rays. Because of refraction, as the light rays enter and leave the glass, the rays begin converging when they exit the prisms. This effect illustrates the basic principle underlying the ability of lenses to form images, as seen in Figure 6.1 earlier. The surface of the lens is curved so that parallel light rays entering the lens from a distant point will converge on a point behind the lens. The distance of this point of focus from the lens defines the lens's **focal length**. Further details can be found in the Tutorials section later in the chapter.

### KEY TERMS

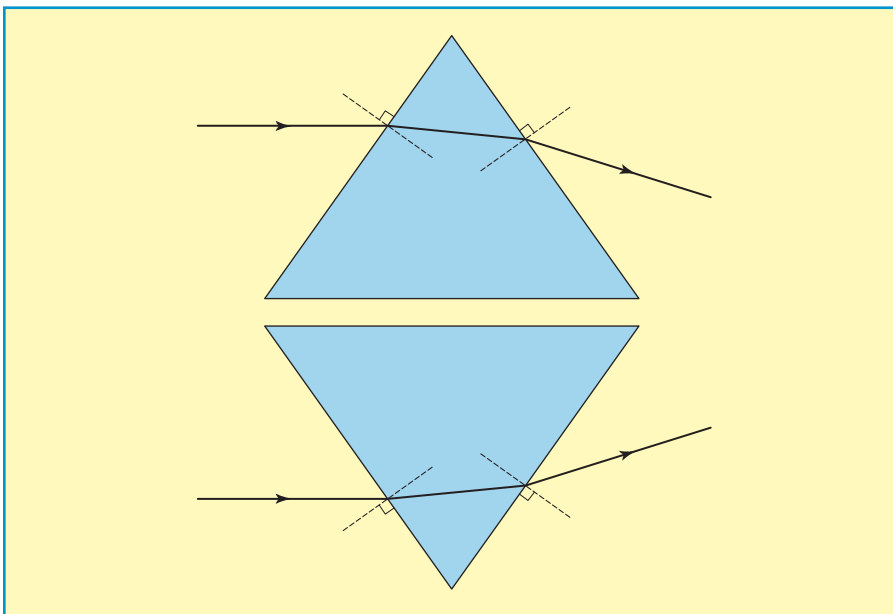
#### Refractive index

The ratio of the velocity of propagation of an electromagnetic wave in a vacuum to its velocity in a given transmitting medium.

#### Focal length

The distance from the center of a lens to its focal plane (the plane in which parallel light rays are brought into sharp focus).

? Think about why your vision is blurred under water.



**FIGURE 6.5**

Refraction. When rays of light from a wavefront strike a transmitting medium such as glass obliquely, their direction of travel is deflected (refracted) as a result of the retardation in the wavefront. When parallel rays strike two glass prisms, they begin converging when they emerge from the prisms. This illustrates the basic principle behind image formation by lenses.

## INTENSITY

The intensity of a light source ultimately depends on the number of quanta it emits per unit of time. A range of physical units, known as **radiometric** units, has been developed to measure intensity. However, the effectiveness of light quanta as a stimulus for vision depends on their wavelength properties, since the human visual system is more sensitive to some wavelengths than to others. So in the context of vision, light intensity is usually specified in **photometric** units that take account of human sensitivity. The most commonly used unit is “candelas per square meter” (abbreviated to  $\text{cd}/\text{m}^2$ , or equivalently  $\text{cd}\cdot\text{m}^{-2}$ ), which measures the intensity of the light emanating from a surface relative to that of a standard light. Further details on different measures of light intensity can be found in the Tutorials section.

Table 6.1 gives typical **luminance** values (in  $\text{cd}/\text{m}^2$ ) for six light sources (based on data in Makous, 1998, and Land & Nilsson, 2002). Corresponding numbers of photons emitted per second are shown in the middle column, calculated according to formulas given in the Tutorials section. Light intensities experienced by organisms living on the surface of the earth seem very high indeed when measured in terms of quanta emitted. Even viewed in moonlight, white paper emits  $10^{15}$  quanta per second ( $10^6$  is a million). In sunlight the paper emits nearly a million times more quanta.

On this basis we might be tempted to disregard the quantal nature of light when considering it as a stimulus for vision. However, it is important to consider natural light intensities in terms of the number of quanta available for vision. As we shall see below, the human eye responds to light by means of many photoreceptor cells distributed around its inner surface. Light is brought to focus on these receptors by the optical apparatus of the eye (cornea, pupil, and lens). The right-hand column of Table 6.1 estimates the number of quanta hitting each receptor per second at the six different light levels (based on Land & Nilsson’s, 2002, estimate that photon numbers are reduced by a factor of  $10^{15}$  when one takes into account the optics and dimensions of photoreceptors). In the brightest conditions, each photoreceptor receives 100,000 quanta per second. In the dimmest borderline conditions supporting human

### KEY TERMS

#### Radiometry

The measurement of electromagnetic radiation.

#### Photometry

The measurement of visible electromagnetic radiation.

#### Luminance

A photometric measure of the energy emitted or reflected by an extended light source, in candelas per square metre of surface ( $\text{cd}\cdot\text{m}^{-2}$ ).

**TABLE 6.1** Luminance values and photon counts for six light sources

Light source	Luminance ( $\text{cd}\cdot\text{m}^{-2}$ )	Photons $\text{m}^{-2}\cdot\text{sr}^{-1}\cdot\text{s}^{-1}$	Photons per receptor
Paper in starlight	0.0003	$10^{13}$	0.01
Paper in moonlight	0.2	$10^{15}$	1
Computer monitor	63	$10^{17}$	100
Room light	316	$10^{18}$	1000
Blue sky	2500	$10^{19}$	10,000
Paper in sunlight	40,000	$10^{20}$	100,000

vision, each receptor receives only 0.01 quanta per second. In other words, minutes may elapse between successive strikes on any one receptor. The quantal nature of light thus becomes an important issue at low light levels (individual photoreceptors are capable of responding to individual quantal strikes).

We can see from Table 6.1 that the visual diet experienced by an organism on earth spans a very wide range (increasing by a factor of 10,000,000, or  $10^7$ , from starlight to sunlight). Individual photoreceptors can respond over a range of intensities spanning less than one hundredth of this range (roughly two rows of the table). Yet humans can see adequately both by starlight and in the midday sun. How, then, does the visual system cope successfully with such a huge range of light levels? At any one moment the intensity in a scene, from the darkest shadow to the brightest surface, varies only by a factor of less than 1 in 100 (see below), a tiny fraction of the full range available on earth. As one moves from well-shaded, interior, or nighttime conditions into bright outdoor conditions, the relatively narrow range of light levels experienced slides up the intensity scale. The visual system possesses mechanisms that adjust the operating range of photoreceptors so that it too slides up and down the intensity range, and thus receptor responses remain well matched to prevailing illumination conditions. This process of adjustment is known as light and dark adaptation, and is discussed in detail in Chapter 8.

**?** *Why do so few photons reach each photoreceptor, relative to the number entering the eye?*

## CONTRAST AND REFLECTANCE

Unless the observer looks directly at a light source (not recommended in the case of the sun, as it is likely to result in permanent eye damage), the pattern of light and dark entering the eye is a result of reflections from surfaces in the scene. Some surfaces reflect a very high proportion of the light that strikes them. White paper reflects approximately 75% of the incident light. Other surfaces absorb a high proportion of the incident light. Black paper and paint, for instance, reflect only 5% of the incident light. Black velvet reflects about 2%.

Consequently, even in a scene containing the extreme combination of both black velvet and white paper, intensity will vary only by a factor of 1 in 38 (the paper will reflect 38 times more light than the velvet). A useful measure of relative luminance is **contrast** (C) defined as:

$$C = (L_{\max} - L_{\min}) / (L_{\max} + L_{\min})$$

Where  $L_{\max}$  is the higher luminance value and  $L_{\min}$  is the lower luminance value. Contrast can vary between 0 and 1.

It is very important to realize that contrast is independent of the absolute level of illumination and (in the absence of variations in illumination such as shadows) is determined by surface reflectance. For example, assume that the velvet and

The proportion of incident light reflected by a surface is known as its **reflectance**. Highly reflecting surfaces appear whitish, and have values approaching unity. Snow, for example, has a reflectance of 0.93, whereas newspaper has a reflectance of 0.38 (Makous, 1998). Surfaces with reflectance values approaching zero appear very dark.

### KEY TERMS

#### Reflectance

The proportion of incident light reflected from a surface.

#### Contrast

A measure of the difference between the highest luminance and the lowest luminance emitted or reflected from a surface

**?** *Think about why luminance is less informative about objects than contrast.*

paper are viewed in moonlight:  $L_{\max}$  corresponds to the luminance of the paper,  $0.2 \text{ cd}\cdot\text{m}^{-2}$ ;  $L_{\min}$  corresponds to the luminance of the velvet,  $0.0053 \text{ cd}\cdot\text{m}^{-2}$ . The contrast between the paper and the velvet is 0.948, according to the equation above. When viewed in sunlight, the luminances of the paper and velvet are  $40,000 \text{ cd}\cdot\text{m}^{-2}$  and  $1066.7 \text{ cd}\cdot\text{m}^{-2}$  respectively. Contrast is again 0.948.

Absolute luminance is relatively uninformative about the properties of surfaces, whereas contrast provides information about surface reflectance. So early neural processes in the visual system are specialized to encode contrast but discard information about absolute luminance.

## WAVELENGTH

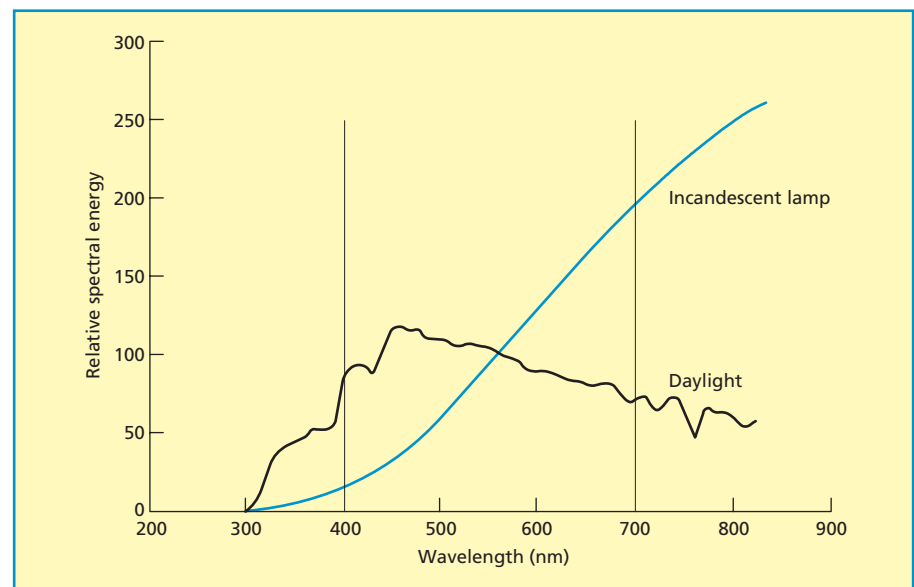
Humans are able to detect wavelengths in the region between 400 nm and 700 nm. Wavelength is correlated with sensory impressions of color. Moving down the wavelength scale from 700 to 400 nm, color varies through the following sequence: red–orange–yellow–green–blue–indigo–violet. The acronym ROYGBIV is sometimes used as a mnemonic. The wavelength composition of light actually reflected from a surface depends jointly on the spectral power distribution of the illuminating light and the spectral reflectance of the surface.

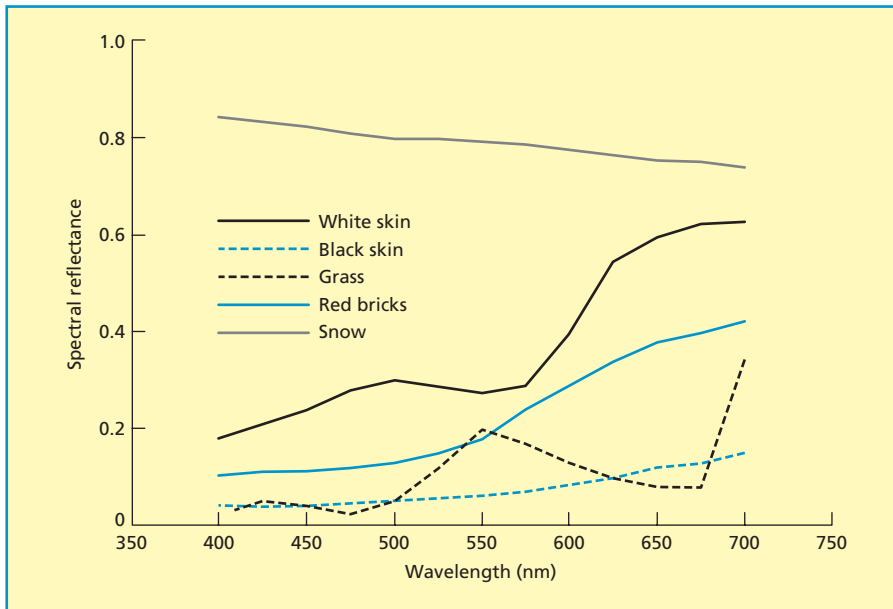
## Spectral power distribution of light sources

Commonly experienced light sources emit radiation across a broad spectrum of wavelengths. Figure 6.6 plots relative energy as a function of wavelength (spectral power distribution) for sunlight and for an incandescent lamp. The vertical lines mark the limits of the visible spectrum. Notice from Figure 6.6 that incandescent lamps such those used in domestic rooms have much more energy in the yellow–red end of the spectrum than daylight.

**FIGURE 6.6**

Emission spectra of two common light sources, the sun and an incandescent lamp (domestic lightbulb). Vertical lines represent the borders of the visible spectrum. Daylight has a peak in energy at wavelengths in the short wavelength region (450 nm) that appears bluish to humans, whereas lamps emit more and more energy at higher wavelengths that appear yellowy-red (graphs based on CIE standard illuminants A and  $D_{65}$ ).





**FIGURE 6.7** Spectral reflectance functions of several familiar surfaces. Notice that some surfaces such as snow reflect a much higher proportion of incident radiation than other surfaces. In addition, the preponderance of different wavelengths in the reflected energy varies between surfaces. Grass, for example, has a peak in the reflectance in the green part of the spectrum (550 nm) (data re-plotted from Wyszecki & Stiles, 1982).

## Spectral reflectance functions

Surface reflectance (the proportion of incident light reflected) generally varies as a function of wavelength to define the surface's spectral reflectance function. Figure 6.7 plots **spectral reflectance functions** for a range of surfaces. Snow reflects a high proportion of light at all wavelengths, whereas grass absorbs light quite efficiently at most wavelengths. Notice the distinct peak in the reflectance of grass at wavelengths in the green region of the spectrum. Natural surfaces tend to have smooth, slowly changing reflectance functions, and generally reflect more light at longer wavelengths than at shorter wavelengths.

## Spectral power distribution of reflective surfaces

As stated earlier, the spectral power distribution of light reflected from a surface depends jointly on the power distribution of the illuminant (e.g., Figure 6.6), and the surface's reflectance function (e.g., Figure 6.7). The two functions are multiplied, wavelength by wavelength, to arrive at the power distribution of the reflected light. Changes in the power distribution of the illuminant can therefore result in marked changes in the power distribution of light reflected from a surface. Surfaces viewed under artificial light, for instance, reflect much more energy in the yellow region of the spectrum than when viewed under daylight, because of the marked differences in incident energy shown in Figure 6.6. However, our perception of surface color tends to remain constant in the face of such changes. This phenomenon is known as *color constancy*, and is discussed in detail in Chapter 12.

## THE EYE

The eye is the peripheral organ of vision. Its function is to catch photons and direct them onto photoreceptors in order to begin the process of vision. Animals have

### KEY TERM

#### Spectral reflectance function

The proportion of light reflected from a surface as a function of the wavelength of the incident light.

evolved a huge variety of organs that respond to light, only some of which can be classed as eyes. Some invertebrates such as worms have single receptors distributed on the surface of their skin. The minimum qualification for such an organ to be called an eye is that it must form some kind of image on a sheet of photoreceptors. Images are vital for effective vision because they preserve the spatial arrangement of the points in space from which the light rays emanated. With suitable neural processing, a great deal of information about the world can be extracted from images, as we shall discover in the rest of the book.

## STRUCTURE OF THE HUMAN EYE

Humans, in common with other mammals, birds, and reptiles, have single-chambered eyes. Figure 6.8 shows the main structures of the human eye. It is a roughly spherical, light-tight chamber, the inside surface of which is lined with a sheet of photoreceptors. An opening in the chamber, covered by a transparent membrane, admits light.

The transparent membrane is known as the **cornea**. Having passed through the cornea, incoming light then enters an aperture known as the **pupil**. The pupil is formed by a muscular diaphragm known as the iris (idiosyncratic pigmentation in the iris determines eye color, and is increasingly used as a form of identification). After passing through the lens, situated behind the pupil, light strikes the photoreceptor sheet, known as the retina. The structure of the retina is very complex, and will be described in detail in the next chapter.

The interior of the eye is filled with two substances, vitreous humor and aqueous humor. Vitreous humor is a viscous gel that fills the large posterior chamber of the eye, maintaining its shape and holding the retina against the inner wall. The watery aqueous humor is pumped into the eye continuously, entering the eye near the attachment of the lens (ciliary processes) and leaving

### KEY TERMS

#### Cornea

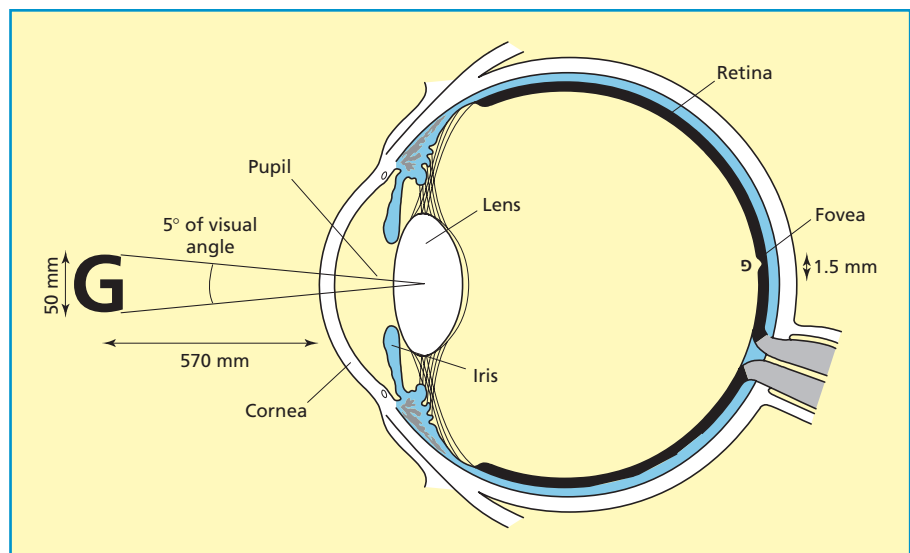
The transparent membrane through which light enters a single-chambered eye.

#### Pupil

The circular aperture formed by a muscular diaphragm in the eye, through which light passes after entering the cornea.

### FIGURE 6.8

Major components of the human eye. Dimensions are also shown for the image produced by a 50 mm tall letter viewed at a distance of 570 mm (similar to a large newspaper headline viewed at arm's length). The angle subtended by the letter at the nodal point of the eye is  $5^\circ$ . The retinal image of the letter is 1.5 mm tall, and spans approximately 500 photoreceptors.



near the margins of the iris (canal of Schlemm). It flows in both the small anterior chamber (behind the cornea) and the main posterior chamber. Rate of flow is such that the entire volume of the fluid is replenished approximately every 45 minutes. The functions of the aqueous humor are to nourish the lens and to keep the eye inflated.

Abnormally high pressure in the eye is known as glaucoma, often caused by blocked outflow of aqueous humor. If untreated, glaucoma causes permanent loss of vision, because the increased pressure impedes blood flow into the eye.

## VISUAL ANGLE

How should we specify the size of an object? Linear size in millimeters is obviously the most appropriate measure for most everyday situations, such as when deciding whether a given item of furniture will fit into an available space. However, when studying the images of objects as stimuli for vision, the most appropriate measures of size relate to the size of the image projected onto the retina. The most frequently used measure is **visual angle**: the angle subtended by the object at the center (nodal point) of the lens. Visual angle depends jointly on the size of the object and its viewing distance. If visual angle is relatively small ( $10^\circ$  or less) it can be calculated easily from trigonometry using the formula:

$$\tan \theta = s/d$$

Where  $\theta$  is visual angle,  $s$  is object size, and  $d$  is viewing distance. One degree is divided into 60 minutes (abbreviated to  $60'$ , and one minute is divided into 60 seconds (abbreviated to  $60''$ ). So  $0.25^\circ$  can also be expressed as  $15'$ , and  $0.01^\circ$  can be expressed as  $36''$ .

The importance of the nodal point of the lens is that light rays pass through it without being refracted (because they strike the surface of the lens at right-angles). So the angle subtended by the image on the retina is equal to the angle subtended by the object at the nodal point. It is sometimes useful to convert this angular subtense into linear units, so specifying the size of the retinal image in millimeters. Image size in linear units depends on eye size. For a given angular subtense, the farther away the retina is from the lens, the larger will be the retinal image. In the case of human eyes, one degree of visual angle is equal to 0.288 mm on the retina. The issue of eye size is discussed in more detail later in the chapter. Retinal image size will be specified in either angular or linear units or both in the remainder of this chapter, as appropriate.

To give an example, Figure 6.8 includes a letter G and the image it projects onto the retina. Values given correspond to a 50 mm tall headline in a newspaper viewed at approximately arm's length (570 mm). The letter subtends a visual angle of  $5^\circ$ , and projects an image 1.5 mm tall on the retina. The width of a thumb held at arm's length corresponds to approximately  $2^\circ$  of visual angle on the retina.

? Which would be preferable, a television 50 cm (20 inches) wide viewed from 3 m (10 feet) away, or a cinema screen 6 m (20 feet) wide viewed from 40 m (130 feet)?

## OPTICAL PROPERTIES OF THE EYE

### Cornea and lens

#### *Optical power*

Refraction occurs at an interface between media having different refractive indices. In the case of the eye, refraction occurs at four surfaces, namely:

- Anterior (front) corneal surface
- Posterior (back) corneal surface

#### KEY TERM

##### Visual angle

The angle an object subtends at the center of a lens; it is used to measure the size of an object as a stimulus for vision.

- Front surface of the lens
- Rear surface of the lens.

The combined effect of these surfaces is to create an optical system with a focal length of 16.8 mm. This means that in a normal, relaxed eye the image of a distant object will fall into focus 16.8 mm behind the center of the lens system, a distance that corresponds precisely to the location of the retina. As discussed in detail in the Tutorials section, optical power is conventionally expressed in **diopters (D)**, which correspond to  $(1/\text{focal length in meters})$ . The power of the eye's optical system is therefore  $(1/16.8 \times 10^{-3})$ , or 59.52 D.

The degree of refraction at an interface between two media depends on the difference in refractive index of the media, as described in the tutorial. The refractive indices of air, cornea, ocular fluid, and the lens are 1.009, 1.376, 1.336, and 1.413 respectively. We can therefore see that the greatest degree of refraction in the eye's optical system occurs at the interface between air and the cornea, because of the large difference in refractive index. In fact, approximately 48 D of the eye's optical power is contributed by refraction at the anterior surface of the cornea.

### Accommodation

Although the optical power of the eye is sufficient to focus parallel rays from far objects on the retina, diverging rays from near objects come into focus behind the retina. There are two ways to bring the image back into focus on the retina. The first is to move the lens further away from the retina. Certain fish (and cameras) adopt this strategy. The alternative is to increase the optical power of the lens. This latter strategy is adopted by reptiles, birds, and mammals, including humans. The lens is deformable, and ciliary muscles located around the margins of the lens where it attaches to the eye can adjust its shape to accommodate objects at different distances. The process of focusing is actually known as **accommodation**. Zonular fibers attach the lens to the ciliary muscles. When the muscles are relaxed, intraocular pressure stretches the zonular fibers, which in turn pull the lens into a thin shape. In this shape the lens has a focal length of 59.52 D, appropriate for far objects. When the muscles are tense, they

relieve the pressure on the zonular fibers, which allows the lens to relax into a thicker shape with a shorter focal length. In young healthy eyes accommodation can increase the optical power of the eye by up to approximately 8 D, allowing objects as close as 250 mm to be brought into focus. This distance is known as the *near point*. Lens flexibility declines with age, so that the near point moves progressively further away. Beyond the age of 50 there is typically little scope for accommodation left, a condition known as **presbyopia** (see Glasser & Campbell, 1998).

**Accommodative errors** Two kinds of error are commonly found. The optical power of the eye can be either too great or too weak, given the size of the eye, resulting in image blur at the retina.

- **Myopia**, or short-sight, occurs when the optical power is too great. Rays from distant objects come

#### KEY TERMS

##### Diopter

A measure of the refractive power of a lens; it corresponds to  $(1/f)$  where  $f$  is its focal length in meters.

##### Accommodation

The process by which the shape of the eye's lens is changed to alter its focal length.

##### Presbyopia

The age-related change in accommodative range, resulting from loss of flexibility in the lens.

##### Myopia

A condition in which the refractive power of the eye's lens is too great, causing the image of distant objects to be defocused.

into focus in front of the retina, and accommodation is no help because it brings the point of focus even further forward. Near objects do fall into focus, and accommodation is required only for very near distances.

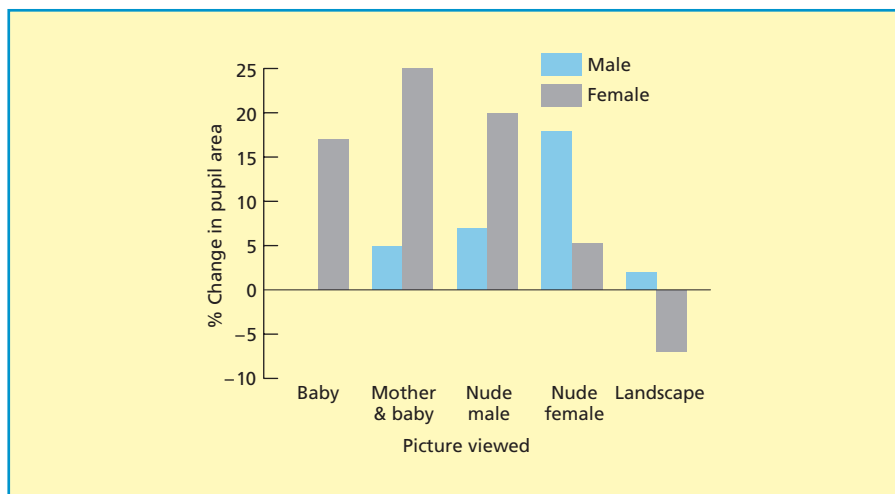
- **Hyperopia**, or long-sight, occurs when the optical power is too weak. Rays from distant objects come into focus behind the retina. In this case accommodation does help, but it comes into play at distances that should not normally require it.

Both kinds of accommodative error can be corrected in two ways. The traditional solution is to wear corrective lenses, either as spectacles or as contact lenses, which adjust the optical power of the eye to remove the error. A more recent solution, known as *photorefractive keratectomy*, is to shave a very small amount of material from the surface of the cornea using a laser. This has the effect of altering the radius of curvature of the cornea in such a way as to alter the optical power of the cornea and correct the accommodative error.

## Pupil

The diameter of the pupil can vary between approximately 2 mm and 8 mm. The resultant change in area equates to a sixteenfold variation in retinal illumination. Since this is a tiny fraction of the range of illumination levels experienced on earth, as explained earlier, we can safely assume that the function of the pupil is not solely to control retinal illumination. Its function may be more subtle, in regulating the balance that must be struck between maximizing the eye's sensitivity and retaining its resolution (ability to resolve detail), as explained later in the chapter.

Pupil size is influenced by emotional responses. Large pupils are associated with positive or pleasurable emotions, whereas small pupils are associated with negative emotions. For example, in a study by Hess and Polt (1960), the pupils of male and female subjects were photographed while they viewed a range of photographs. Figure 6.9 plots the mean change in pupil size as a function of subject matter. Male subjects showed a large increase in pupil size while viewing pictures of nude females, and very small increases while viewing landscapes. Female subjects showed large increases while viewing pictures of mother and baby, and nude males, but decreases while viewing landscapes.



? How can presbyopia be treated?

? What kinds of lenses must spectacles contain?

### KEY TERM

#### Hyperopia

A condition in which the refractive power of the eye's lens is too weak, causing the image of near objects to be defocused.

Other old studies (e.g., Hess, 1975) also claim that large pupils make female faces appear more attractive, perhaps because they indicate an interest in the viewer.

#### FIGURE 6.9

Mean change in pupil size as a function of image viewed, for male and female subjects. Male subjects show a large increase in pupil diameter only when viewing pictures of nude females. Female subjects show increases in pupil diameter when viewing pictures of babies and nude males. An increase in pupil size is usually interpreted as an indicator of positive emotional responses (data re-plotted from Hess & Polt, 1960).

## Photoreceptors

The retina of each eye contains over 100 million photoreceptor cells, responsible for converting light energy into neural activity (transduction). Each photoreceptor is a long, thin tube consisting of an outer segment that contains light-sensitive pigment and an inner segment that in effect forms the cell body. A detailed discussion of how photoreceptors achieve transduction will be postponed until the next chapter. The discussion here will concentrate on the optical properties of photoreceptors.

### Rods and cones

Human photoreceptors fall into two classes, called **rods** and **cones** on the basis of the shape of their outer segments. Rods and cones differ in several important respects:

Curiously, there is a cone-rich rim at the extreme edge of the retina, where the far lateral periphery of the visual field is imaged; it may form part of a rapid early warning mechanism (Williams, 1991).

- They contain different light-sensitive pigments (discussed in the next chapter). Rod pigment is very sensitive at low light levels. Cones are 30–100 times less sensitive, so function only at high light levels.
- There are far more rods in each eye (approximately 120,000,000) than cones (approximately 6,000,000).
- They differ in width, length, and retinal distribution. An important landmark on the retina is the *fovea*, a small pit at the optical centre of the retina, 0.5 mm (1.7°) wide. It is entirely devoid of rods and contains only cones (more details below).

### Photoreceptor width

The light-sensitive portion of each cone has a diameter of approximately 1–4  $\mu\text{m}$  in the fovea, and 4–10  $\mu\text{m}$  outside the fovea. Rods have a diameter of 1  $\mu\text{m}$  near the fovea (Wandell, 1995). The width of each photoreceptor obviously imposes a limit on the spacing between adjacent photoreceptors. Spacing, in turn, determines the ability of the retina to resolve detail. As we shall see in a moment, reducing the spacing between receptors increases their ability to resolve fine spatial detail. So why are the photoreceptors not narrower still? The answer to this question lies in the wave properties of light. As each photoreceptor's width approaches the wavelength of visible light (0.4–0.7  $\mu\text{m}$ ) it becomes unable to retain light by total internal reflection. Instead, some of the light leaks out through the sides of the photoreceptor, and excites adjacent receptors. This “cross-talk” between receptors reduces the effective resolution of the retinal mosaic, because each photoreceptor's response depends not just on the light striking it, but also on the light striking its neighbors. There is consequently nothing to be gained in terms of resolution from having photoreceptors narrower than 1  $\mu\text{m}$ , and indeed none have been found in the eyes of any animal.

#### KEY TERMS

##### Rod

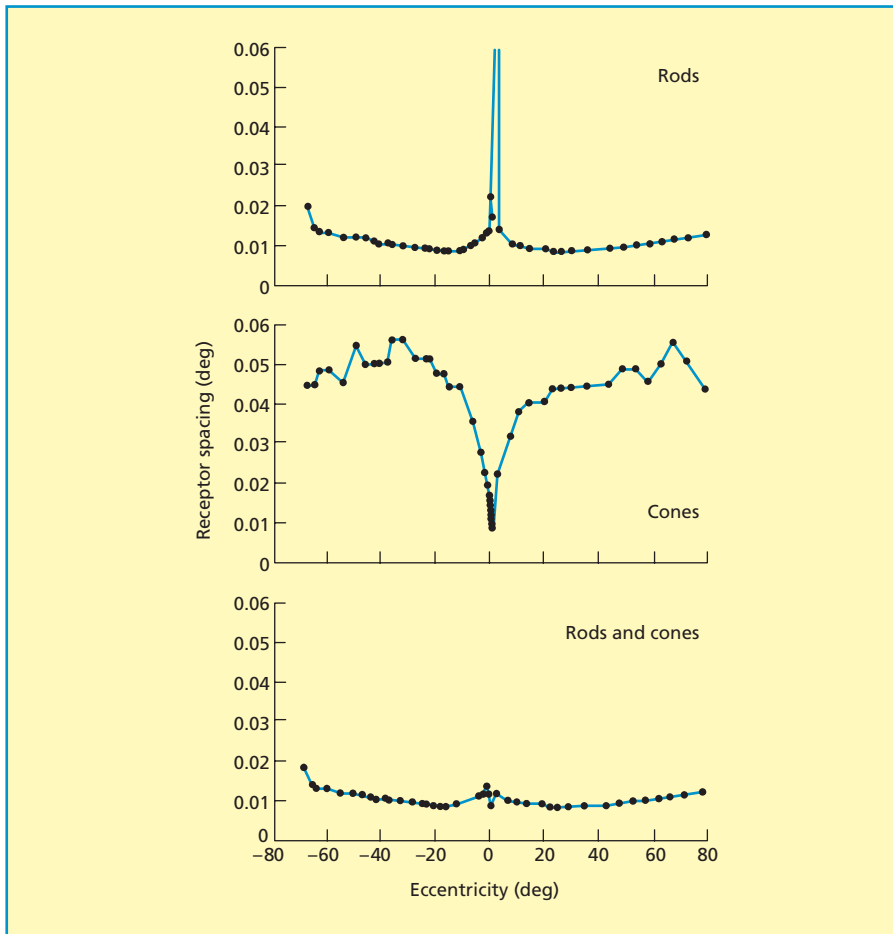
A type of photoreceptor that is specialized for responses at low light levels.

##### Cone

A type of photoreceptor that is specialized for responses at high light levels.

### Photoreceptor length

The light-sensitive portion of each human cone is up to 80  $\mu\text{m}$  long in the fovea and 40  $\mu\text{m}$  long outside the fovea; rods are 60  $\mu\text{m}$  long (Wandell, 1995). The proportion of incident light absorbed by a photoreceptor depends on its length. Inside the fovea, cones absorb up to 50% of incident light. Outside the fovea, cones absorb 33% of incident light. Rods absorb 42% of incident light (see Warrant & Nilsson, 1998).



**FIGURE 6.10** Distance between adjacent photoreceptors in the human retina as a function of retinal position for rods, cones, and all receptors combined. Cones are concentrated in the fovea, where no rods are found. Taking both receptor types together, spacing remains fairly stable across the retina (data taken from Osterberg, 1935, which were expressed as photoreceptors per square mm; the data plotted were calculated as the square root of his values, to give an approximate value for spacing).

### Photoreceptor spacing

Figure 6.10 plots photoreceptor spacing for cones, for rods, and for both combined, as a function of retinal location. Cone spacing is smallest in the fovea—0.003 mm (0.01°, or 0.6' arc). Moving outside the fovea, cone spacing increases fourfold to approximately 0.013 mm (0.045°, or 2.7' arc), while rod spacing is 0.003 mm (0.01°, or 0.6' arc). Taking both classes of photoreceptor together, Figure 6.10 indicates that spacing is surprisingly stable across the retina, at a value (3  $\mu\text{m}$ ) approaching the minimum available given the wavelengths of visible light.

## Resolution and sensitivity

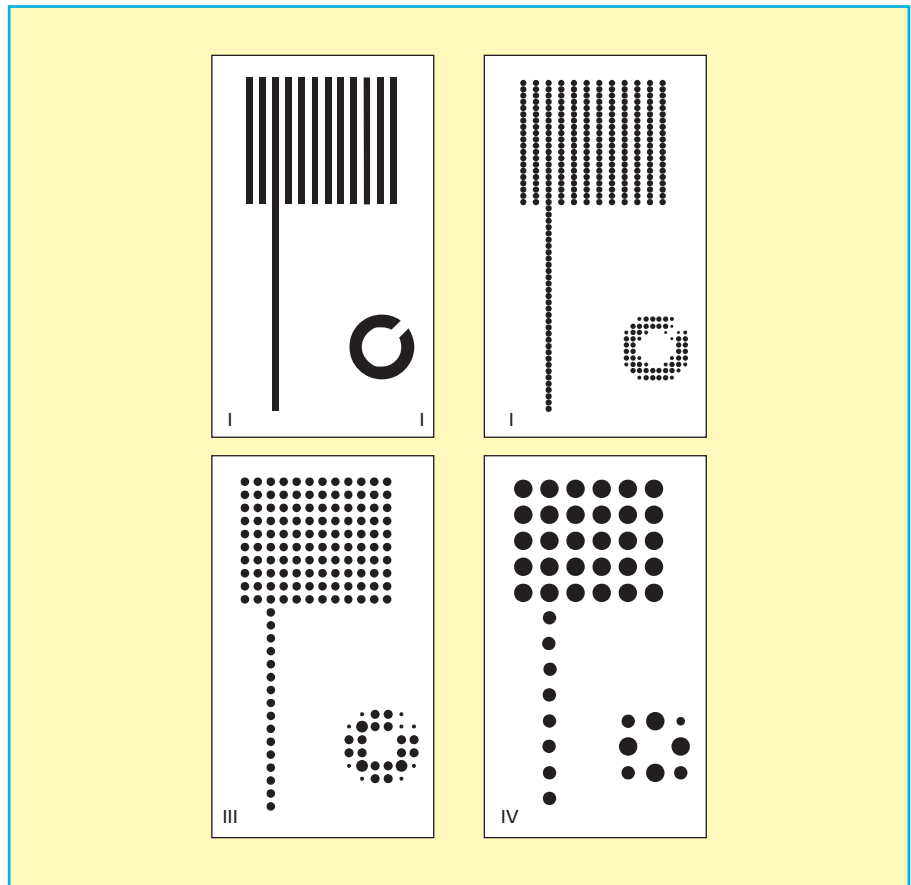
The *resolution* of the eye is its ability to resolve fine spatial detail in the retinal image. *Sensitivity* refers to the eye's ability to respond at very low illumination levels. Both aspects of performance are important for vision, but they place different demands on the optical components of the eye.

### Resolution

Figure 6.11 illustrates how photoreceptor spacing affects resolution. It shows a black-and-white test image (upper left) along with corresponding patterns

**FIGURE 6.11**

Effect of receptor spacing on acuity. The stimulus pattern (top left) consists of a vertical grating and a broken circle. This pattern was superimposed on retinal mosaics at three different spacings: small (top right), medium (bottom left), and large (bottom right). Each circle represents a receptor positioned over an element of the pattern. Small receptor spacings permit a faithful rendition of the pattern—all grating bars and the break in the circle are visible. At the largest receptor spacing individual grating bars cannot be resolved, and the break in the circle is lost (re-drawn from Pirenne, 1948). Used with permission of Taylor & Francis, Inc.



superimposed on three imaginary retinal mosaics with different receptor spacing. Each circle represents an individual photoreceptor.

The test image includes a **grating** consisting of alternating black and white bars. Gratings are used very frequently to assess spatial resolution, for reasons that will become clear in Chapter 8. Notice that the finest mosaic (top right) can represent both the grating pattern and the broken circle faithfully. The coarsest mosaic (bottom right) cannot resolve individual grating bars, and provides only a crude rendition of the broken circle. Mathematical procedures allow us to calculate the finest grating bars that can be resolved by a given photoreceptor spacing. In simple terms, the grating can be resolved faithfully if each adjacent light and dark bar falls on a separate receptor. Each pair of light and dark bars constitutes one cycle of the grating pattern. So there must be two receptors per grating cycle in order to accurately represent the grating (the so-called Nyquist Limit). With fewer receptors it is not possible to distinguish all the bars of the grating.

Photoreceptor spacing is limited by photoreceptor width, which, in turn, is limited by the wavelengths of visible light. Once the minimum photoreceptor width is achieved, the only other way to increase the resolving power of the retina is to increase the size of the image. Larger images allow greater detail to be resolved because they are sampled by more photoreceptors. Larger images require larger eyes, since image size or **magnification** is a function of focal length (see the Tutorials

## KEY TERMS

### Grating

A pattern of alternating light and dark bars, widely used in vision research.

### Magnification

The size of the image produced by a lens; it depends on the focal length of the lens.

section at the end of the chapter). In the case of the human eye (focal length 16.8 mm), an object 50 mm tall viewed from a distance of 570 mm (such as the headline in a newspaper held at arm's length; see Figure 6.8) would cast an image 1.5 mm tall on the retina. This image would span 500 photoreceptors. An eye half the size of the human eye would produce an image half as tall, spanning half as many photoreceptors (assuming constant photoreceptor spacing).

? How well would a miniature person, say 20 cm (8 inches) tall, be able to see?

**Interreceptor spacing** Receptor spacing ( $s$ ) and eye size or focal length ( $f$ ) jointly determine the **interreceptor angle** ( $\Delta\Phi = s/f$ ). This angle is the defining feature of the eye's resolving power. For example, eyes with an interreceptor angle  $\Delta\Phi$  of  $0.01^\circ$  can resolve successive dark bars in a grating no closer than  $0.02^\circ$ , corresponding to a grating spatial frequency of 50 cycles per degree of visual angle (cpd). Assuming that photoreceptor spacing is close to its optical limit, resolution is governed by eye size. Other things being equal, animals with small eyes have less acute vision than animals with large eyes. Cats, for example, have poorer spatial resolution than humans.

### Sensitivity

Sensitivity is limited by **photon noise**, as Figure 6.12 illustrates. It shows an array of 400 photoreceptors (small circles), receiving an image of a central dark disk (large circle) on a light background. Each white small circle represents a photon strike on a receptor. At high illumination levels (IV, bottom right), photon strikes define the image accurately. As light level falls towards the absolute threshold for vision (I, upper left), the image becomes less distinct because of the uncertainty associated with individual photon strikes (photon noise).

Retinal illumination at low light levels naturally depends on pupil diameter. Eyes capable of very large pupil diameters have an advantage in terms of sensitivity, since they admit more light. Image degradation as a result of lens imperfections at wide apertures is not an issue, since resolution is limited by photon noise as Figure 6.12 illustrates. At higher illumination levels there are so many photons available that photon noise is no longer relevant. In these conditions smaller pupil diameters are called for in order to minimize the deleterious effects of lens imperfections. A pupil diameter of 2–3 mm is considered optimal for retinal image quality. Pupil diameters smaller than 2 mm suffer increased blur because of the effects of diffraction. At diameters greater than 3 mm the effects of **chromatic** and **spherical aberration** become more pronounced (a detailed discussion of diffraction and aberration can be found in the Tutorials section).

### Optimal eye size

The foregoing discussion would indicate that both resolution and sensitivity are best served by larger eyes, which have the smallest possible interreceptor angles and large maximum pupil diameters. This observation begs the question—why are human eyes

#### KEY TERMS

##### Interreceptor angle

The visual angle between two neighboring photoreceptors; it determines the resolving power of the eye.

##### Photon noise

The inherent natural variation in the rate at which photons strike a receiving surface such as the retina.

##### Chromatic aberration

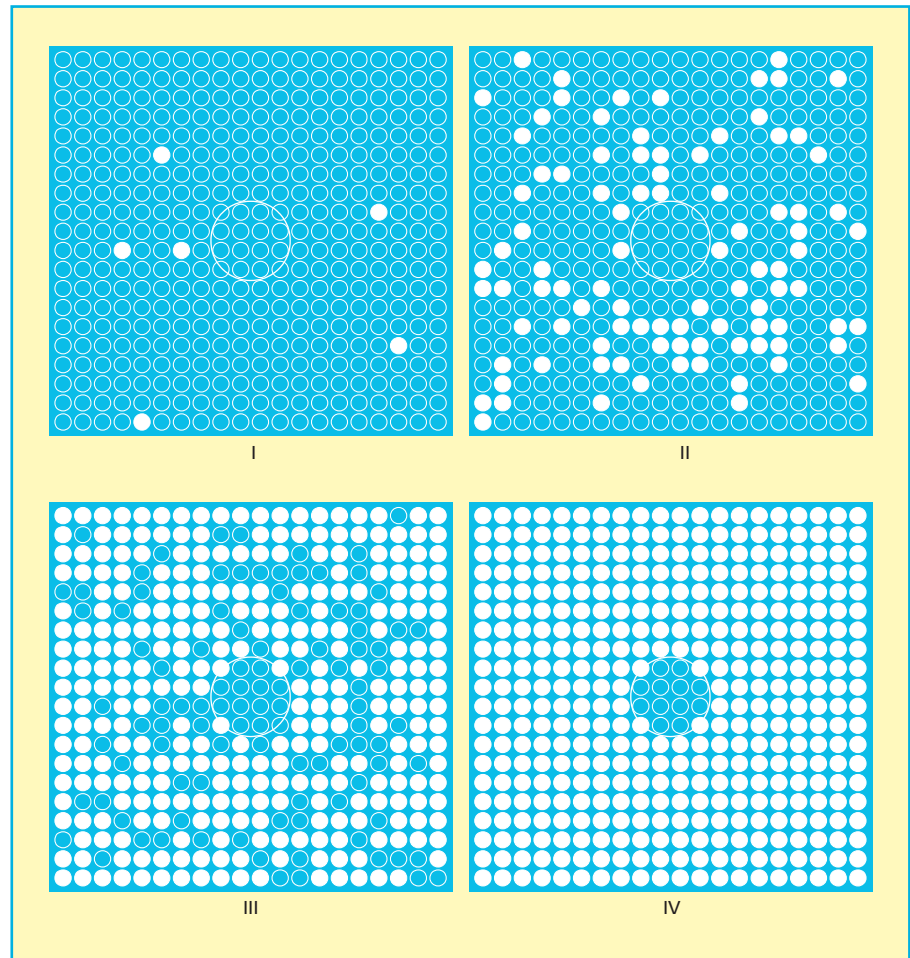
The property of an optical system that causes light rays at different wavelengths to be focused in different planes, so degrading the image.

##### Spherical aberration

The failure of light rays striking all parts of a lens to converge in the same focal plane, so degrading the image.

**FIGURE 6.12**

Effect of photon noise on acuity. The small circles represent locations of individual photoreceptors, with white circles representing active receptors. The large circle in the center of each panel shows the position of a large dark disk presented as an image against a white background for a short time. The four panels represent photoreceptor responses at four different light levels. Under extremely dim illumination (top left), when few photons are emitted, the probability that any one receptor will be struck by a photon is very low. Just six active receptors are shown. As illumination level and photon numbers rise, the probability of activity in each receptor also rises. At the highest level (bottom right), so many photons are emitted that all receptors are activated by the light region of the image. The ability of the photoreceptor mosaic to resolve the pattern at low light levels therefore depends on the number of photons emitted, not on the fineness of the mosaic or blur in the image (re-drawn from Pirenne, 1948). Used with permission of Taylor & Francis, Inc.



not larger than 24 mm in diameter? Eyes are expensive organs, because they occupy a significant amount of space in the head, and they consume a large amount of energy. It has been estimated, for example, that 10% of the oxygen consumption of a walking fly is devoted to phototransduction (Laughlin, de Ruyter van Steveninck, & Anderson, 1998). It therefore makes sense for eyes to be no larger than strictly necessary given the visual requirements of their host. Once the eyes have achieved the level of resolution required by their host in order to catch prey, avoid predators, and so on, pressures on energy consumption and cranial real estate limit further increases in eye size. Nocturnal and deep-sea dwelling animals have the largest eyes, in the interests of maximizing sensitivity at low levels of ambient illumination. Deep-sea squid possess the largest eyes of all, with a diameter of 40 cm (Land & Nilsson, 2002).

### *Rods versus cones*

The relatively constant spacing of rods and cones combined (Figure 6.10) might lead one to expect that our ability to resolve detail is also constant across the retina. However, as mentioned earlier, rods and cones operate at different light levels, with rods operating at low light levels and cones operating at high light levels. The

differing distributions of rods and cones aim to strike a balance between maximizing resolution while retaining sensitivity. In high illumination, resolution is very high (near the 50 cpd optical limit of the eye) but only in central vision, since this is where cone spacing is smallest. Outside the fovea, resolution drops to a value dictated by rod spacing—only 11 cpd. On the other hand, the fact that we have any sensitivity at all at low illumination levels is because of rods outside the fovea.

## EYE MOVEMENTS

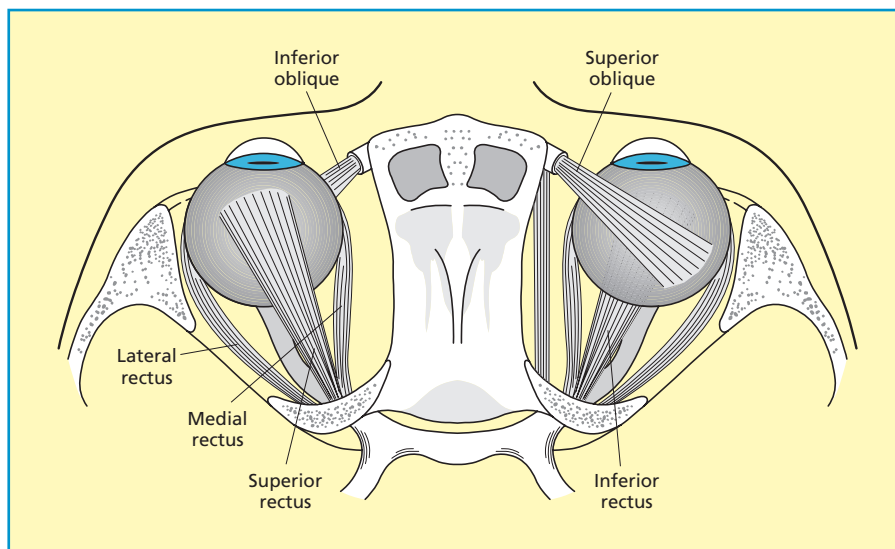
### The eye muscles

Humans have six extraocular muscles that allow the eyes to rotate quickly and accurately about any combination of the three possible axes. Figure 6.13 illustrates the attachment points of the muscles. They work as three antagonistic pairs. The medial and lateral recti control side-to-side rotation about the vertical axis (known as adduction and abduction); the superior and inferior recti control up-and-down rotation around the horizontal axis running from side to side across the head (known as elevation and depression); and the superior and inferior obliques control rotation about the visual axis itself around the horizontal axis running from front to back through the head (known as intorsion and extorsion).

### Types of eye movement

There are six types of large-scale eye movement, which can be categorized in terms of whether they are voluntary (under conscious control) or involuntary (under reflex control), and whether they are *conjugate* or *disjunctive*. The latter classification relates to how the two eyes move together.

In conjugate movements, the two eyes move by the same amount and in the same direction (e.g., both eyes turn to the left). In disjunctive movements, the two eyes move by the same amount but in opposite directions (e.g., the eyes both turn inwards towards the nose, so that one becomes cross-eyed).



**FIGURE 6.13**  
The extraocular muscles. Six muscles working in three pairs allow each eye to rotate in its socket about the three possible axes (based on Walls, 1963).

**TABLE 6.2** Classification of eye movements

	Conjugate movement	Disjunctive movement
Voluntary	Saccade Pursuit	Convergence Divergence
Involuntary	Vestibulo-ocular Optokinetic	

Table 6.2 categorizes the six different types of large-scale movement according to the two classifications:

- **Saccades** are rapid, voluntary shifts in eye position between steady fixations, which typically last only 45 ms or less. Saccade means “jerk” in French.
- Voluntary *pursuit* movements are engaged when the eyes lock on to a moving target and track it as it moves across the visual field. It is impossible to initiate smooth pursuit movements without having a target to track.
- Vergence eye movements can be divided into *convergent* movements in which the visual axes of the two eyes move further away from parallel (becoming more cross-eyed), and *divergent* movements in which the visual axes of the eyes move towards parallel (becoming less cross-eyed).
- *Vestibulo-ocular* movements are triggered by signals generated in the vestibular system in response to head acceleration or deceleration. These movements were considered in detail in Chapter 3.
- *Optokinetic nystagmus* is triggered by image motion. It consists of an alternating series of saccadic and smooth pursuit movements. Optokinetic nystagmus is easily experienced when looking sideways out of a moving train or car. Your eyes involuntarily latch onto a stationary point in the scene outside, track it back smoothly for a short distance, and then flick or saccade forward to latch onto another stationary point.

In addition to the large-scale movements, the eyes also engage in small, rapid, involuntary movements known as microsaccades.

## Why do the eyes move?

Microsaccades seem to be essential for refreshing visual responses, perhaps preventing adaptation to unchanging stimulation. When the retinal image is perfectly stabilized visual sensations disappear entirely (Heckenmueller, 1965). Turning to large-scale movements, there are two general reasons why it is useful to have mobile eyes—preservation of spatial resolution, and binocular registration.

### KEY TERM

#### Saccade

The rapid, jerky eye movement used to shift gaze direction.

### Spatial resolution

An immobile eye would be prone to poor spatial resolution partly because of variation in acuity across the retina and partly because of image motion.

**Acuity variation** As we saw in the previous section, the ability of the retina to resolve fine spatial detail varies with retinal location and with illumination level. Cones operate only in bright conditions, so resolution is much higher near the visual axis in the fovea than elsewhere on the retina. Eye movements allow the most acute portion of the retina to be brought to bear on a particular region of interest in the visual field. For this reason humans tend to adopt a fixate–saccade strategy. Short periods of fixation, typically lasting 300 ms, alternate with saccades to ensure that the eyes are always directed at the center of current interest. It seems that relatively little specific detail about the content of the visual scene is stored in the visual system from one saccade to the next, though more general information may be retained. This explains why saccades occur so frequently—if detailed information is required, the eye simply executes a saccade to acquire it.

**Image motion** Any movement of the image across the retina degrades the quality of the information provided by photoreceptors, because photoreceptor responses are relatively slow. Figure 6.14 shows the time course of responses in photoreceptors to a brief flash of light. It can take a tenth of a second or more for receptor response to reach its peak, and each response lasts at least 100 ms even for very brief flashes. Imagine that you are fixating steadily on a stationary point as a person walks across your field of view at a distance of 10 meters (about 33 feet). The image of the person will move across your retina at a speed of  $8^\circ \text{ s}^{-1}$ , passing over photoreceptors at a rate of one every 1.25 ms (assuming a walking speed of 5 kph; i.e., 3 mph, or  $140 \text{ cm s}^{-1}$ ). At this speed the image of the person will not dwell on each photoreceptor long enough for that receptor to reach its maximum response before the image moves on—there will be a reduction in effective contrast. Since each photoreceptor’s response lasts tens of milliseconds, at any one instant in time a whole array of receptors will be responding. Receptors that were passed over many milliseconds ago will still be responding when new responses are just building in other receptors. Consequently, the image of the moving figure will be spread over many receptors, an effect known as **motion blur**. The deleterious effects of image motion can be overcome by moving the eyes to compensate for the movement and stabilize the position of the image on the retina. Voluntary pursuit movements and optokinetic nystagmus keep the center of interest—a moving object—stationary on the retina (at the cost of blurring and contrast reduction in the background). Vestibulo-ocular movements stabilize the retinal image of the stationary world during head movements.

Saccadic eye movements themselves generate motion of the image across the retina. Chapter 11 on motion perception contains a discussion of why we are not aware of this motion.

### Binocular registration

We have already seen that in order to maximize acuity each eye must be positioned so that the center of interest in the image is projected onto the fovea. The eyes are necessarily located a short distance apart in the head. This means that if both eyes are to engage in foveal fixation on the same point in the world, their optical axes must be made to converge using vergence eye movements. The degree of convergence depends on viewing distance. Points very close to the observer require large convergence angles, while very distant points require extremely small convergence angles.

Even when converged to fixate on the same object, the two eyes receive slightly different views of the world, because of their different positions in the head. These slight differences provide a very powerful visual depth cue, discussed in detail in Chapter 10, which also contains more information about convergence.

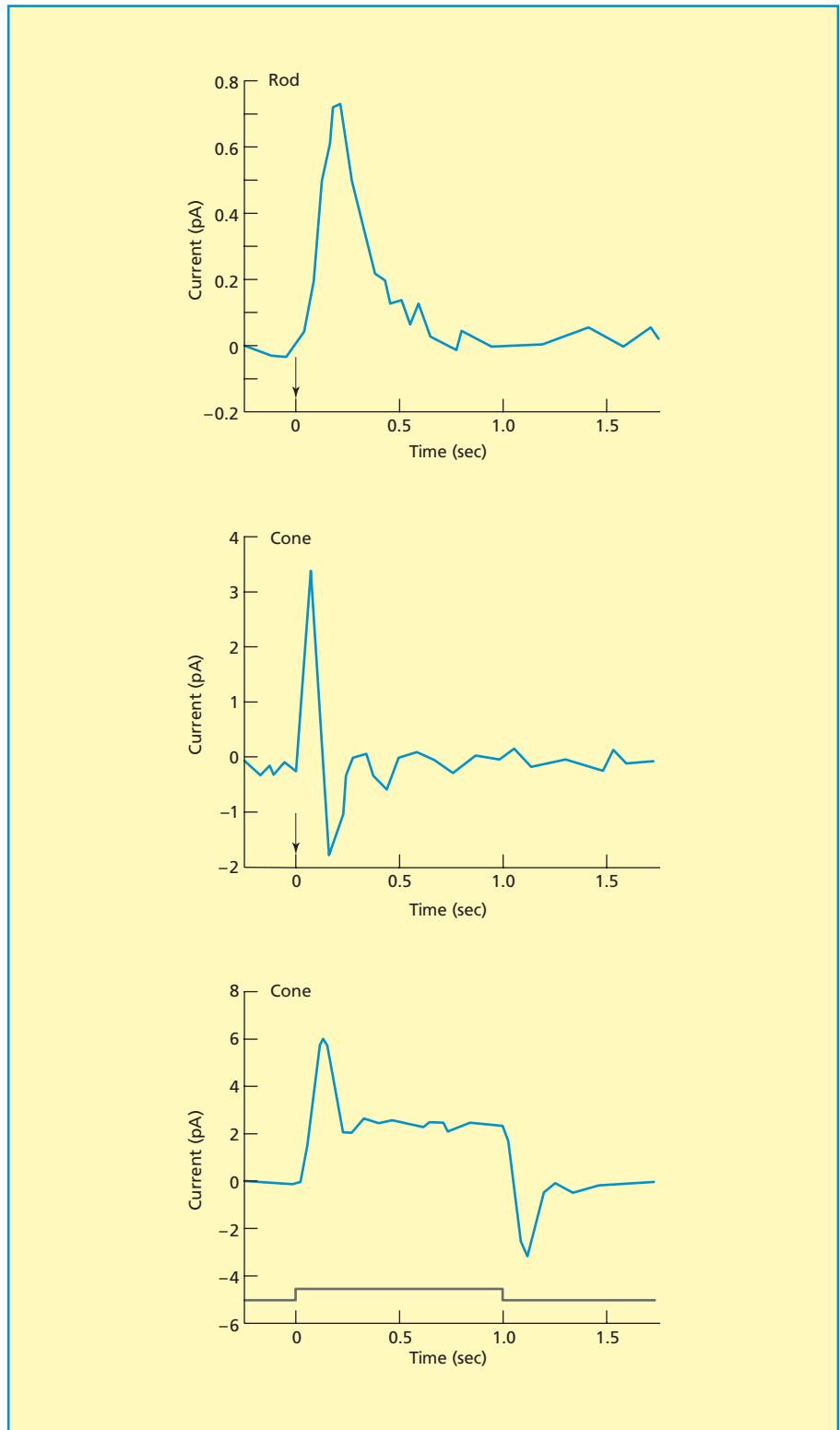
#### KEY TERM

##### Motion blur

Smearing in an image caused by movement of an object relative to the imaging surface.

**FIGURE 6.14**

Time course of photoreceptor responses to a brief, dim flash of light (top two traces), and a 1-second pulse of light (bottom trace) (re-plotted from recordings in macaque monkey photoreceptors reported by Schnapf & Baylor, 1987).



## CHAPTER SUMMARY

### LIGHT

Light is a form of energy that can be described as both a ray, a wave, and a stream of particles:

- The particle or quantal nature of light is important for understanding how light is emitted and absorbed, especially at low intensities.
- Ray properties are useful for understanding large-scale properties of light, including how it is refracted during transmission through optical devices.
- Wave properties are useful for understanding much finer scale effects such as diffraction.

Three important aspects of light as a stimulus for vision are:

- Intensity (number of quanta emitted per second).
- Contrast (ratio of the lightest to the darkest parts of an image).
- Wavelength (emission spectra of light sources, and reflectance functions of object surfaces).

### THE EYE

- Humans have single-chambered eyes. The cornea and lens refract incoming rays to form an image on the light-sensitive inner surface of the eye (the retina). Two thirds of the optical power of the eye is provided by the cornea.
- Variation in lens shape allows the eye to adjust its optical power to maintain a focused image of objects at different distances.
- Photoreceptor cells called rods and cones catch incoming photons and generate electrical currents that are transmitted through the network of neurons in the retina to the optic nerve.
- The optical properties of the photoreceptors (width, length, and distribution) place fundamental limits on the information transmitted up the optic nerve.
- The structure of the eye represents a compromise between properties that maximize spatial resolution and sensitivity to light.
- Eye movements are mediated by six extraocular muscles. Their functions are to maintain spatial resolution in the face of image movement across the retina, and to allow binocular registration of objects seen through both eyes.

## TUTORIALS

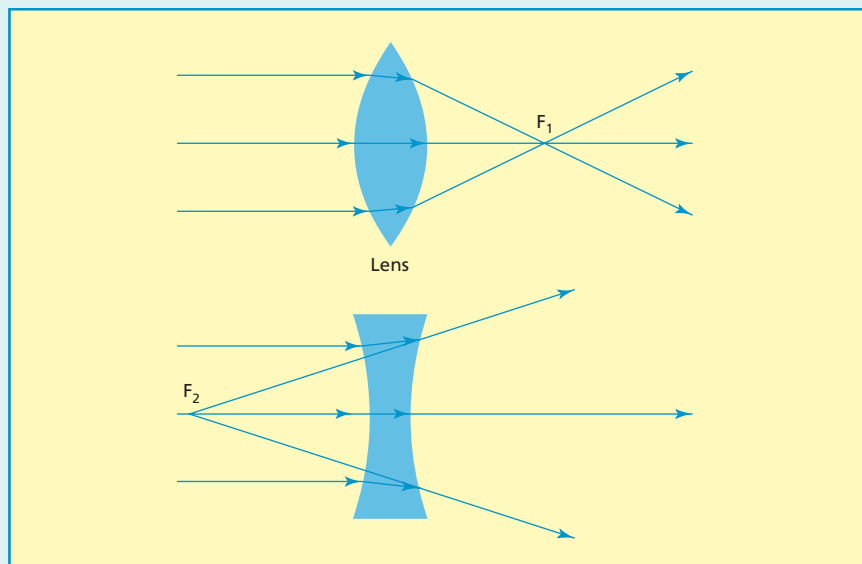
## OPTICS

## Lenses

The surface of an illuminated or self-luminous object can be regarded as a large collection of point sources. Rays emanate from each point radially in all directions. Figure 6.1 (p. 160) shows one such point, placed in the vicinity of a lens. Hecht (2002) defines a lens as “a refracting device that reconfigures a transmitted energy distribution” (p. 150). Some portion of the rays emanating from the point passes through the lens. In the case of a convex or converging lens, the bundle of rays from a far object converges on a point some distance behind the lens, known as the focal point ( $F_1$  at the top of Figure 6.15). A *real image* of the point would be formed if an imaging surface were placed at the focal point, to form a focal plane. In the case of a concave or diverging lens, the bundle of rays diverges on leaving the lens, as if emanating from a point in front of the lens ( $F_2$  in Figure 6.15). No image would appear on a screen placed at focal point  $F_2$ , since it is just a projection from the path of the diverging rays, so the image at  $F_2$  is known as a *virtual image*. The distance of the focal point from the center of the lens is known as the *focal length*,  $f$ , of the lens. The power of a lens is often expressed in terms of the reciprocal of focal length ( $1/f$ ). If  $f$  is expressed in meters, then power is measured in *diopters* (D).

**FIGURE 6.15**

Converging and diverging lenses. Top: A converging lens forms a real image of an object at its focal point ( $F_1$ ). An imaging surface placed at this point would show an image of the object. Bottom: In a diverging lens, rays emanate as if from an object positioned at focal point  $F_2$ . The image at  $F_2$  is known as a virtual image, since no image would appear on a surface placed at  $F_2$  (the rays do not actually reach  $F_2$ ).

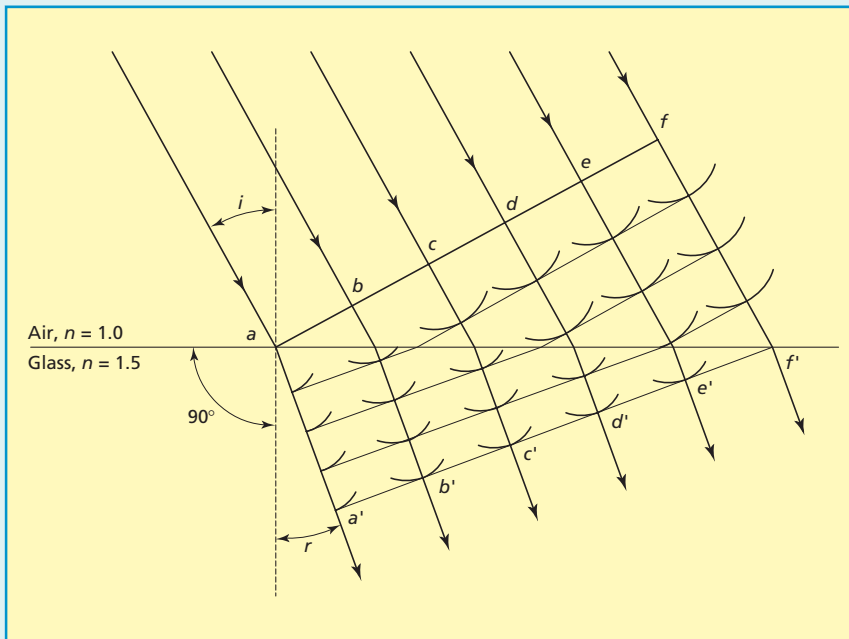


## Refraction

Refraction is the principle underlying the formation of images by lenses. As mentioned earlier in the chapter, the effective speed with which a light wavefront passes through a medium may be retarded (even though individual quanta always travel at the speed of light), because of interference between the original wave and waves produced by forward scattering. An important consequence of the retardation of light during transmission through a medium is *refraction*, a change in the direction of the path of light rays as they enter a transmitting medium obliquely (see Figure 6.16). Refraction occurs because the retardation of the wavefront skews its direction of travel as it enters the medium, similar to the way a moving vehicle's direction would be skewed if one front wheel left the road and entered gravel at the roadside. Imagine that rays *a* and *f* in Figure 6.16 were the wheel tracks of a vehicle as it left the road (air), and entered gravel (glass). Wheels in track *a* would reach the gravel and begin slowing down before the wheels in track *f*. As a result, the direction of the vehicle's travel would be skewed towards the slow side of the vehicle.

Media that transmit light have an *index of refraction*, which defines the extent to which a light wavefront is retarded during transmission. The index of refraction, *n*, is defined as follows:

$$n = c / v$$



**FIGURE 6.16**

Refraction. A wavefront containing the bundle of rays *a–f* is shown striking a glass surface. The wavefront is retarded as it enters the glass. Since waves in one part of the wavefront (*a*) are retarded before waves at other parts (e.g., *f*) have reached the glass, the direction of the wavefront is skewed once it enters the glass. The angle of each refracted ray (*r*) differs from the angle of each incident ray (*i*) by an amount that depends on the refractive indices of air and glass.

where  $c$  is the speed of light in a vacuum,  $v$  is its speed in the medium. Air has a refractive index  $n$  of 1.00029. For water  $n$  equals 1.333, for glass  $n$  equals approximately 1.5, and for the cornea (outermost surface of the eye)  $n$  equals 1.376. The degree to which light rays are deflected or refracted as they pass from one medium into another depends on the refractive index of each medium. The angle of refraction is defined in Snell's Law:

$$\sin i / \sin r = n_2 / n_1$$

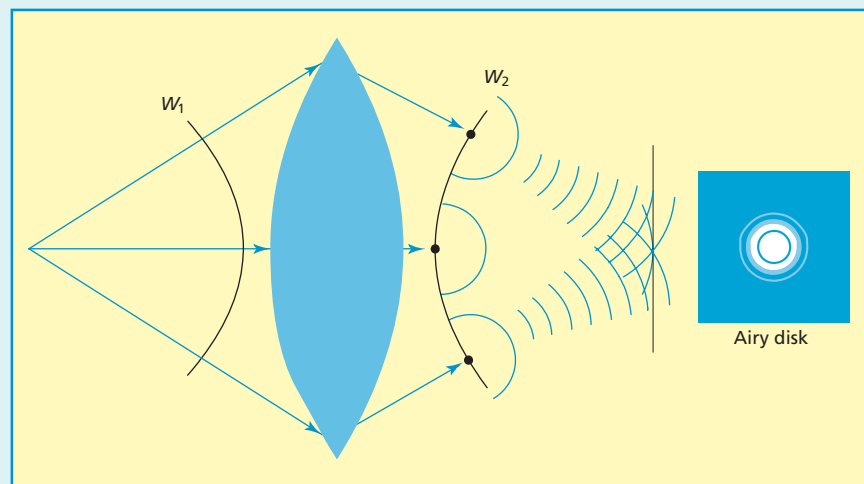
where  $\sin i$  is the angle of the incident light ray as it strikes the interface between medium 1 and medium 2,  $\sin r$  is the angle of the refracted light ray traveling through medium 2, and  $n_2, n_1$  are the indices of refraction of the two media (see Figure 6.16). The angle through which light rays are refracted on entering a given medium is higher for media with larger refractive indices.

### Airy disk

According to ray or geometric optics, the real image of the point source in Figure 6.1 should itself be a point. However, images formed by actual lenses never conform to this ideal. Even in the best lenses, the image of a point is always slightly blurred. To understand why this is so, we must consider image formation in terms of wave or physical optics rather than geometrical optics. Light from a point strikes the lens as a wavefront, shown as  $W_1$  in Figure 6.17 (rays are lines at right-angles to the wavefront).

The part of the wavefront passing through the center of the lens is delayed more than the part passing through the edge of the lens,

**FIGURE 6.17**  
Formation of the Airy disk. The wavefront ( $W_1$ ) emanating from a point is curved in an arc centered on the point. After this wavefront has passed through a lens, it is curved in an arc centered on the focal point of the lens ( $W_2$ ). Each point on a wavefront can be considered as the source of new wavefronts. Three points are shown on  $W_2$ . As these wavefronts interact when they reach the focal point, constructive and destructive interference produces a central bright disk (the Airy disk) surrounded by dimmer rings.



because the lens is thinner at its edges. Consequently, the wavefront that emerges from the lens is curved in an arc centered on the focal point ( $W_2$  in Figure 6.17). As the various parts of the wavefront meet at the focal point, they interfere to create an interference pattern of the same kind as that observed by Thomas Young. The pattern has a central bright spot, known as the **Airy disk**, surrounded by an alternating series of faint dark and bright rings. Figure 6.17 illustrates how interference produces the Airy disk. Each point on the wavefront emanating from the lens ( $W_2$  in the figure) can be considered as the source of a new wavefront. Three such wavefronts are shown in the figure. Just as in the case of Young's double slit experiment (see Figure 6.2), when these different wavefronts cross they interact to either cancel out or augment each other. All of the wavefronts combine constructively at the focal point to create a bright spot, but alternating destructive and constructive interference creates a series of rings surrounding this spot.

Optical systems, including eyes, usually have a circular aperture placed between the light source and the lens in order to control light intensity and depth of field. The radius of the Airy disk depends on the diameter of the aperture, according to the following equation:

$$r \approx 1.22 \cdot f\lambda/D$$

where  $r$  is the radius of the disk (radius to the first dark ring),  $f$  is focal length,  $D$  is aperture diameter, and  $\lambda$  is the wavelength of the light (all measures in mm). The width of the Airy disk is inversely proportional to aperture diameter—wider apertures create smaller disks. You may be able to understand why this is so from inspection of Figure 6.17. An aperture placed in front of the lens limits the size of the wavefront emanating from the lens. A narrow aperture, for example, would remove the more peripheral (top and bottom) wavefronts and so broaden the interference pattern at the focal point.

Figure 6.18 plots the intensity of the retinal image created by a very thin line, at two different pupil diameters. The dotted line is the **linespread** expected on the basis of diffraction effects alone. The solid line is the actual image measured by Campbell and Gubisch (1966). At the narrower pupil diameter, the actual linespread is very close to that predicted by diffraction—the image is said to be *diffraction-limited*. At the wider pupil diameter, diffraction effects predict a narrower spread, according to the equation above. Actual linespread at wider pupil diameters is much worse than that predicted by diffraction—optical imperfections play a much greater role in determining image quality. Small pupil diameters are therefore optimal for preserving image quality.

## KEY TERMS

### Airy disk

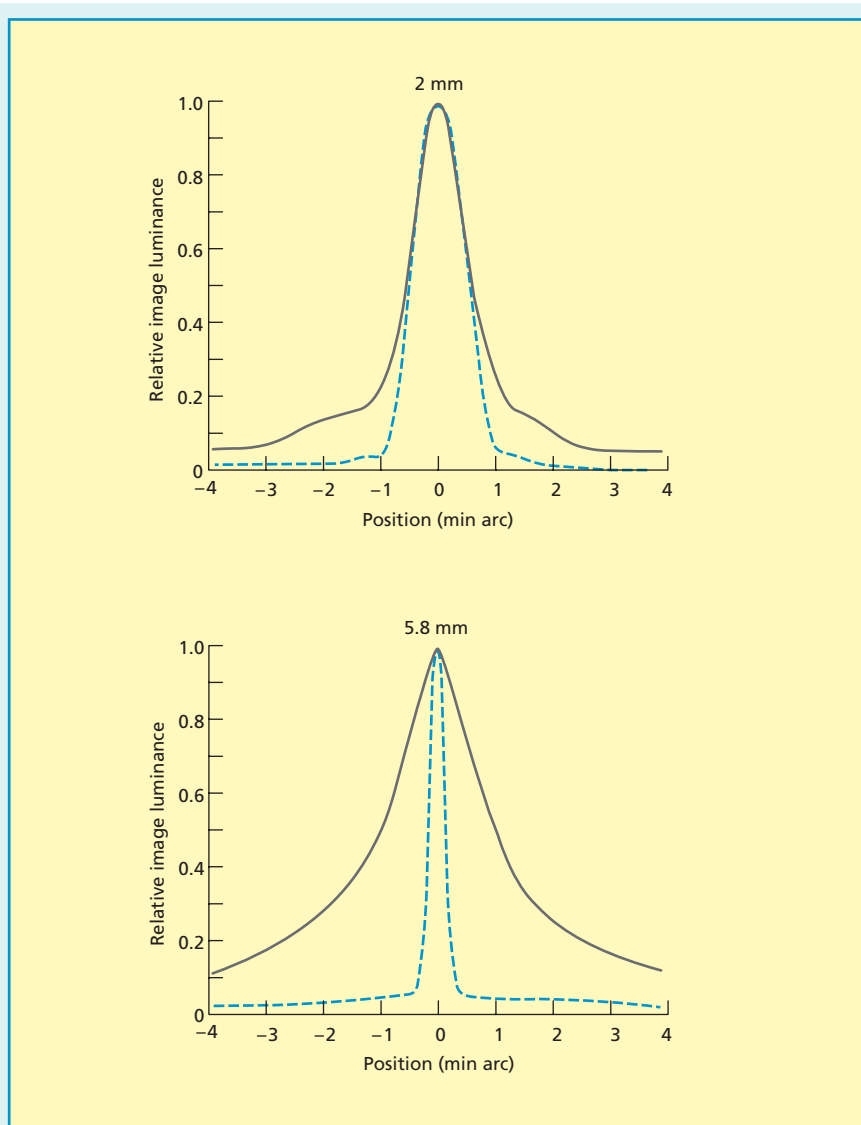
The image of a point light source created by an optical system; it contains a bright central spot surrounded by several faint rings.

### Linespread function

The image (or a mathematical function describing the image) of a very thin line created by an optical system.

**FIGURE 6.18**

Linespread functions. These functions plot the luminance profile across the retinal image formed by a thin bright line. The functions on the top relate to a pupil diameter of 2.0 mm, and the functions on the bottom relate to a pupil diameter of 5.8 mm. The solid functions show the actual luminance profile of the line. The broken functions show the profiles predicted on the basis of diffraction effects illustrated in Figure 6.17. The difference between the solid and broken functions can be attributed to aberrations of the kind shown in Figure 6.19, which become more severe as pupil diameter increases (re-plotted from Campbell & Gubisch, 1966).

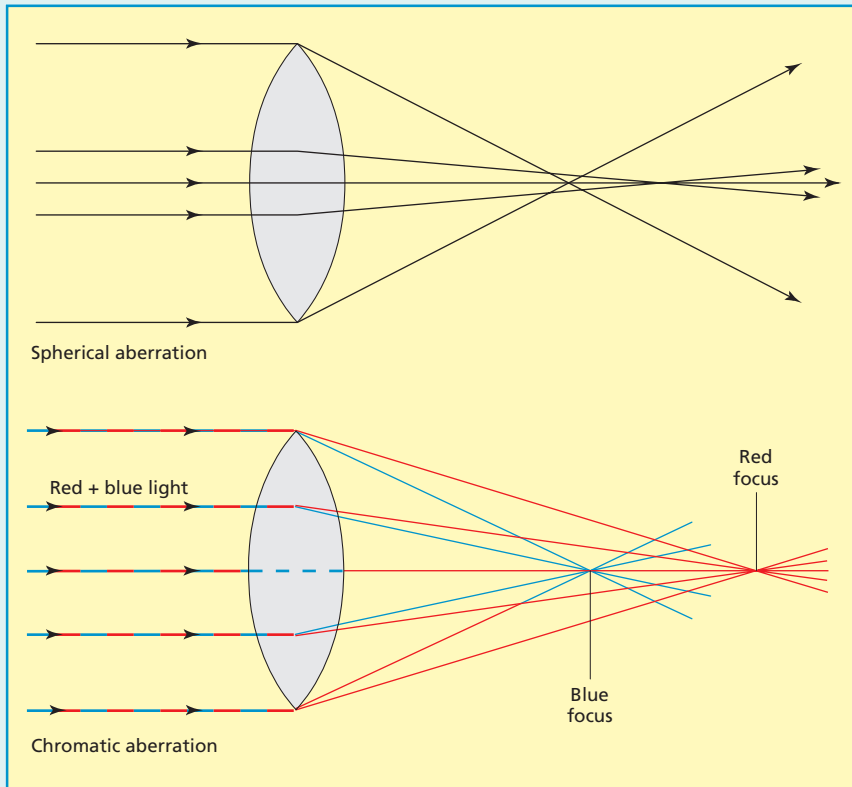


## Aberrations

The two most significant optical imperfections that affect image quality are spherical aberration and chromatic aberration.

### *Spherical aberration*

A lens with a spherical surface will not bring all rays to focus at the same point. Peripheral rays are refracted more than central rays (see top of Figure 6.19), so the image of a point will be a blurred circle. One solution to this problem is to use an appropriately nonspherical

**FIGURE 6.19**

Lens aberrations. Top: Spherical aberration. Light rays passing through the lens near its center come into focus at a further distance than rays that pass through the lens near its edges. Consequently, an imaging surface placed at either distance will reveal a blurred image. Bottom: Chromatic aberration. Light rays at longer (red) wavelengths come into focus at a further distance from the lens than rays at short (blue) wavelengths. Hence an imaging surface placed at a particular distance will show color fringes from out-of-focus wavelengths.

surface. The surface of the human cornea has a hyperbolic shape for this reason. A second solution, also adopted in human and other eyes, is to vary the refractive index of the lens material, adjusting the angle of refraction across the lens to compensate for the focusing error. This solution requires that the lens has a gradient of refractive index from high in the center to low at the periphery. Even after such measures are taken to avoid spherical aberration, slight deviations from a perfect hyperbolic shape, or refractive index, will introduce some degree of blurring in the image.

### *Chromatic aberration*

Chromatic aberration arises from the manner in which the wavefront emanating from a light source is retarded during its passage through a refracting medium. The degree to which the wavefront is retarded varies with frequency, because the retardation is a result of interference between the original wave and forward scattered waves. Shorter wavelengths are retarded more than longer wavelengths. Since refraction (a change in the direction of the path of light rays as they enter a transmitting medium obliquely; refer back to p. 185) depends

on retardation, the angle through which a light ray is refracted depends on its frequency. Shorter (violet) wavelengths are deflected more than longer (red) wavelengths. If the refracting device is a prism, then white light (composed of many wavelengths) will be dispersed into a rainbow spectrum of colors. If the refracting device is a lens, then each different wavelength will have a different focal point (see bottom of Figure 6.19). The image of light from a white point will be a blurred circle of colored fringes. Cameras attempt to compensate for this effect by combining two lenses of different material and different shape, so that their aberrations cancel out. Eyes attempt to deal with the problem by reducing sensitivity to wavelengths at the short end of the visible spectrum.

### Lens equations

Lens equations allow us to calculate the size and location of the image produced by a lens. For a thin lens, the distance ( $d_i$ ) of the image from the focal plane depends on the distance of the object ( $d_o$ ), as defined in the Newtonian lens equation (which first appeared in Isaac Newton's *Opticks* in 1704):

$$d_i = f^2 / d_o$$

For an object very far away from the lens ( $d_o$  essentially infinite),  $d_i$  is effectively zero, so the image falls in the focal plane of the lens. As the object approaches the lens,  $d_i$  grows progressively because the point of focus falls beyond the focal plane of the lens. An imaging surface fixed in position at the focal plane would render a blurred image of the object. In order to maintain a focused image, one of two things must happen. The imaging surface could be moved back away from the lens until it coincides with the point of focus. This is the solution used in many cameras. Alternatively, the power (focal length) of the lens could be adjusted to maintain focus on a fixed imaged plane. As objects move closer to the lens, its power must be increased to maintain focus. This is the solution adopted in human eyes.

The size of the image,  $H_i$ , is an important consideration for eyes. The following equations specify image height:

$$H_i / H_o = f / d_o, \text{ or}$$

$$H_i = H_o \cdot (f / d_o)$$

Thus, for a given size of object (i.e.,  $H_o$  fixed), at a given distance away (i.e.,  $d_o$  fixed), the size of the image scales directly with focal length  $f$ . Lenses with small focal lengths project smaller images than those with long focal lengths. The human eye has a focal length of

approximately 16.77 mm (59.6 D, see Land & Nilsson, 2002). So a person 1.8 m (6 ft) tall standing 15 m away would project an image in your eye that was 2 mm tall. The ability of an eye to resolve fine detail is partly governed by the size of the image projected by the lens, so animals with smaller eyes are inherently limited in their ability to resolve detail.

## MEASURING LIGHT INTENSITY

Light intensity can be measured according to two different systems, the *radiometric* system and the *photometric* system.

### The radiometric system

The radiometric system for measuring light intensity uses physical energy units that can be traced back to photons. Measures fall into four categories, as shown in the left-hand column of Table 6.3.

#### Total radiant energy

The total energy emitted by a source, also called *radiant energy* or *radiant flux*, is measured in watts. One watt corresponds approximately to  $10^{18}$  photons at a wavelength of 555 nm.

**TABLE 6.3** Photometric and radiometric measures of light intensity

Measure	Radiometric term	Radiometric unit	Photometric term	Photometric unit
Total energy emitted	Radiant energy or flux	Watts (W)	Luminous flux	Lumen (lm)
Energy from a point source	Radiant intensity	Watts per steradian ( $\text{W}\cdot\text{sr}^{-1}$ )	Luminous intensity	Lumens per steradian ( $\text{lm}\cdot\text{sr}^{-1}$ ), known as candelas (cd)
Energy from an extended source	Radiance	Watts per square meter per steradian ( $\text{W}\cdot\text{m}^{-2}\cdot\text{sr}^{-1}$ )	Luminance	Lumens per square meter per steradian ( $\text{lm}\cdot\text{m}^{-2}\cdot\text{sr}^{-1}$ ), or candelas per square meter ( $\text{cd}\cdot\text{m}^{-2}$ )
Energy received at a surface	Irradiance	Watts per square meter ( $\text{W}\cdot\text{m}^{-2}$ )	Illuminance	Lumens per square meter ( $\text{lm}\cdot\text{m}^{-2}$ ), known as lux

### *Radiant energy from a point source*

Energy emitted by a point source emanates in all directions, so it is usually more convenient to specify the range of directions over which the measured amount of energy is emitted. The convention is to consider a point source as positioned at the center of a sphere, and to divide the sphere into conical sectors. These sectors are measured in units of solid angle known as *steradians*. A complete sphere contains  $4\pi$  steradians. Energy emitted by a point source, also called *radiant intensity*, is therefore specified in watts per steradian.

### *Radiant energy from an extended source*

Most light-emitting sources, such as TV and computer screens, are extended over space. The appropriate measure of intensity for such sources must therefore specify the unit of surface area over which it applies. Energy emitted by an extended source, also called *radiance*, is therefore specified in watts per square meter per steradian.

### *Radiant energy received at a surface*

Energy falling on a receiving surface can simply be specified in terms of watts received per square meter of surface area, also called *irradiance*. The amount of energy received depends on both the energy emitted by the source and the distance between the receiving surface and the source. Irradiance  $E_e$  can be calculated from radiant intensity  $I_e$  using the following relation:

$$E_e = I_e / r^2$$

where  $r$  is the distance between the source and the receiving surface. Energy falling on the surface declines according to the square of the distance, known as the *inverse square law*. Each doubling in distance results in a fourfold decline in irradiance. This occurs because as distance increases, energy emanating over a particular range of directions falls on a progressively greater area of the receiving surface (the same effect occurs with sound intensity, for the same reasons). Strictly speaking, the inverse square law holds only for point sources. Practically speaking, it operates with an error of less than 1% if the diameter of the source is less than 1/10th of the distance to the receiving surface (Pokorny & Smith, 1986).

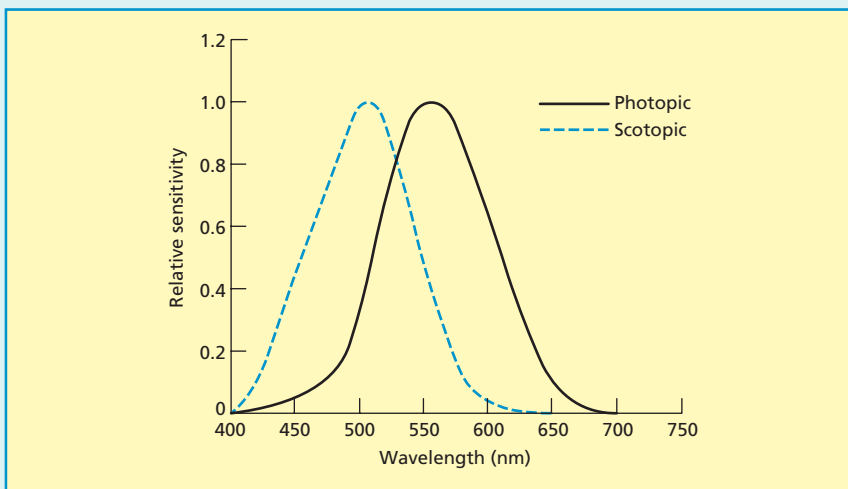
## **The photometric system**

Light was defined at the beginning of the chapter as energy that is capable of evoking a visual sensation. Since this definition includes a

reference to perception, purely physical radiometric measures of light are not sufficient. The majority of frequencies in the spectrum of radiant energy are invisible to humans, and even the visible frequencies vary in their effectiveness. Radiometric measures do not therefore accurately represent light intensity as a stimulus for vision. The photometric system of light measurement was developed by the Commission Internationale de l'Éclairage (CIE) to take account of human sensitivity to different wavelengths.

### Spectral luminous efficiency functions: $V(\lambda)$ and $V'(\lambda)$

The spectral *luminous efficiency function* specifies the relative sensitivity of the eye to different wavelengths. There are a number of ways to estimate the spectral luminous efficiency function, but in 1924 CIE adopted a standard function  $V(\lambda)$  based on the average of estimates obtained in a number of different laboratories. Most of the estimates were obtained using a technique known as heterochromatic flicker photometry, in which a fixed reference light alternates rapidly with a comparison light to create flicker. The observer adjusts the intensity of the comparison light to minimize or eliminate the sensation of flicker. In this way lights of many different wavelengths can be defined in terms of their sensory “efficiency” relative to a light of standard intensity. Figure 6.20 shows the luminous efficiency function for the standard observer defined by CIE in 1924. This function was obtained at high light levels, known as **photopic vision**. But relative sensitivity has been found to change slightly at low light levels. So in 1951 CIE introduced a second standard function  $V'(\lambda)$  appropriate for lower light levels, known as **scotopic vision**, also shown in Figure 6.20.



### KEY TERMS

#### Photopic vision

Vision at high illumination levels (above approximately  $4 \text{ cd} \cdot \text{m}^{-2}$ ), mediated by cone photoreceptors.

#### Scotopic vision

Vision at low illumination levels (below approximately  $1 \text{ cd} \cdot \text{m}^{-2}$ ), mediated by rod photoreceptors.

**FIGURE 6.20**

Photopic and scotopic luminous efficiency functions, as defined by CIE. These show the relative sensitivity to light of different wavelengths at high (photopic) illumination levels (solid line), and low (scotopic) illumination levels (broken line). The peak sensitivity of human vision shifts to shorter wavelengths under scotopic viewing conditions.

Units in the photometric system of measurement are based on corresponding units in the radiometric system, adjusted for the relative efficiencies defined in  $V(\lambda)$  and  $V'(\lambda)$ , as shown in Table 6.3.

### *Total luminous energy*

Total energy emitted, or *luminous flux*, is specified in *lumens*. One lumen is defined as the luminous flux of 1/683 W of monochromatic radiation at a wavelength of 555 nm (Makous, 1998), or approximately  $4 \times 10^{15}$  photons. The total luminous flux emitted by a source is calculated by multiplying the radiant flux at each wavelength by its luminous efficacy defined on the luminous efficiency function, and summing the products.

### *Luminous energy from a point source*

Energy emitted by a point source, or *luminous intensity*, is specified in lumens per steradian, also known as candelas (cd).

### *Luminous energy from an extended source*

Energy emitted by an extended source, or *luminance*, is specified in candelas per square meter (lumens per square meter per steradian), abbreviated to  $\text{cd} \cdot \text{m}^{-2}$ .

### *Luminous energy received at a surface*

Energy received at a surface, or *illuminance*, is specified in lux (lumens per square meter).

Photometric units are used very frequently in the research literature, the most commonly used unit being candelas per square meter ( $\text{cd} \cdot \text{m}^{-2}$ ), since this measures surface luminance of visual stimuli. Luminance is usually measured by pointing a telescopic spot photometer at the surface to be measured. The photometer is similar in size and shape to a small camcorder. The center of its viewfinder contains a small gray spot. A digital display on the photometer reports the luminance of the area covered by the spot, in  $\text{cd} \cdot \text{m}^{-2}$ .

### *Retinal illumination*

Even photometric luminance units may not provide a sufficiently precise measure of stimulus intensity in certain situations. Light enters the eye via the pupil, and variation in the diameter of the pupil can result in significant variation in the amount of light that falls on the retina of the eye (see earlier in the chapter for a discussion of the pupil). **Troland** units (td) specify retinal illumination, taking pupil size into account. One troland is defined as the retinal illumination that would result from

#### KEY TERM

##### **Troland**

A photometric unit specifying retinal illuminance, which takes into account pupil diameter.

viewing a surface at  $1 \text{ cd}\cdot\text{m}^{-2}$  through a pupil with an area of  $1 \text{ mm}^2$  (Makous, 1998). There are two limitations on the accuracy of troland measures. First, troland value does not make any correction for absorption by ocular media. Second, troland value does not take into account the part of the pupil through which light enters the eye. Light entering near the edge of the pupil is less effective than light entering near the center of the pupil, because of the optical properties of the retinal photoreceptors (light rays that strike the photoreceptors obliquely are less effective than rays that strike them straight on). This effect is known as the **Stiles-Crawford** effect.

**KEY TERM****Stiles-Crawford effect**

The variation in the sensitivity of the retina with the place of entry of light rays at the pupil.

# Subject index

Note: References in **bold** are to key terms; those in *italic* are to chapter summaries.

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