

# The Eye

# 9

## INTRODUCTION

## PROPERTIES OF LIGHT

LIGHT  
OPTICS

## THE STRUCTURE OF THE EYE

GROSS ANATOMY OF THE EYE

OPHTHALMOSCOPIC APPEARANCE OF THE EYE

- Box 9.1 *Of Special Interest: Demonstrating the Blind Regions of Your Eye*

CROSS-SECTIONAL ANATOMY OF THE EYE

- Box 9.2 *Of Special Interest: Eye Disorders*

## IMAGE FORMATION BY THE EYE

REFRACTION BY THE CORNEA

ACCOMMODATION BY THE LENS

- Box 9.3 *Of Special Interest: Vision Correction*

THE PUPILLARY LIGHT REFLEX

THE VISUAL FIELD

VISUAL ACUITY

## MICROSCOPIC ANATOMY OF THE RETINA

THE LAMINAR ORGANIZATION OF THE RETINA

PHOTORECEPTOR STRUCTURE

REGIONAL DIFFERENCES IN RETINAL STRUCTURE

## PHOTOTRANSDUCTION

PHOTOTRANSDUCTION IN RODS

PHOTOTRANSDUCTION IN CONES

*Color Detection*

- Box 9.4 *Of Special Interest: The Genetics of Color Vision*

DARK AND LIGHT ADAPTATION

*Calcium's Role in Light Adaptation*

## RETINAL PROCESSING

- Box 9.5 *Path of Discovery: A Glimpse into the Retina*, by John Dowling

TRANSFORMATIONS IN THE OUTER PLEXIFORM LAYER

*Bipolar Cell Receptive Fields*

## RETINAL OUTPUT

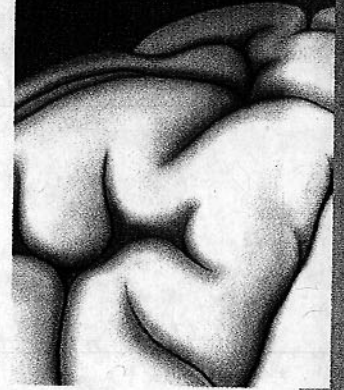
GANGLION CELL RECEPTIVE FIELDS

TYPES OF GANGLION CELLS

*Color-Opponent Ganglion Cells*

PARALLEL PROCESSING

## CONCLUDING REMARKS



## ▼ INTRODUCTION

**Vision** is remarkable—it lets us detect things as tiny and close as a mosquito on the tip of our nose, or as immense and far away as a galaxy near the fringes of the universe. Sensitivity to light enables animals, including humans, to detect prey, predators, and mates. Based on the light bounced into our eyes from objects around us, we somehow make sense of a complex world. While this process seems effortless, it is in reality extremely complicated. Indeed, it has proven quite difficult to make computer visual systems with even a small fraction of the capabilities of the human visual system.

Light is electromagnetic energy that is emitted in the form of waves. We live in a turbulent sea of electromagnetic radiation. Like any ocean, this sea has large waves and small waves, short wavelets and long rollers. The waves crash into objects and are absorbed, scattered, reflected, and bent. Because of the nature of electromagnetic waves and their interactions with the environment, the visual system can extract information about the world. This is a big job, and it requires a lot of neural machinery. However, the mastery of vision over the course of vertebrate evolution has had surprising rewards. It has provided new ways to communicate, given rise to brain mechanisms for predicting the trajectory of objects and events in time and space, allowed for new forms of mental imagery and abstraction, and led to the creation of a world of art. The significance of vision is perhaps best demonstrated by the fact that about half of the human cerebral cortex is involved with analyzing the visual world.

The mammalian visual system begins with the eye. At the back of the eye is the **retina**, which contains photoreceptors specialized to convert light energy into neural activity. The rest of the eye acts like a camera and forms crisp, clear images of the world on the retina. Like a camera, the eye automatically adjusts to differences in illumination and automatically focuses itself on objects of interest. The eye has some additional features not yet available on cameras, such as the ability to track moving objects (by eye movement) and the ability to keep its transparent surfaces clean (by tears and blinking).

While much of the eye functions like a camera, the retina is much more than film. In fact, as mentioned in Chapter 7, the retina is actually part of the brain. (Think about that the next time you look deeply into someone's eyes.) In a sense, each eye has two overlapping retinas: one specialized for low light levels that we encounter from dusk to dawn, and another specialized for higher light levels and for the detection of color, from sunrise to sunset. Regardless of the time of day, however, the output of the retina is not a faithful reproduction of the intensity of the light falling on it. Rather, the retina is specialized to detect *differences* in the intensity of light falling on different parts of it. Image processing is well under way in the retina, before any visual information reaches the rest of the brain.

Axons of retinal neurons are bundled into optic nerves, which distribute visual information (in the form of action potentials) to several brain structures that perform different functions. Some targets of the optic nerves are involved in regulating biological rhythms, which are synchronized with the light-dark daily cycle; others are involved in the control of eye position and optics. However, the first synaptic relay in the pathway that serves visual perception occurs in a cell group of the dorsal thalamus called the *lateral geniculate nucleus*, or *LGN*. From the LGN, visual information ascends to the cerebral cortex, where it is interpreted and remembered.

In this chapter, we explore the eye and the retina. We'll see how light carries information to our visual system, how the eye forms images on the retina, and how the retina converts light energy into neural signals that can

be used to extract information about luminance and color differences. In Chapter 10, we will pick up the visual pathway at the back of the eye and take it through the thalamus to the cerebral cortex.

## ▼ PROPERTIES OF LIGHT

The visual system uses light to form images of the world around us. Let's briefly review the physical properties of light and its interactions with the environment.

### Light

Electromagnetic radiation is all around us. It comes from innumerable sources, including radio antennas, mobile phones, X-ray machines, and the sun. Light is the electromagnetic radiation that is visible to our eyes. Electromagnetic radiation can be described as a wave of energy. Like any wave, electromagnetic radiation has a *wavelength*, the distance between successive peaks or troughs; a *frequency*, the number of waves per second; and an *amplitude*, the difference between wave trough and peak (Figure 9.1).

The energy content of electromagnetic radiation is proportional to its frequency. Radiation emitted at a high frequency (short wavelengths) has the highest energy content; examples are gamma radiation emitted by some radioactive materials and X-rays used for medical imaging, with wavelengths less than  $10^{-9}$  m ( $<1$  nm). Conversely, radiation emitted at lower frequencies (longer wavelengths) has less energy; examples are radar and radio waves, with wavelengths greater than 1 mm. Only a small part of the electromagnetic spectrum is detectable by our visual system; visible light consists of wavelengths of 400–700 nm (Figure 9.2). As first shown by Isaac Newton early in the eighteenth century, the mix of wavelengths in this range emitted by the sun appears to humans as white, whereas light of a single wavelength appears as one of the colors of the rainbow. It is interesting to note that a “hot” color like red or orange consists of light with a longer wavelength, and hence has less energy, than a “cool” color like blue or violet. Clearly, colors are themselves “colored” by the brain, based on our subjective experiences.

### Optics

In a vacuum, a wave of electromagnetic radiation will travel in a straight line and thus can be described as a *ray*. Light rays in our environment also

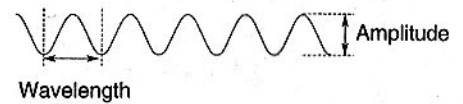


FIGURE 9.1  
Characteristics of electromagnetic radiation.

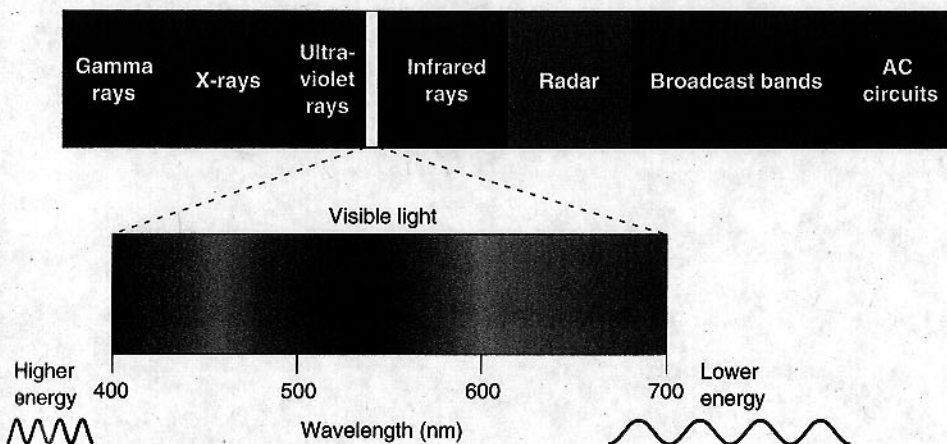
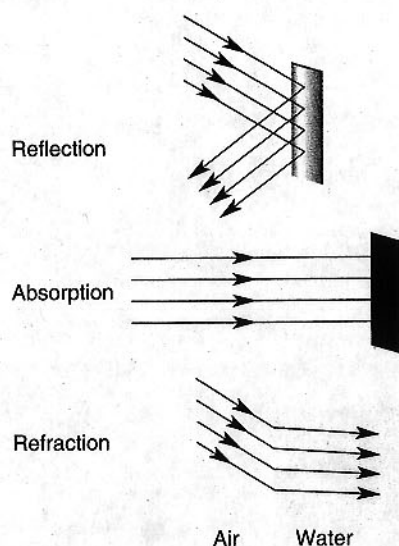


FIGURE 9.2  
The electromagnetic spectrum. Only electromagnetic radiation with wavelengths of 400–700 nm is visible to the naked human eye. Within this visible spectrum, different wavelengths appear as different colors.



**FIGURE 9.3**  
**Interactions between light and the environment.** Reflection and absorption determine what light enters the eye. Images are formed in the eye by refraction. In this example of light passing through air and then water, the light rays bend toward a line perpendicular to the air-water interface.

travel in straight lines until they interact with the atoms and molecules of the atmosphere and objects on the ground. These interactions include reflection, absorption, and refraction (Figure 9.3). The study of light rays and their interactions is called *optics*.

**Reflection** is the bouncing of light rays off a surface. The manner in which a ray of light is reflected depends on the angle at which it strikes the surface. A ray striking a mirror perpendicularly is reflected 180° back upon itself, a ray striking the mirror at a 45° angle is reflected 90°, and so on. Most of what we see is light that has been reflected off objects in our environment.

**Absorption** is the transfer of light energy to a particle or surface. You can feel this energy transfer on your skin on a sunny day, as visible light is absorbed and warms you up. Surfaces that appear black absorb the energy of all visible wavelengths. Some compounds absorb light energy only in a limited range of wavelengths, then reflect the remaining wavelengths. This property is the basis for the colored pigments of paints. For example, a blue pigment absorbs long wavelengths but reflects a range of short wavelengths centered on 430 nm that are perceived as blue. As we will see in a moment, light-sensitive photoreceptor cells in the retina contain pigments and use the energy absorbed from light to generate changes in membrane potential.

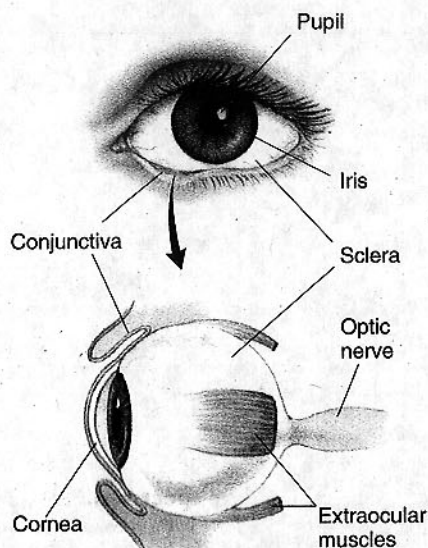
Images are formed in the eye by **refraction**, the bending of light rays that can occur when they travel from one transparent medium to another. Consider a ray of light passing from the air into a pool of water. If the ray strikes the water surface perpendicularly, it will pass through in a straight line. However, if light strikes the surface at an angle, it will bend toward a line that is perpendicular to the surface. This bending of light occurs because the speed of light differs in the two media; light passes through air more rapidly than through water. The greater the difference between the speed of light in the two media, the greater the angle of refraction. The transparent media in the eye bend light rays to form images on the retina.

## ▼ THE STRUCTURE OF THE EYE

The eye is an organ specialized for the detection, localization, and analysis of light. Here we introduce the structure of this remarkable organ in terms of its gross anatomy, ophthalmoscopic appearance, and cross-sectional anatomy.

### Gross Anatomy of the Eye

When you look into someone's eyes, what are you really looking at? The main structures are shown in Figure 9.4. The **pupil** is the opening that allows light to enter the eye and reach the retina; it appears dark because of the light-absorbing pigments in the retina. The pupil is surrounded by the **iris**, whose pigmentation provides what we call the eye's color. The iris contains two muscles that can vary the size of the pupil; one makes it smaller when it contracts, the other makes it larger. The pupil and iris are covered by the glassy transparent external surface of the eye, the **cornea**. The cornea is continuous with the **sclera**, the "white of the eye," which forms the tough wall of the eyeball. The eyeball sits in a bony eye socket in the skull, also called the eye's orbit. Inserted into the sclera are three pairs of **extraocular muscles**, which move the eyeball in the orbit. These muscles normally are not visible because they lie behind the **conjunctiva**, a membrane that folds back from the inside of the eyelids and attaches to the sclera. The **optic nerve**, carrying axons from the retina, exits the back of the eye, passes through the orbit, and reaches the base of the brain near the pituitary gland.



**FIGURE 9.4**  
**Gross anatomy of the human eye.**

## Ophthalmoscopic Appearance of the Eye

Another view of the eye is afforded by the ophthalmoscope, a device that enables one to peer into the eye through the pupil to the retina (Figure 9.5). The most obvious feature of the retina viewed through an ophthalmoscope is the blood vessels on its surface. These retinal vessels originate from a pale circular region called the **optic disk**, which is also where the optic nerve fibers exit the retina.

It is interesting to note that the sensation of light cannot occur at the optic disk because there are no photoreceptors here, nor can it occur where the large blood vessels exist because the vessels cast shadows on the retina. And yet, our perception of the visual world appears seamless. We are not aware of any holes in our field of vision because the brain fills in our perception of these areas. However, there are tricks by which we can demonstrate the "blind" retinal regions (Box 9.1).

At the middle of each retina is a darker-colored region with a yellowish hue. This is the **macula** (from the Latin word for "spot"), the part of the retina for central (as opposed to peripheral) vision. Besides its color, the macula is distinguished by the relative absence of large blood vessels. Notice in Figure 9.5 that the vessels arc from the optic disk to the macula; this is also the trajectory of the optic nerve fibers from the macula en route to the optic disk. The relative absence of large blood vessels in this region of the retina is one of the specializations that improves the quality of central vision. Another specialization of the central retina can sometimes be discerned with the ophthalmoscope: the **fovea**, a dark spot about 2 mm in diameter. The term is from the Latin for "pit," and the retina is thinner in the fovea than elsewhere. Because it marks the center of the retina, the fovea is a convenient anatomical reference point. Thus, the part of the retina that lies closer to the nose than the fovea is called **nasal**, the part that lies near the temple is called **temporal**, the part of the retina above the fovea is called **superior**, and that below it is called **inferior**.

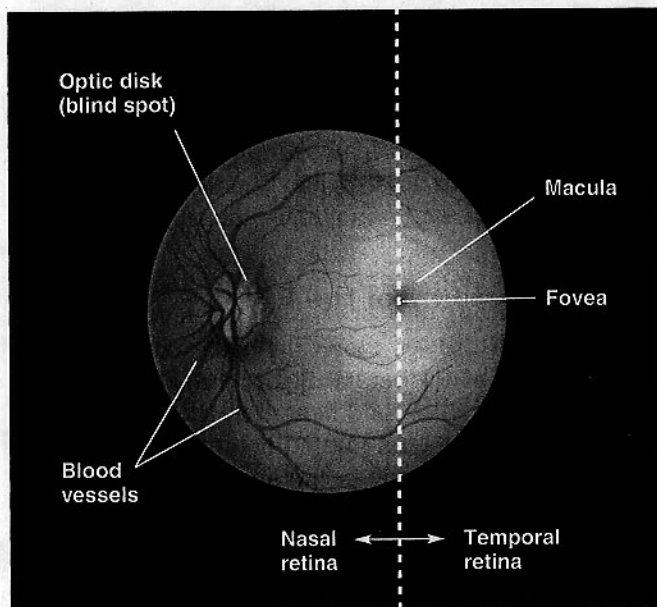


FIGURE 9.5

**The retina, viewed through an ophthalmoscope.** The dotted line through the fovea represents the demarcation between the side of the eye nearer the nose (nasal retina) and the side of the eye nearer the ear (temporal retina).

## Box 9.1



## OF SPECIAL INTEREST

## Demonstrating the Blind Regions of Your Eye

A look through an ophthalmoscope reveals that there is a sizable hole in the retina. The region where the optic nerve axons exit the eye and the retinal blood vessels enter the eye, the optic disk, is completely devoid of photoreceptors. Moreover, the blood vessels coursing across the retina are opaque and block the light from falling on photoreceptors beneath them. Although we normally don't notice them, these blind regions can be demonstrated. Look at Figure A. Hold the book about 1.5 ft away, close your right eye, and fixate on the cross with your left eye. Move the book (or your head) around slightly, and eventually you will find a position where the black circle disappears. At this position, the spot is imaged on the optic disk of the left eye. This region of visual space is called the *blind spot* for the left eye.

The blood vessels are a little tricky to demonstrate, but give this a try. Get a standard household flashlight. In a dark or dimly lit room, close your left eye (it helps to hold the eye closed with your finger so you can open your

right eye further). Look straight ahead with the open right eye, and shine the flashlight at an angle into the corner of the eye from the side. Jiggle the light back and forth, up and down. If you're lucky, you'll see an image of your own retinal blood vessels. This is possible because the illumination of the eye at this oblique angle causes the retinal blood vessels to cast long shadows on the adjacent regions of retina. For the shadows to be visible, they must be swept back and forth on the retina, hence the jiggling of the light.

If we have all these light-insensitive regions in the retina, why does the visual world appear uninterrupted and seamless? The answer is that mechanisms in the visual cortex appear to "fill in" the missing regions. Perceptual filling-in can be demonstrated with the stimulus shown in Figure B. Fixate on the cross with your left eye and move the book closer and farther from your eye. You'll find a distance at which you will see a continuous uninterrupted line. At this point, the space in the line is imaged on the blind spot, and your brain fills in the gap.



FIGURE A



FIGURE B



### Cross-Sectional Anatomy of the Eye

A cross-sectional view of the eye shows the path taken by light as it passes through the cornea toward the retina (Figure 9.6). The cornea lacks blood vessels and is nourished by the fluid behind it, the **aqueous humor**. This view reveals the transparent **lens** located behind the iris. The lens is suspended by ligaments (called zonule fibers) attached to the **ciliary muscles**, which are attached to the sclera and form a ring inside the eye. As we shall see, changes in the shape of the lens enable our eyes to adjust their focus to different viewing distances.

The lens also divides the interior of the eye into two compartments containing slightly different fluids. The aqueous humor is the watery fluid that lies between the cornea and the lens. The more viscous, jellylike **vitreous humor** lies between the lens and the retina; its pressure serves to keep the eyeball spherical.

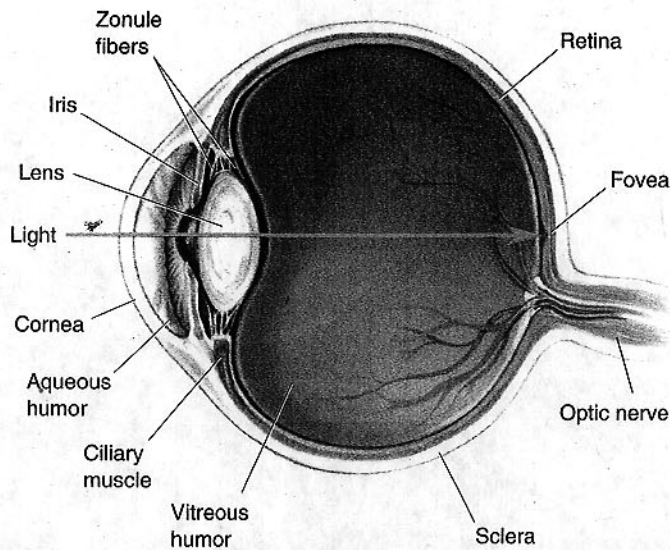


FIGURE 9.6

**The eye in cross section.** Structures at the front of the eye regulate the amount of light allowed in and refract the light onto the retina at the back.

Although the eyes do a remarkable job of delivering precise visual information to the rest of the brain, a variety of disorders can compromise this ability (Box 9.2).

## ▼ IMAGE FORMATION BY THE EYE

The eye collects the light rays emitted by or reflected off objects in the environment, and focuses them onto the retina to form images. Bringing objects into focus involves the combined refractive powers of the cornea and lens. You may be surprised to learn that the cornea, rather than the lens, is the site of most of the refractive power of the eyes.

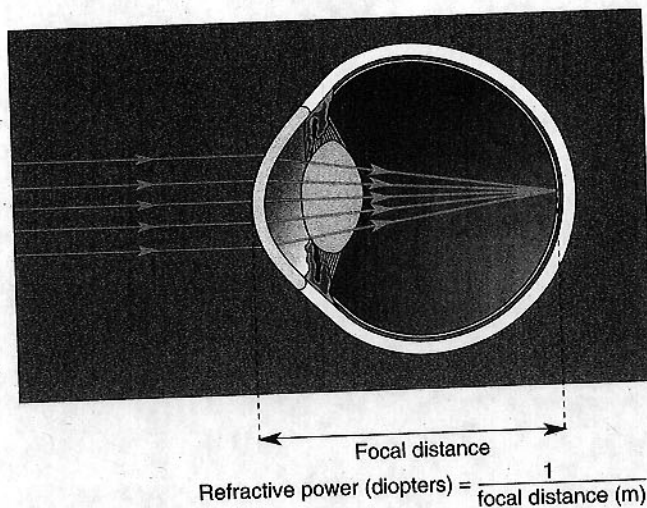
### Refraction by the Cornea

Consider the light emitted from a distant source, perhaps a bright star at night. We see the star as a point of light because the eye focuses the star's light to a point on the retina. The light rays striking the surface of the eye from a distant star are virtually parallel, so they must be bent by the process of refraction.

Recall that as light passes into a medium where its speed is slowed, it will bend toward a line that is perpendicular to the border, or interface, between the media (see Figure 9.3). This is precisely the situation as light strikes the cornea and passes from the air into the aqueous humor. As shown in Figure 9.7, the light rays that strike the curved surface of the cornea bend so that they converge on the back of the eye; those that enter the center of the eye pass straight to the retina. The distance from the refractive surface to the point where parallel light rays converge is called the *focal distance*. Focal distance depends on the curvature of the cornea—the tighter the curve, the shorter the focal distance. The equation in Figure 9.7 shows that the reciprocal of the focal distance in meters is a unit of measurement called the **diopter**. The cornea has a refractive power of about 42 diopters, which means that parallel light rays striking the corneal surface will be focused 0.024 m (2.4 cm) behind it, about the distance from cornea to retina. To get a sense of the large amount of refraction produced

FIGURE 9.7

**Refraction by the cornea.** The cornea must have sufficient refractive power, measured in diopters, to focus light on the retina at the back of the eye.



by the cornea, note that many prescription eyeglasses have a power of only a few diopters.

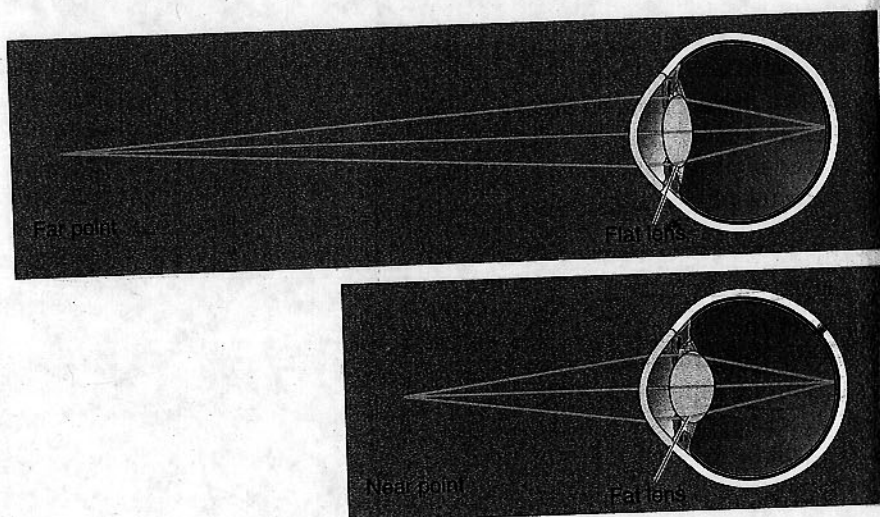
Remember that refractive power depends on the slowing of light at the air-cornea interface. If we replace air with a medium that passes light at about the same speed as the eye, the refractive power of the cornea will be eliminated. This is why things look blurry when you open your eyes underwater; the water-cornea interface has very little focusing power. A scuba mask restores the air-cornea interface and, consequently, the refractive power of the eye.

### Accommodation by the Lens

Although the cornea performs most of the eye's refraction, the lens also contributes another dozen or so diopters to the formation of a sharp image at a distant point. However, the lens is involved more importantly in forming crisp images of objects located closer than about 9 m from the eye. As objects approach, the light rays originating at a point can no longer be considered to be parallel. Rather, these rays diverge, and greater refractive power is required to bring them into focus on the retina. This additional focusing power is provided by changing the shape of the lens, a process called **accommodation** (Figure 9.8).

FIGURE 9.8

**Accommodation by the lens.** To focus the eye on a distant point, relatively little refraction is required, and it is provided by a flat lens. Near objects require greater refraction provided by a more spherical lens.



## Box 9.2



## OF SPECIAL INTEREST

## Eye Disorders

Once you know the basic structure of the eye, you can understand how a partial or complete loss of vision results from abnormalities in various components. For example, if there is an imbalance in the extraocular muscles of the two eyes, the eyes will point in different directions. Such a misalignment or lack of coordination between the two eyes is called *strabismus*, and there are two varieties. In *esotropia*, the directions of gaze of the two eyes cross, and the person is said to be cross-eyed. In *exotropia*, the directions of gaze diverge, and the person is said to be wall-eyed (Figure A). In most cases, strabismus of either type is congenital; it can and should be corrected during early childhood. Treatment usually involves the use of prismatic glasses or surgery to the extraocular muscles to realign the eyes. Without treatment, conflicting images are sent to the brain from the two eyes, degrading depth perception, and, more importantly, causing the person to suppress input from one eye. The dominant eye will be normal but the suppressed eye will become *amblyopic*, meaning that it has poor visual acuity. If medical intervention is delayed until adulthood, the condition cannot be corrected.

A common eye disorder among older adults is *cataract*, a clouding of the lens (Figure B). Many people over 65 years of age have some degree of cataract; if it significantly impairs vision, surgery is usually required. In a cataract operation, the lens is removed and replaced with an artificial plastic lens. Although the artificial lens cannot adjust its focus like the normal lens, it provides a clear image, and glasses can be used for near and far vision (see Box 9.3).

*Glaucoma*, a progressive loss of vision associated with elevated intraocular pressure, is a leading cause of blindness. Pressure in the aqueous humor plays a crucial role in maintaining the shape of the eye. As this pressure increases, the entire eye is stressed, ultimately damaging the relatively weak point where the optic nerve leaves the eye. The optic nerve axons are compressed, and vision is

gradually lost from the periphery inward. Unfortunately, by the time a person notices a loss of more central vision, the damage is advanced and a significant portion of the eye is permanently blind. For this reason, early detection and treatment with medication or surgery to reduce intraocular pressure are essential.

The light-sensitive retina at the back of the eye is the site of numerous disorders that pose a significant risk of blindness. You may have heard of a professional boxer having a *detached retina*. As the name implies, the retina pulls away from the underlying wall of the eye from a blow to the head or by shrinkage of the vitreous humor. Once the retina has started to detach, fluid from the vitreous space flows through small tears in the retina resulting from the trauma, thereby causing more of the retina to separate. Symptoms of retinal detachment include abnormal perception of shadows and flashes of light. Treatment often involves laser surgery to scar the edge of the retinal tear, thereby reattaching the retina to the back of the eye.

*Retinitis pigmentosa* is characterized by a progressive degeneration of the photoreceptors. The first sign is usually a loss of peripheral vision and night vision. Subsequently, total blindness may result. The cause of this disease is unknown. In some forms, it clearly has a strong genetic component, and more than 100 genes have been identified that can contain mutations leading to retinitis pigmentosa. There is currently no cure, but taking vitamin A may slow its progression.

In contrast to the tunnel vision typically experienced by patients with retinitis pigmentosa, people with *macular degeneration* lose only central vision. The condition is quite common, affecting more than 25% of all Americans over 65 years of age. While peripheral vision usually remains normal, the ability to read, watch television, and recognize faces is lost as central photoreceptors gradually deteriorate. Laser surgery can sometimes minimize further vision loss, but the disease currently has no known cure.



FIGURE A  
Exotropia. (Source: Newell, 1965, p. 330.)

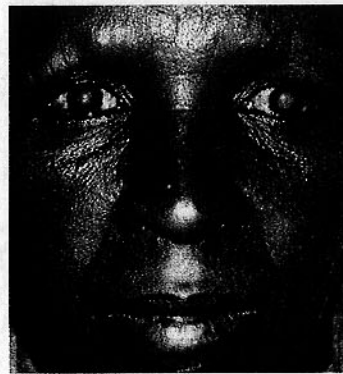


FIGURE B  
Cataract. (Source: Schwab, 1987, p. 22.)

## Box 9.3



## OF SPECIAL INTEREST

## Vision Correction

When the ciliary muscles are relaxed and the lens is flat, the eye is said to be *emmetropic* if parallel light rays from a distant point source are focused sharply on the back of the retina. (The word is from the Greek *emmetros*, “in proper measure,” and *ope*, “sight.”) Stated another way, the emmetropic eye focuses parallel light rays on the retina without the need for accommodation (Figure A).

Now consider what happens when the eyeball is too short from front to back (Figure B). The light rays are focused at some point *behind* the retina, and the image of a point of light is a blurry spot on the retina. This condition is known as *hyperopia*, or farsightedness, because the eye can focus on far objects but the lens cannot accommodate enough to form an image on near points. Farsightedness can be corrected by placing a convex glass or plastic lens in front of the eye (Figure C). The curved front edge of the lens, like the cornea, bends light toward the center of the retina. Also, as the light passes from glass into air as it exits the lens, the back of the lens also increases the refraction (light going from glass to air speeds up and is bent away from the perpendicular).

If the eyeball is too long rather than too short, parallel rays will converge before the retina, cross, and again be imaged on the retina as a blurry circle (Figure D). This condition is known as *myopia*, or nearsightedness. The amount of refraction provided by the cornea and lens is too great to focus distant objects. Thus, for the nearsighted eye to see distant points clearly, artificial concave lenses must be used to move the point image back onto the retina (Figure E).

Some eyes have irregularities such that the curvature and refraction in the horizontal and vertical planes is different. This condition is called *astigmatism*, and it can be corrected

by using an artificial lens that is curved more along one axis than others.

Even if you are fortunate enough to have perfectly shaped eyeballs and a symmetrical refractive system, you probably will not escape *presbyopia* (from the Greek meaning “old eye”). This condition is a hardening of the lens that accompanies the aging process and is thought to be explained by the fact that while new lens cells are generated throughout life, none are lost. The hardened lens is less elastic, leaving it unable to change shape and accommodate sufficiently to focus on both near and far objects. The correction for presbyopia, first introduced by Benjamin Franklin, is a bifocal lens. These lenses are concave on top to assist far vision and convex on the bottom to assist near vision.

In hyperopia and myopia, the amount of refraction provided by the cornea is either too little or too great for the length of the eyeball. But modern techniques can now change the amount of refraction the cornea provides. In *radial keratotomy*, a procedure to correct myopia, tiny incisions through the peripheral portion of the cornea relax and flatten the central cornea, thus reducing the amount of refraction and minimizing the myopia. The most recent techniques use lasers to reshape the cornea. In *photorefractive keratectomy* (PRK), a laser is used to reshape the outer surface of the cornea by vaporizing thin layers. In *laser in situ keratomileusis* (LASIK), a thin flap of the cornea is lifted so the laser can reshape the cornea from the inside. Nonsurgical methods are also being used to reshape the cornea. A person can be fitted with special retainer contact lenses or plastic corneal rings, which alter the shape of the cornea and correct refractive errors.

Recall that the ciliary muscle forms a ring around the lens. During accommodation, the ciliary muscle contracts and swells in size, thereby making the area inside the muscle smaller and decreasing the tension in the suspensory ligaments. Consequently, the lens becomes rounder and thicker because of its natural elasticity. This rounding increases the curvature of the lens surfaces, thereby increasing their refractive power. Conversely, relaxation of the ciliary muscle increases the tension in the suspensory ligaments, and the lens is stretched into a flatter shape.

The ability to accommodate changes with age. An infant's eyes can focus objects just beyond his or her nose, whereas many middle-aged adults cannot clearly see objects closer than about arm's length. Fortunately, artificial lenses can compensate for this and other defects of the eye's optics (Box 9.3).

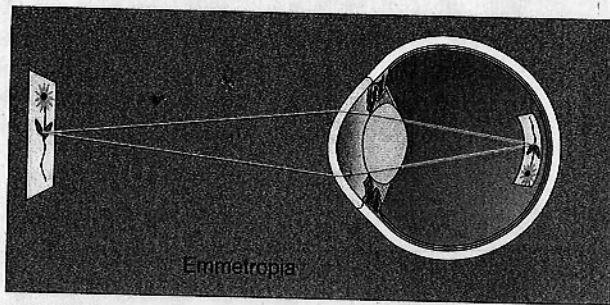


FIGURE A

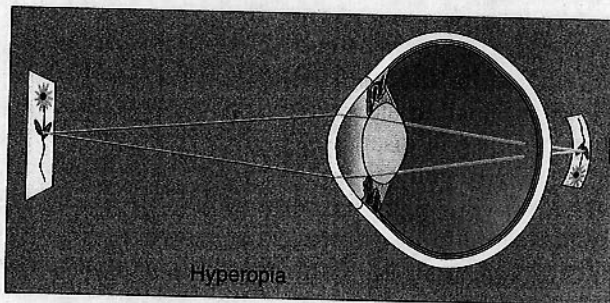


FIGURE B

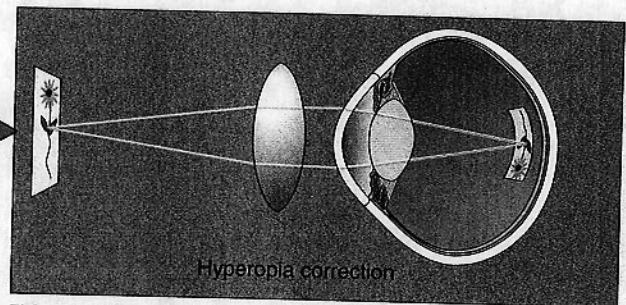


FIGURE C

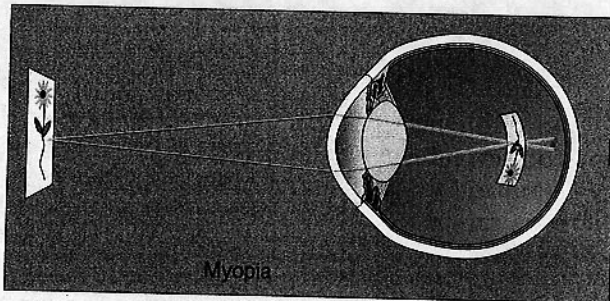


FIGURE D

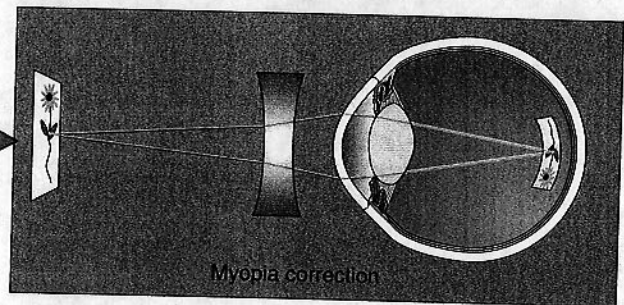


FIGURE E

## The Pupillary Light Reflex

In addition to the cornea and the lens, the pupil contributes to the optical functioning of the eye by continuously adjusting for different ambient light levels. To check this for yourself, stand in front of a bathroom mirror with the lights out for a few seconds, and then watch your pupils change size when you turn the lights on. This **pupillary light reflex** involves connections between the retina and neurons in the brain stem that control the muscles that constrict the pupils. An interesting property of this reflex is that it is consensual; shining a light into only one eye causes the constriction of the pupils of both eyes. It is unusual, indeed, when the pupils are not the same size; the lack of a consensual pupillary light reflex is often taken as a sign of a serious neurological disorder involving the brain stem.

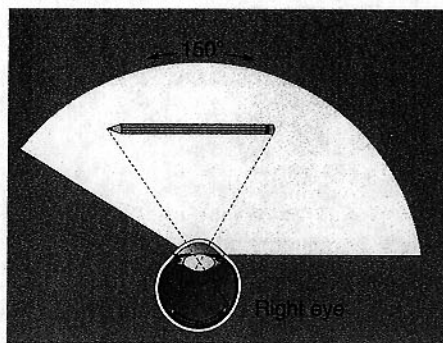


FIGURE 9.9

**The visual field for one eye.** The visual field is the total amount of space that can be viewed by the retina when the eye is fixated straight ahead. Notice how the image of an object in the visual field (pencil) is inverted on the retina.

Constriction of the pupil has the effect of increasing the depth of focus, just like decreasing the aperture size (increasing the f-stop) on a camera lens. To understand why this is true, consider two points in space, one close and the other far away. When the eye accommodates to the closer point, the image of the farther point on the retina no longer forms a point, but rather a blurred circle. Decreasing the aperture—constricting the pupil—reduces the size of this blurred circle so that its image more closely approximates a point. In this way, distant objects appear to be less out of focus.

## The Visual Field

The structure of the eyes, and where they sit in our head, limits how much of the world we can see at any one time. Let's investigate the extent of the space seen by one eye. Holding a pencil in your right hand, close your left eye and look at a point straight ahead. Keeping your eye fixated on this point, slowly move the pencil to the right (toward your right ear) across your field of view until the pencil disappears. Repeat this exercise, moving the pencil to the left where it will disappear behind your nose, and then up and down. The points where you can no longer see the pencil mark the limits of the visual field for your right eye. Now look at the middle of the pencil as you hold it horizontally in front of you. Figure 9.9 shows how the light reflected off this pencil falls on your retina. Notice that the image is inverted; the left visual field is imaged on the right side of the retina, and the right visual field is imaged on the left side of the retina.

## Visual Acuity

The ability of the eye to distinguish two nearby points is called **visual acuity**. Acuity depends on several factors, but especially on the spacing of photoreceptors in the retina and the precision of the eye's refraction.

Distance across the retina can be described in terms of degrees of **visual angle**. A right angle subtends (spans)  $90^\circ$ , and the moon, for example, subtends an angle of about  $0.5^\circ$  (Figure 9.10). We can speak of the eye's ability to resolve points that are separated by a certain number of degrees of visual angle. The Snellen eye chart, which we have all read at the doctor's office, tests our ability to discriminate letters and numbers at a viewing distance of 20 feet. Your vision is 20/20 when you can recognize a letter that subtends an angle of  $0.083^\circ$  (equivalent to 5 minutes of arc, where 1 minute is  $1/60$  of a degree).

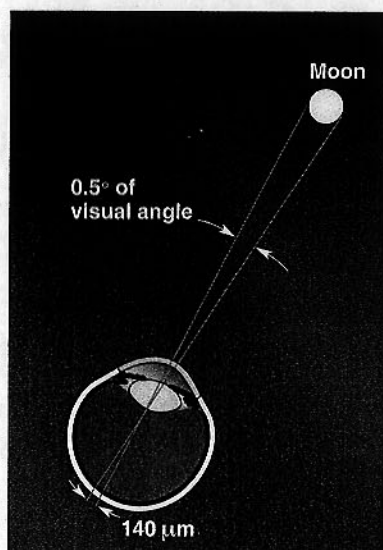


FIGURE 9.10

**Visual angle.** Distances across the retina can be expressed as degrees of visual angle.

## ▼ MICROSCOPIC ANATOMY OF THE RETINA

Now that we have an image formed on the retina, we can get to the neuroscience of vision: the conversion of light energy into neural activity. To begin our discussion of image processing in the retina, we must introduce the cellular architecture of this bit of brain.

The basic system of retinal information processing is shown in Figure 9.11. The most direct pathway for visual information to exit the eye is from **photoreceptors** to **bipolar cells** to **ganglion cells**. The ganglion cells fire action potentials in response to light, and these impulses propagate down the optic nerve to the rest of the brain. Besides the cells in this direct path from photoreceptor to brain, retinal processing is influenced by two additional cell types. **Horizontal cells** receive input from the photoreceptors and project neurites laterally to influence surrounding bipolar cells and photoreceptors. **Amacrine cells** receive input from bipolar cells and project

laterally to influence surrounding ganglion cells, bipolar cells, and other amacrine cells.

There are two important points to remember here:

1. *The only light-sensitive cells in the retina are the photoreceptors.* All other cells are influenced by light only via direct and indirect synaptic interactions with the photoreceptors. (We will see in Chapter 19 that there is one exception to this rule involving neurons that control circadian rhythms. However, these unusual photoreceptive cells do not appear to be involved in visual perception.)
2. *The ganglion cells are the only source of output from the retina.* No other retinal cell type projects an axon through the optic nerve.

Now let's take a look at how the different cell types are arranged in the retina.

## The Laminar Organization of the Retina

Figure 9.12 shows that the retina has a *laminar organization*: Cells are organized in layers. Notice that the layers are seemingly inside-out; light must pass from the vitreous humor through the ganglion cells and bipolar cells before it reaches the photoreceptors. Because the retinal cells above the

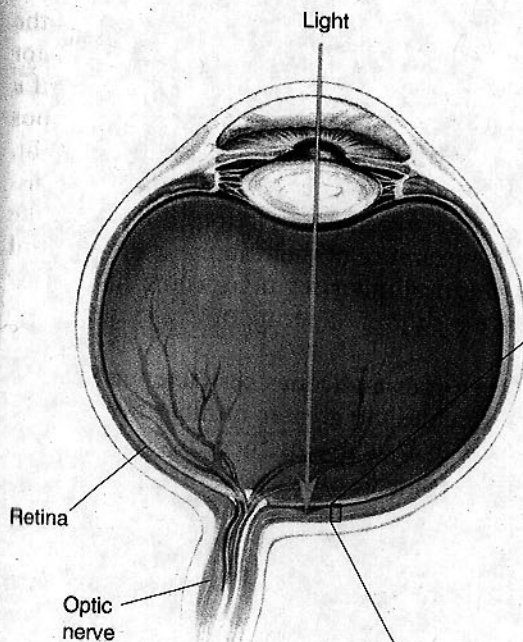


FIGURE 9.12

### The laminar organization of the retina.

Notice how light must pass through several cell layers before it reaches the photoreceptors at the back of the retina.

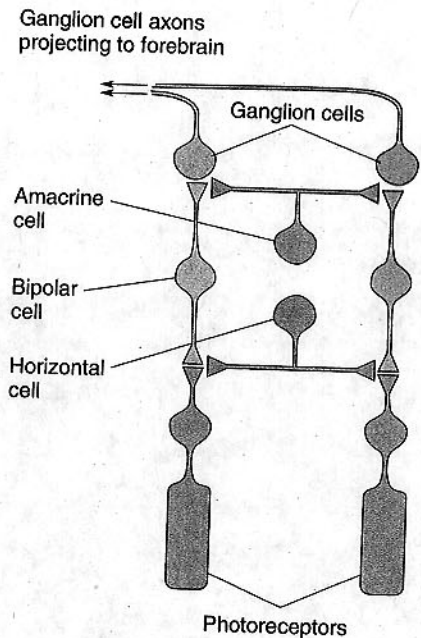
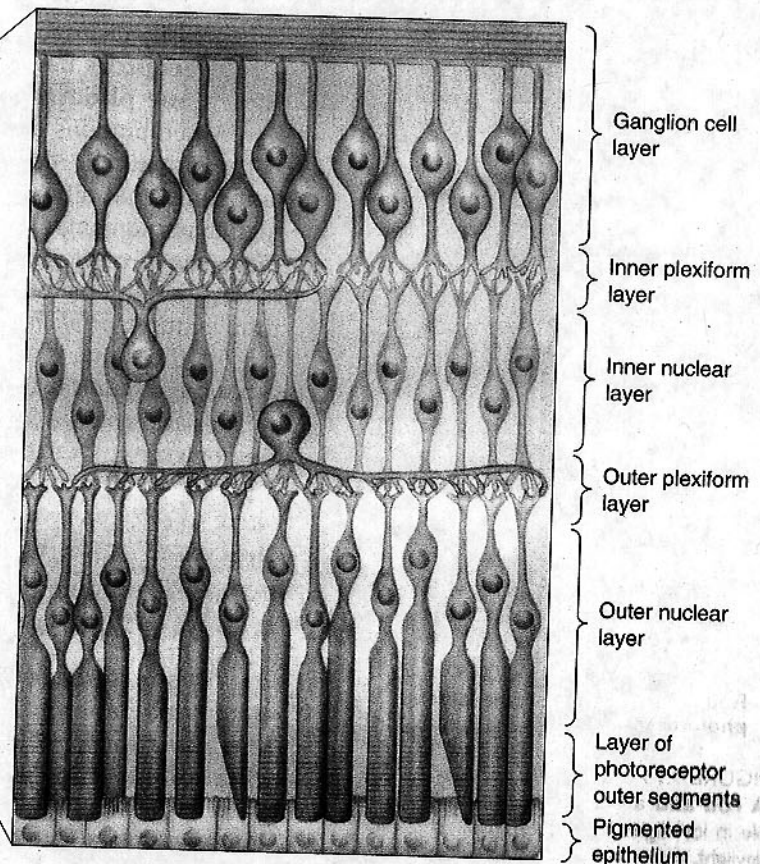


FIGURE 9.11

### The basic system of retinal information processing.

Information about light flows from the photoreceptors to bipolar cells to ganglion cells, which project axons out of the eye in the optic nerve. Horizontal cells and amacrine cells modify the responses of bipolar cells and ganglion cells via lateral connections.



photoreceptors are relatively transparent, image distortion is minimal as light passes through them. One reason the inside-out arrangement is advantageous is that the *pigmented epithelium* that lies below the photoreceptors plays a critical role in the maintenance of the photoreceptors and photopigments. The pigmented epithelium also absorbs any light that passes entirely through the retina, thus minimizing the reflection of light within the eye that would blur the image.

The cell layers of the retina are named in reference to the middle of the eyeball. Thus, the innermost layer is the **ganglion cell layer**, which contains the cell bodies of the ganglion cells. Next is the **inner nuclear layer**, which contains the cell bodies of the bipolar cells, the horizontal and amacrine cells. The next layer is the **outer nuclear layer**, which contains the cell bodies of the photoreceptors. Finally, the **layer of photoreceptor outer segments** contains the light-sensitive elements of the retina. The outer segments are embedded in the pigmented epithelium.

Between the ganglion cell layer and the inner nuclear layer is the **inner plexiform layer**, which contains the synaptic contacts between bipolar cells, amacrine cells, and ganglion cells. Between the outer and inner nuclear layers is the **outer plexiform layer**, where the photoreceptors make synaptic contact with the bipolar and horizontal cells.

### Photoreceptor Structure

The conversion of electromagnetic radiation into neural signals occurs in the 125 million photoreceptors at the back of the retina. Every photoreceptor has four regions: an outer segment, an inner segment, a cell body, and a synaptic terminal. The outer segment contains a stack of membranous disks. Light-sensitive *photopigments* in the disk membranes absorb light, thereby triggering changes in the photoreceptor membrane potential (discussed below). Figure 9.13 shows the two types of photoreceptor in the retina, easily distinguished by the appearance of their outer segments. **Rod photoreceptors** have a long, cylindrical outer segment, containing many disks. **Cone photoreceptors** have a shorter, tapering outer segment with fewer membranous disks.

The structural differences between rods and cones correlate with important functional differences. For example, the greater number of disks and higher photopigment concentration in rods makes them over 1000 times more sensitive to light than cones. Indeed, under nighttime lighting, or *scotopic* conditions, only rods contribute to vision. Conversely, under daytime lighting, or *photopic* conditions, cones do the bulk of the work. For this reason, the retina is said to be *duplex*—a scotopic retina using only rods, and a photopic retina using mainly cones.

Rods and cones differ in other respects as well. All rods contain the same photopigment, but there are three types of cone, each containing a different pigment. The variations among pigments make the different cones sensitive to different wavelengths of light. As we shall see in a moment, only the cones, not the rods, are responsible for our ability to see color.

### Regional Differences in Retinal Structure

Retinal structure varies from the fovea to the retinal periphery. In general, the peripheral retina has a higher ratio of rods to cones (Figure 9.14). It also has a higher ratio of photoreceptors to ganglion cells. The combined effect of this arrangement is that the peripheral retina is more sensitive to light, because (1) rods are specialized for low light, and (2) there are more photoreceptors feeding information to each ganglion cell. You can prove

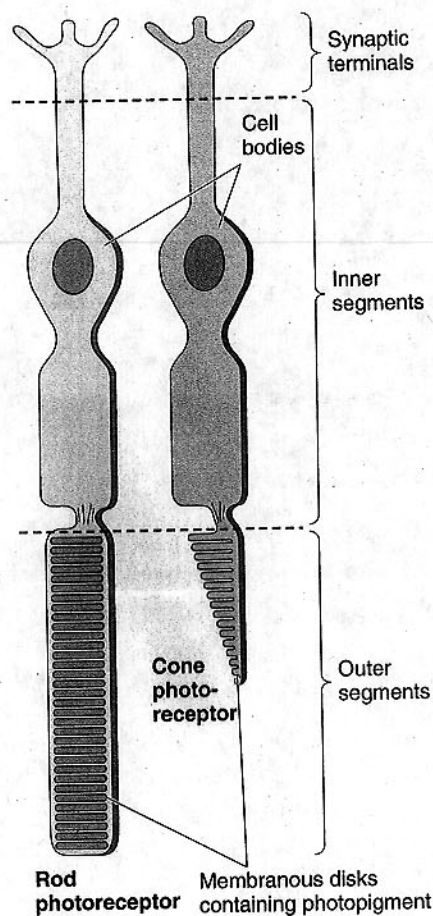


FIGURE 9.13  
**A rod and a cone.** Rods make vision possible in low light, and cones enable us to see in daylight.

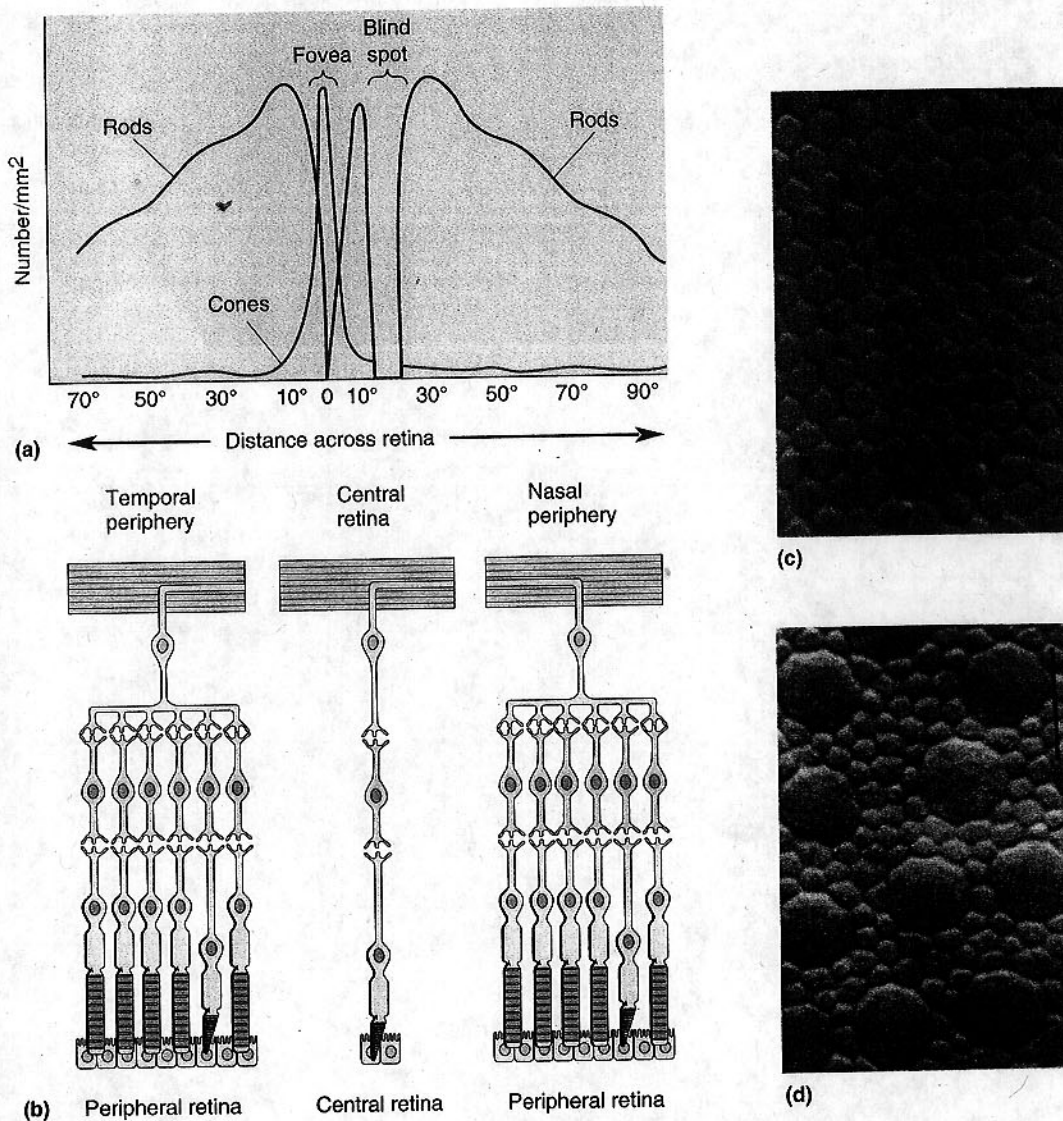


FIGURE 9.14

**Regional differences in retinal structure.** (a) Cones are found primarily in the central retina, within 10° of the fovea. Rods are absent from the central fovea and are found mainly in the peripheral retina. (b) In the central retina, relatively few photoreceptors feed information directly to a ganglion cell; in the peripheral retina, many photoreceptors provide input. This arrangement makes the peripheral retina better at detecting dim light but the central retina better for high-resolution vision. (c) This magnified cross section of the human central retina shows the dense packing of cone inner segments. (d) At a more peripheral location on the retina, the cone inner segments are larger and appear as islands in a sea of smaller rod inner segments. (Source for parts c and d: Curcio et al., 1990, p. 500.)

this to yourself on a starry night. (It's fun; try it with a friend.) First, spend about 20 minutes in the dark getting oriented, and then gaze at a bright star. Fixating on this star, search your peripheral vision for a dim star. Then move your eyes to look at this dim star. You will find that the faint star disappears when it is imaged on the central retina (when you look straight at it) but reappears when it is imaged on the peripheral retina (when you look slightly to the side of it).

The same characteristics that enable the peripheral retina to detect faint stars at night make it relatively poor at resolving fine details in daylight. This is because daytime vision requires cones, and because good visual acuity

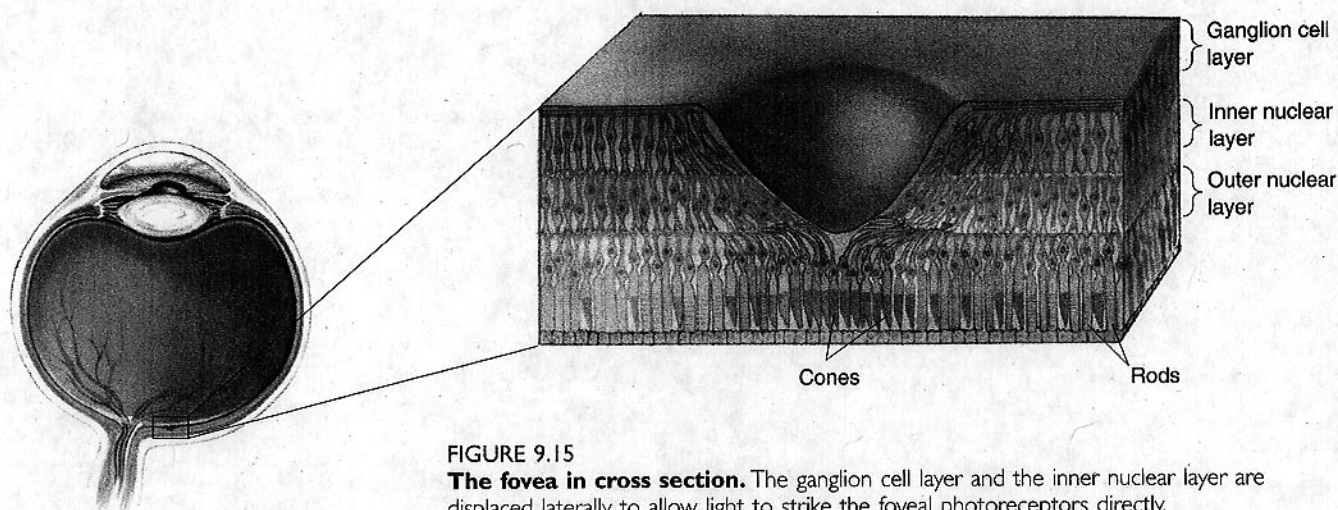


FIGURE 9.15

**The fovea in cross section.** The ganglion cell layer and the inner nuclear layer are displaced laterally to allow light to strike the foveal photoreceptors directly.

requires a low ratio of photoreceptors to ganglion cells. The region of retina most highly specialized for high-resolution vision is the fovea. Recall that the fovea is a thinning of the retina at the center of the macula. In cross section, the fovea appears as a pit in the retina. Its pitlike appearance is due to the lateral displacement of the cells above the photoreceptors, allowing light to strike the photoreceptors without passing through the other retinal cell layers (Figure 9.15). This structural specialization maximizes visual acuity at the fovea by pushing aside other cells that might scatter light and blur the image. The central fovea also is unique because it contains no rods; all the photoreceptors are cones.

### ▼ PHOTOTRANSDUCTION

The photoreceptors convert, or *transduce*, light energy into changes in membrane potential. We begin our discussion of phototransduction with rods, which outnumber cones in the human retina by 20 to 1. Most of what has been learned about phototransduction by rods has proven to be applicable to cones as well.

#### Phototransduction in Rods

As we discussed in Part I, one way information is represented in the nervous system is as changes in the membrane potential of neurons. Thus, we look for a mechanism by which the absorption of light energy can be transduced into a change in the photoreceptor membrane potential. In many respects, this process is analogous to the transduction of chemical signals into electrical signals that occurs during synaptic transmission. At a G-protein-coupled neurotransmitter receptor, for example, the binding of transmitter to the receptor activates G-proteins in the membrane, which in turn stimulate various effector enzymes (Figure 9.16a). These enzymes alter the intracellular concentration of cytoplasmic second messenger molecules, which (directly or indirectly) change the conductance of membrane ion channels, thereby altering membrane potential. Similarly, in the photoreceptor, light stimulation of the photopigment activates G-proteins, which in turn activate an effector enzyme that changes the cytoplasmic concentration of a second messenger molecule. This change causes a membrane ion channel to close, and the membrane potential is thereby altered (Figure 9.16b).

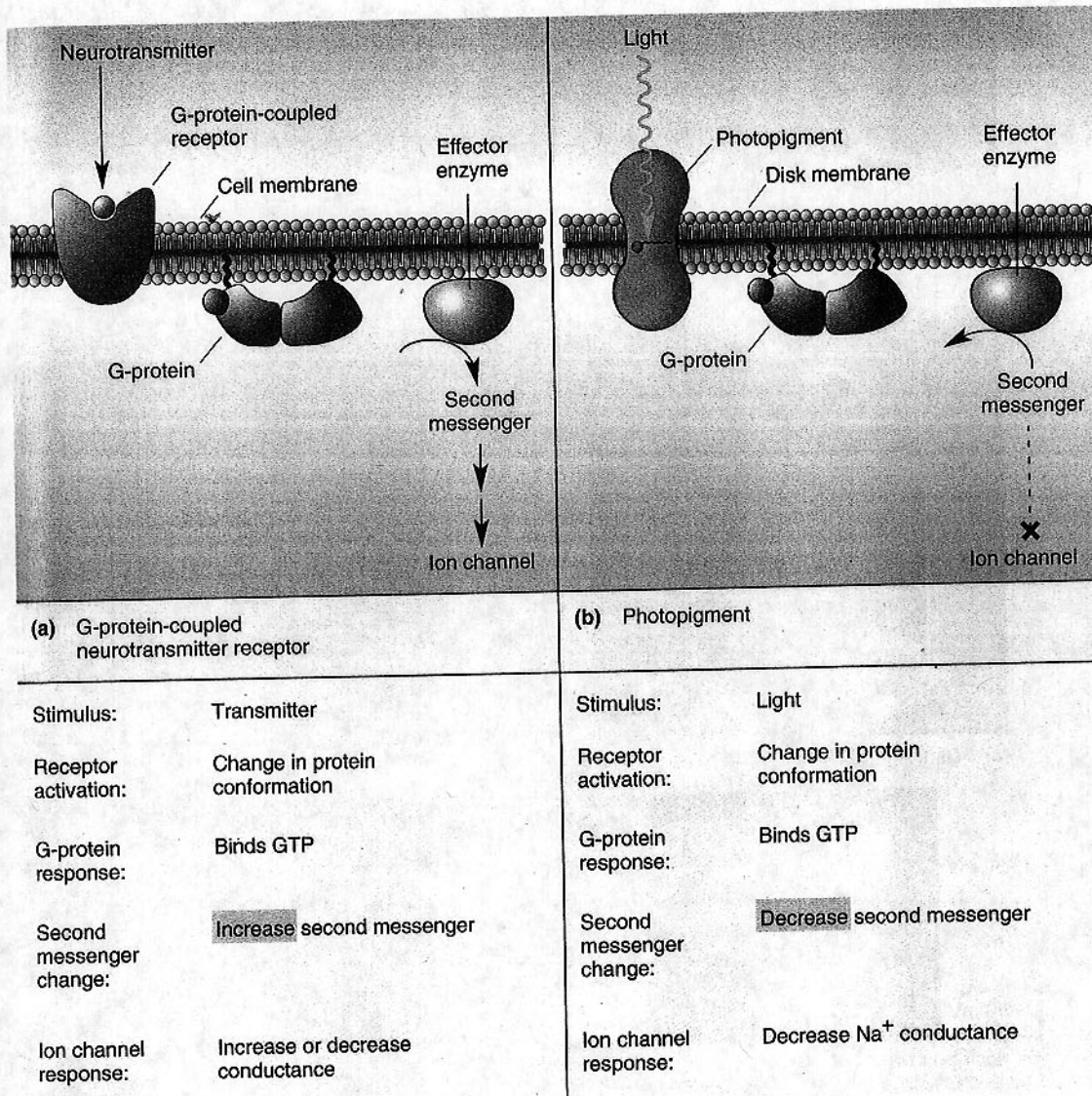


FIGURE 9.16

**Light transduction and G-proteins.** G-protein-coupled receptors and photoreceptors use similar mechanisms. (a) At a G-protein-coupled receptor, the binding of neurotransmitter activates G-proteins and effector enzymes. (b) In a photoreceptor, light begins a similar process using the G-protein transducin.

Recall from Chapter 3 that a typical neuron at rest has a membrane potential of about  $-65$  mV, close to the equilibrium potential for  $K^+$ . In contrast, in complete darkness, the membrane potential of the rod outer segment is about  $-30$  mV. This depolarization is caused by the steady influx of  $Na^+$  through special channels in the outer segment membrane (Figure 9.17a). The movement of positive charge across the membrane, which occurs in the dark, is called the **dark current**. Sodium channels are stimulated to open—are gated—by an intracellular second messenger called **cyclic guanosine monophosphate**, or **cGMP**. Evidently, cGMP is continually produced in the photoreceptor by the enzyme guanylyl cyclase, keeping the  $Na^+$  channels open. Light reduces cGMP, causing the  $Na^+$  channels to close, and the membrane potential becomes more negative (Figure 9.17b). Thus, *photoreceptors hyperpolarize in response to light*.

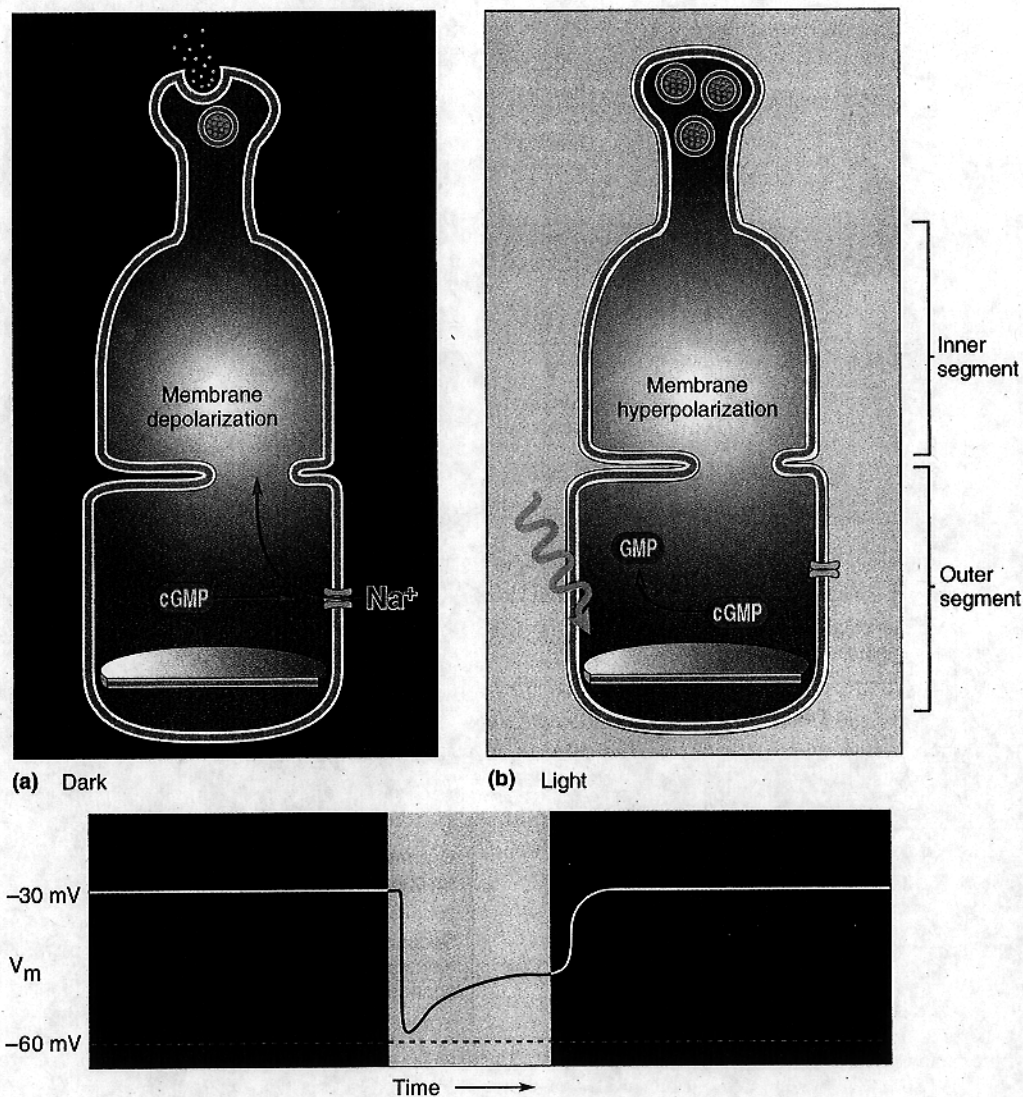


FIGURE 9.17

**The hyperpolarization of photoreceptors in response to light.** Photoreceptors are continuously depolarized in the dark because of an inward sodium current, the dark current.

**(a)** Sodium enters the photoreceptor through a cGMP-gated channel. **(b)** Light leads to the activation of an enzyme that destroys cGMP, thereby shutting off the  $\text{Na}^+$  current and hyperpolarizing the cell.

The hyperpolarizing response to light is initiated by the absorption of electromagnetic radiation by the photopigment in the membrane of the stacked disks in the rod outer segments. In the rods, this pigment is called **rhodopsin**. Rhodopsin can be thought of as a receptor protein with a pre-bound chemical agonist. The receptor protein is called *opsin*, and it has the seven transmembrane alpha helices typical of G-protein-coupled receptors throughout the body. The prebound agonist is called *retinal*, a derivative of vitamin A. The absorption of light causes a change in the conformation of retinal so that it activates the opsin (Figure 9.18). This process is called **bleaching** because it changes the wavelengths absorbed by the rhodopsin (the photopigment literally changes color from purple to yellow). The bleaching of rhodopsin stimulates a G-protein called **transducin** in the disk membrane, which in turn activates the effector enzyme **phosphodiesterase (PDE)**, which breaks down the cGMP that is normally present in

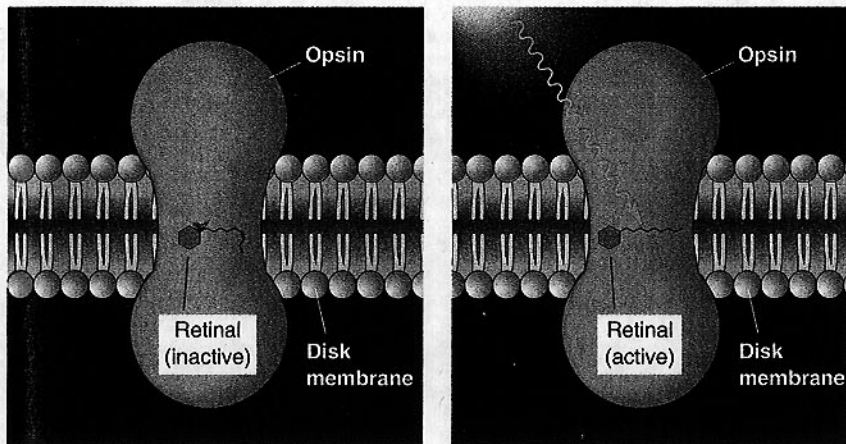


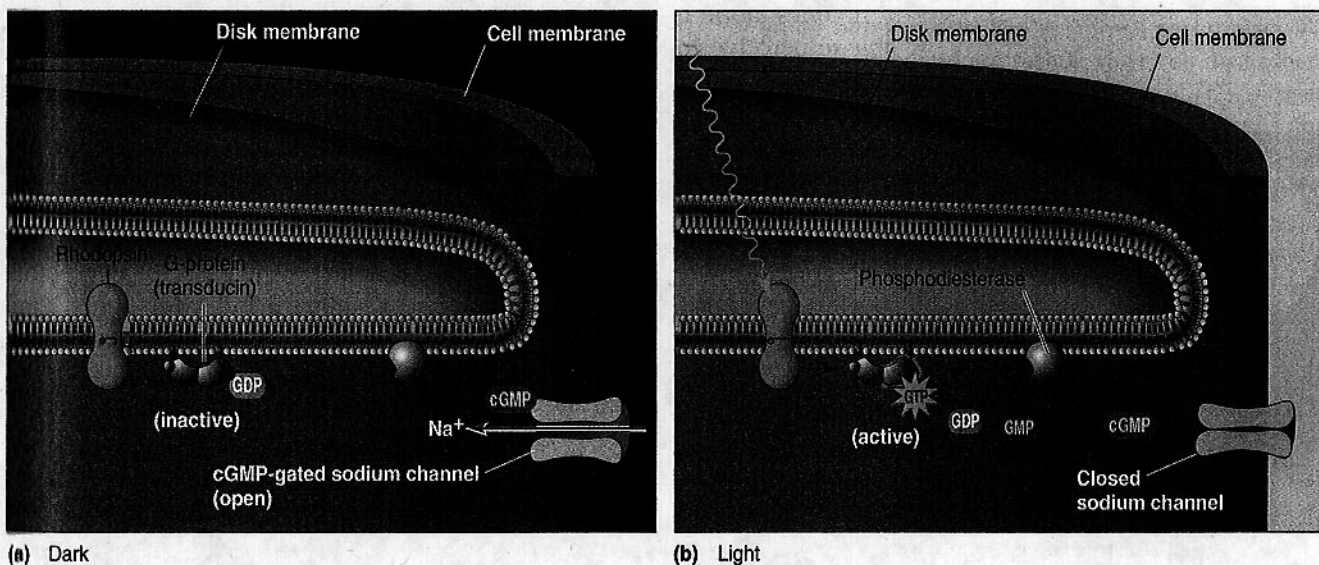
FIGURE 9.18

**The activation of rhodopsin by light.** Rhodopsin consists of opsin, a protein with seven transmembrane alpha helices, and retinal, a small molecule derived from vitamin A. Retinal undergoes a change in conformation when it absorbs light, thereby activating the opsin.

the cytoplasm of the rod (in the dark). The reduction in cGMP causes the  $\text{Na}^+$  channels to close and the membrane to hyperpolarize.

One of the interesting functional consequences of using a biochemical cascade for transduction is signal *amplification*. Many G-proteins are activated by each photopigment molecule, and each PDE enzyme breaks down more than one cGMP molecule. This amplification gives our visual system the ability to detect as little as a single photon, the elementary unit of light energy.

The complete sequence of events of phototransduction in rods is illustrated in Figure 9.19.



(a) Dark

(b) Light

FIGURE 9.19

**The light-activated biochemical cascade in a photoreceptor.** (a) In the dark, cGMP gates a sodium channel, causing an inward  $\text{Na}^+$  current and depolarization of the cell. (b) The activation of rhodopsin by light energy causes the G-protein (transducin) to exchange GDP for GTP (see Chapter 6), which in turn activates the enzyme phosphodiesterase (PDE). PDE breaks down cGMP and shuts off the dark current.

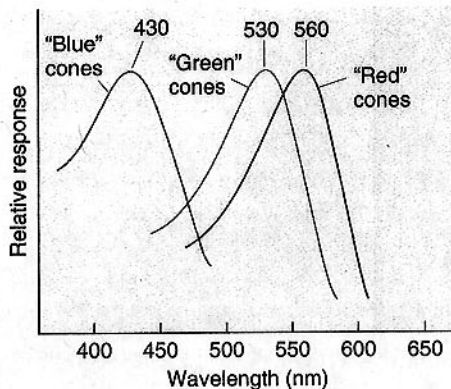


FIGURE 9.20  
The spectral sensitivity of the three types of cone pigments.

### Phototransduction in Cones

In bright sunlight, cGMP levels in rods fall to the point where the response to light becomes *saturated*; additional light causes no more hyperpolarization. Thus, vision during the day depends entirely on the cones, whose photopigments require more energy to become bleached.

The process of phototransduction in cones is virtually the same as in rods; the only major difference is in the type of opsins in the membranous disks of the cone outer segments. The cones in our retinas contain one of three opsins that give the photopigments different spectral sensitivities. Thus, we can speak of "blue" cones that are maximally activated by light with a wavelength of about 430 nm, "green" cones that are maximally activated by light with a wavelength of about 530 nm, and "red" cones that are maximally activated by light with a wavelength of about 560 nm (Figure 9.20).

**Color Detection.** The color that we perceive is largely determined by the relative contributions of blue, green, and red cones to the retinal signal. The fact that our visual system detects colors in this way was actually predicted almost 200 years ago by British physicist Thomas Young. Young showed in 1802 that all the colors of the rainbow, including white, could be created by mixing the proper ratio of red, green, and blue light (Figure 9.21). He proposed, quite correctly, that at each point in the retina there exists a cluster of three receptor types, each type being maximally sensitive to either blue, green, or red. Young's ideas were later championed by Hermann von Helmholtz, an influential nineteenth-century German physiologist. (Among his accomplishments is the invention of the ophthalmoscope in 1851.) This theory of color vision came to be known as the **Young-Helmholtz trichromacy theory**. According to the theory, the brain assigns colors based on a comparison of the readout of the three cone types. When all types of cones are equally active, as in broad-spectrum light, we perceive "white." Various forms of color blindness result when one or more of the cone photopigment types is missing (Box 9.4).

If cones alone make the perception of color possible, we should be unable to perceive color differences when cones are inactive. This inference is correct, and you can demonstrate it to yourself. Go outside on a dark night and try to distinguish the colors of different objects. It is difficult to detect colors at night because only the rods, with a single type of photopigment, are activated under dim lighting conditions. (Bright neon signs are still seen as colored because they emit sufficient light to affect the cones.) The peak sensitivity of the rods is to a wavelength of about 500 nm, perceived as blue-green (under photopic conditions). This fact is the basis for two points of view about the design of automobile dashboard indicator lights. One view is that the lights should be dim blue-green to take advantage of the spectral sensitivity of the rods. An alternate view is that the lights should be bright red because this wavelength affects mainly cones, leaving the rods unsaturated, resulting in better night vision.

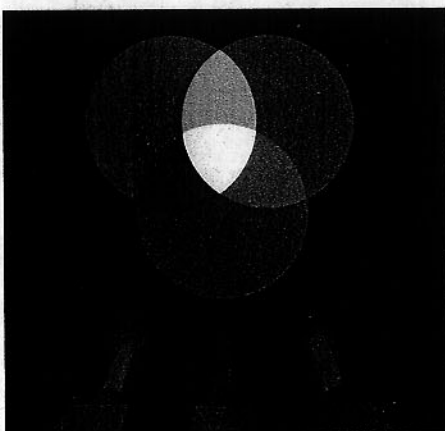


FIGURE 9.21  
**Mixing colored lights.** The mixing of red, green, and blue light causes equal activation of the three types of cones, and the perception of "white" results.

### Dark and Light Adaptation

This transition from all-cone daytime vision to all-rod nighttime vision is not instantaneous; it takes about 20–25 minutes (hence the time needed to get oriented in the star-gazing exercise above). This phenomenon is called **dark adaptation**, or getting used to the dark. Sensitivity to light actually increases a millionfold or more during this period. Dark adaptation is

## Box 9.4



## OF SPECIAL INTEREST

## The Genetics of Color Vision

The color we perceive is largely determined by the relative amounts of light absorbed by the red, green, and blue visual pigments in our cones. This means it's possible to perceive any color of the rainbow by mixing different amounts of red, green, and blue light. For example, the perception of yellow light can be matched by an appropriate mixture of red and green light. Because we use a "three-color" system, humans are referred to as *trichromats*. However, not all normal trichromats perceive colors exactly the same. For example, if a group of people are asked to choose the wavelength of light that most appears green without being yellowish or bluish, there will be small variations in the choices. However, significant abnormalities of color vision extend well beyond this range of normal trichromatic vision.

Most abnormalities in color vision are the result of small genetic errors that lead to the loss of one visual pigment or a shift in the spectral sensitivity of one type of pigment. The most common abnormalities involve red-green color vision, and they are much more common in men than women. The reason for this pattern is that the genes encoding the red and green pigments are on the X chromosome, whereas the gene that encodes the blue pigment is on chromosome 7. Men will have abnormal red-green vision if there is a defect on the single X chromosome they inherit from their mother. Women will have abnormal red-green vision only if both parents contribute abnormal X chromosomes.

About 6% of men have a red or green pigment that absorbs somewhat different wavelengths of light than the pigments of the rest of the population. These men are referred to as *anomalous trichromats* because they require somewhat different mixtures of red, green, and blue to see intermediate colors (and white) than other people do. Most anomalous trichromats have normal genes to encode the blue pigment and either the red or the green pigment, but they also have a hybrid gene that encodes a protein with an abnormal absorption spectrum between that of normal red and green pigments. For example, a person with an anomalous green pigment can match a yellow light with a red-green mixture containing less red than a normal trichromat. Anomalous trichromats per-

ceive the full spectrum of colors that normal trichromats perceive, but in rare instances they will disagree about the precise color of an object (e.g., blue versus greenish blue).

About 2% of men actually lack either the red or the green pigment, making them red-green color-blind. Because this leaves them with a "two-color" system, they are referred to as *dichromats*. People lacking the green pigment are less sensitive to green, and they confuse certain red and green colors that appear different to trichromats. A "green dichromat" can match a yellow light with either red or green light, no mixture is needed. In contrast to the roughly 8% of men that are either missing one pigment or have an anomalous pigment, only about 1% of women have such color abnormalities.

People without one color pigment are considered color-blind, but they actually perceive quite a colorful world. Estimates of the number of people lacking all color vision vary, but less than about 0.001% of the population is thought to have this condition. In one type, both red and green cone pigments are missing, in many cases because mutations of the red and green genes make them non-functional. These people are blue cone *monochromats* and they live in a world that varies only in lightness, like a trichromat's perception of a black-and-white movie.

Recent research has shown that, precisely speaking, there may not be such a thing as normal color vision. In a group of males classified as normal trichromats, it was found that some require slightly more red than others to perceive yellow in a red-green mixture. This difference, which is tiny compared to the deficits discussed above, results from a single alteration of the red pigment gene. The 60% of males who have the amino acid serine at site 180 in the red pigment gene are more sensitive to long-wavelength light than the 40% who have the amino acid alanine at this site. Imagine what would happen if a woman had different red gene varieties on her two X chromosomes. Both red genes should be expressed, leading to different red pigments in two populations of cones. In principle, such women should have a form of tetrachromatic color vision, a rarity among all animals.

explained by a number of factors. Perhaps the most obvious is dilation of the pupils, which allows more light to enter the eye. However, the diameter of the human pupil only ranges from about 2–8 mm, meaning that changes in its size can increase the pupil area by a factor of only 16. The larger component of dark adaptation involves the regeneration of unbleached rhodopsin and an adjustment of the functional circuitry of the retina so that information from more rods is available to each ganglion cell. Because of this tremendous increase in sensitivity, when the dark-adapted eye goes back into bright light, it is temporarily saturated. This explains what happens when you first go outside on a bright day. Over the next 5–10 minutes, the eyes undergo **light adaptation**, reversing the changes in the retina that accompanied dark adaptation. This light-dark adaptation in the duplex retina gives our visual system the ability to operate in light intensities ranging from moonless midnight to bright high noon.

**Calcium's Role in Light Adaptation.** In addition to the factors mentioned above, the ability of the eye to adapt to changes in light level relies on changes in calcium concentration within the cones. When you step out into bright light from a dark theater, initially the cones are hyperpolarized as much as possible (i.e., to  $E_K$ , the equilibrium potential for  $K^+$ ). If the cones stayed in this state, we would be unable to see changes in light level. As we discussed above, the constriction of the pupil helps a bit in reducing the light entering the eye. However, the most important change is a gradual depolarization of the membrane back to about  $-35$  mV.

The reason this happens stems from the fact that the cGMP-gated sodium channels we discussed previously also admit calcium. In the dark,  $Ca^{2+}$  enters the cones and has an inhibitory effect on the enzyme (guanylyl cyclase) that synthesizes cGMP. When the cGMP-gated channels close, the flow of  $Ca^{2+}$  into the photoreceptor is curtailed; as a result, more cGMP is synthesized (because the synthetic enzyme is less inhibited), thereby allowing the cGMP-gated channels to open again. Stated more simply, when the channels close, a process is initiated that gradually reopens them even if the light level does not change. Calcium also appears to affect photopigments and phosphodiesterase in ways that decrease their response to light. These calcium-based mechanisms ensure that the photoreceptors are always able to register relative changes in light level, though information about the absolute level is lost.

## ▼ RETINAL PROCESSING

Well before the discovery of how photoreceptors work, researchers were able to explain some of the ways the retina processes visual images. Since about 1950, neuroscientists have studied the action potential discharges of retinal ganglion cells as the retina is stimulated with light. The pioneers of this approach were neurophysiologists Keffer Hartline, Stephen Kuffler, and Horace Barlow, with Hartline and Kuffler working in the United States and Barlow working in England. Their research uncovered which aspects of a visual image were encoded as ganglion cell output. Early studies of horseshoe crabs and frogs gave way to investigations of cats and monkeys. Researchers learned that similar principles are involved in retinal processing across a wide range of species.

Progress in understanding how ganglion cell properties are generated by synaptic interactions in the retina has been slower. This is because *only ganglion cells fire action potentials*; all other cells in the retina (except some amacrine cells) respond to stimulation with graded changes in membrane potential. The detection of such graded changes requires technically challenging

intracellular recording methods, whereas action potentials can be detected using simple extracellular recording methods (see Box 4.1). It was not until the early 1970s that John Dowling and Frank Werblin at Harvard University were able to show how ganglion cell responses are built from the interactions of horizontal and bipolar cells (Box 9.5).

The most direct path for information flow in the retina is from a cone photoreceptor to bipolar cell to ganglion cell. At each synaptic relay, the responses are modified by the lateral connections of horizontal cells and amacrine cells. We first focus on how information is transformed as it passes from photoreceptors to bipolar cells and then explore ganglion cell output in the last section.

## Transformations in the Outer Plexiform Layer

Photoreceptors, like other neurons, release neurotransmitter when depolarized. The transmitter released by photoreceptors is the amino acid glutamate. As we have seen, photoreceptors are depolarized in the dark and are *hyperpolarized* by light. We thus have the counterintuitive situation in which photoreceptors actually release fewer transmitter molecules in the light than in the dark. However, we can reconcile this apparent paradox if we take the point of view that *dark* rather than *light* is the preferred stimulus for a photoreceptor. Thus, when a shadow passes across a photoreceptor, it responds by depolarizing and releasing neurotransmitter.

In the outer plexiform layer, each photoreceptor is in synaptic contact with two types of retinal neuron: bipolar cells and horizontal cells. Recall that bipolar cells create the direct pathway from photoreceptors to ganglion cells; horizontal cells feed information laterally in the outer plexiform layer to influence the activity of neighboring bipolar cells and photoreceptors (see Figures 9.11 and 9.12).

**Bipolar Cell Receptive Fields.** Bipolar cells can be categorized into two classes, based on their responses to the glutamate released by photoreceptors. In **OFF bipolar cells**, glutamate-gated cation channels mediate a classical depolarizing EPSP from the influx of  $\text{Na}^+$ . **ON bipolar cells** have G-protein-coupled receptors and respond to glutamate by hyperpolarizing. Notice that the names OFF and ON refer to whether these cells depolarize in response to light *off* (more glutamate) or to light *on* (less glutamate).

Each bipolar cell receives direct synaptic input from a cluster of photoreceptors. The number of photoreceptors in this cluster ranges from one at the center of the fovea to thousands in the peripheral retina. In addition to these direct connections with photoreceptors, bipolar cells also are connected via horizontal cells to a circumscribed ring of photoreceptors that surrounds this central cluster. The **receptive field** of a bipolar cell (or any other cell in the visual system) is the area of retina that, when stimulated with light, changes the cell's membrane potential. The receptive field of a bipolar cell consists of two parts: a circular area of retina providing direct photoreceptor input, called the *receptive field center*, and a surrounding area of retina providing input via horizontal cells, called the *receptive field surround* (Figure 9.22a). Receptive field dimensions can be measured in millimeters across the retina or, more commonly, in degrees of visual angle. One millimeter on the retina corresponds to a visual angle of about  $3.5^\circ$ . Bipolar cell receptive field diameters range from a fraction of a degree in the central retina to several degrees in the peripheral retina.

The response of a bipolar cell's membrane potential to light in the receptive field center is opposite to that of light in the surround. For example, if illumination of the center causes depolarization of the bipolar cell

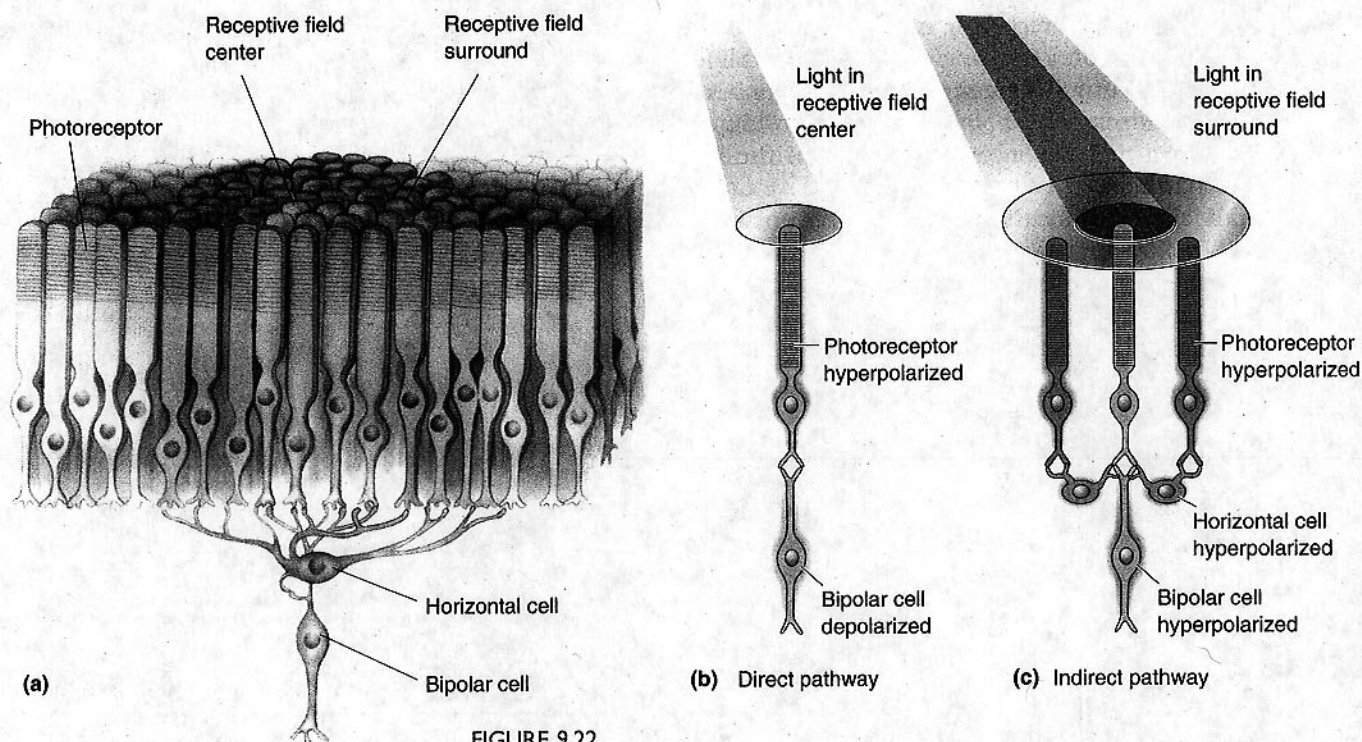


FIGURE 9.22

**Direct and indirect pathways from photoreceptor to bipolar cell.** (a) Bipolar cells receive direct synaptic input from a cluster of photoreceptors, constituting the receptive field center. In addition, they receive indirect input from surrounding photoreceptors via horizontal cells. (b) An ON-center bipolar cell is depolarized by light in the receptive field center via the direct pathway. (c) Light in the receptive field surround hyperpolarizes the ON-center bipolar cell via the indirect pathway. Because of the intervening horizontal cell, the effect of light on the surround photoreceptors is always opposite the effect of light on the center photoreceptors.

(an ON response), then illumination of the surround will cause an antagonistic hyperpolarization of the bipolar cell (Figure 9.22b, c). Likewise, if the cell is depolarized by a spot turning from light to dark in the center of its receptive field (an OFF response), it will be hyperpolarized by the same dark stimulus applied to the surround. Thus, these cells are said to have antagonistic **center-surround receptive fields**. The antagonistic surround appears to come from a complex interaction of horizontal cells, photoreceptors, and bipolar cells at their synapses.

The center-surround receptive field organization is passed on from bipolar cells to ganglion cells via synapses in the inner plexiform layer. The lateral connections of the amacrine cells in the inner plexiform layer also contribute to the elaboration of ganglion cell receptive fields and the integration of rod and cone input to ganglion cells. Numerous types of amacrine cells have been identified, and their particular contributions to ganglion cell responses are still being investigated.

### ▼ RETINAL OUTPUT

The sole source of output from the retina to the rest of the brain is the action potentials arising from the million or so ganglion cells. The activity of these cells can be recorded electrophysiologically not only in the retina but also in the optic nerve where their axons travel.

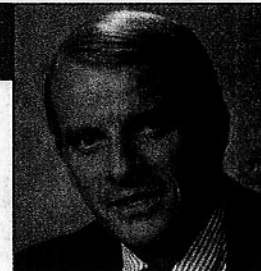
## Box 9.5

## PATH OF DISCOVERY



## A Glimpse into the Retina

by John Dowling



Much of my scientific life has been spent studying the functional organization of the vertebrate retina—how the retinal cells are wired, how they respond when the retina is illuminated, and how the retina processes visual information. What led me to undertake this research? As both an undergraduate and graduate student, I worked in George Wald's laboratory at Harvard. Wald discovered the role of vitamin A in vision (for which he won a Nobel Prize) and had long been interested in photoreceptor mechanisms. With Wald, I studied the effects of vitamin A deficiency on photoreceptors, which brought me to the question of how visual sensitivity relates to visual pigment levels in photoreceptors. In other words, what mechanisms underlie the loss of visual sensitivity in vitamin A deficiency, and does this relate to the sensitivity changes that occur during light and dark adaptation?

This early work was carried out in the rat, and I found there is a relationship between visual pigment (rhodopsin) levels and the logarithm of visual sensitivity in both vitamin A deficiency and during dark adaptation. Rat retinas, however, possess mainly rod photoreceptors, and an obvious next question was whether a similar relationship between visual pigment levels and light sensitivity holds also for cones. I decided to test this by switching to ground squirrels, whose retinas possess mainly cones. Among other things, I was curious about how cone photoreceptors differ from rod photoreceptors, and so I examined the ground squirrel photoreceptors by electron microscopy. What caught my eye one day were the cone synaptic terminals and the realization that I could follow an occasional process from a synaptic terminal back to its cell of origin. Bipolar cell branches extended to the synaptic terminals, as expected, but I could also identify horizontal cell processes synapsing with the photoreceptors! This was new and exciting. Horizontal cells were very much a mystery then; indeed, some investigators thought they were glial cells, but the fact that they made synapses with the photoreceptors clearly indicated they were neurons.

What, then, is the neuronal circuitry of the retina, and what is the role of the retinal interneurons—the

horizontal and amacrine cells? This became an area of intense interest and study. I joined forces with Brian Boycott, and we explored the cellular (Brian) and synaptic organization (myself) of the outer and inner plexiform layers of the retina. We found that the photoreceptor and bipolar cell terminals make ribbon synapses onto multiple postsynaptic targets, whereas amacrine cells and at least some horizontal cell processes make conventional synapses on single postsynaptic elements. In addition to ground squirrel retinas, we examined monkey, human, cat, frog, and goldfish retinas, and they all showed basic similarities in retinal wiring.

The next step was to record from the various retinal cells, and that work was undertaken in my laboratory by Frank Werblin, a graduate student with training in electrical engineering. We chose the mudpuppy retina as our animal because of its large cells, and soon Frank had recordings from all the retinal cell types. He confirmed the identity of the recorded cells by staining them intracellularly after the recording—a routine technique today, but then very difficult and on occasion messy. More than once, Frank emerged from the darkroom where the experiments were carried out covered with the blue dye we then used. What those experiments told us was that there are both ON-center and OFF-center bipolar cells in the retina and that bipolar cells have a center-surround receptive field organization, with the horizontal cells accounting for the antagonistic surround response. Further, many amacrine cells respond transiently to illumination, giving ON-OFF responses, and appear to be involved in detecting movement.

These recordings, along with electron microscopic observations on the mudpuppy retina I made, enabled us to suggest the main pathways of information flow through the retina and the roles of the various cells and synapses. Many questions remained, many of which are being explored even today. However, being able to draw a diagram of the functional organization of the retina at that time, however imperfect and incomplete, was immensely satisfying, and it has encouraged, I like to believe, numerous additional studies on retinal mechanisms in the 35 years since.

### Ganglion Cell Receptive Fields

Most retinal ganglion cells have the concentric center-surround receptive field organization discussed above for bipolar cells. ON-center and OFF-center ganglion cells receive input from the corresponding type of bipolar cell. Thus, an ON-center ganglion cell will be depolarized and respond with a barrage of action potentials when a small spot of light is projected onto the middle of its receptive field. Likewise, an OFF-center cell will respond to a small dark spot presented to the middle of its receptive field. However, in both types of cell, the response to stimulation of the center is canceled by the response to stimulation of the surround (Figure 9.23). The surprising implication is that most retinal ganglion cells are not particularly responsive to changes in illumination that include both the receptive field center and the receptive field surround. Rather, it appears that the ganglion cells are mainly responsive to *differences* in illumination that occur within their receptive fields.

To illustrate this point, consider the response generated by an OFF-center cell as a light-dark edge crosses its receptive field (Figure 9.24). Remember that in such a cell, dark in the center of the receptive field causes the cell to depolarize, whereas dark in the surround causes the cell to hyperpolarize. In uniform illumination, the center and surround cancel to yield some low level of response (Figure 9.24a). When the edge enters the surround region of the receptive field without encroaching on the center, the dark area has the effect of hyperpolarizing the neuron, leading to a decrease in the cell's firing rate (Figure 9.24b). As the dark area begins to include the center, however, the partial inhibition by the surround is overcome, and the cell response increases (Figure 9.24c). But when the dark area finally fills the entire surround, the center response is again canceled (Figure 9.24d). Notice that the cell response in this example is only slightly different in uniform light and in uniform dark; the response is modulated mainly by the presence of the light-dark edge in its receptive field.

Now let's consider the output of *all* the OFF-center ganglion cells that are stimulated by a stationary light-dark edge imaged on the retina. The responses will fall into the same four categories illustrated in Figure 9.24. Thus, the cells that will register the presence of the edge are those with receptive field centers and surrounds that are differentially affected by the light and dark areas. The population of cells with receptive field centers "viewing" the light side of the edge will be inhibited (Figure 9.24b). The population of cells with centers "viewing" the dark side of the edge will be excited (Figure

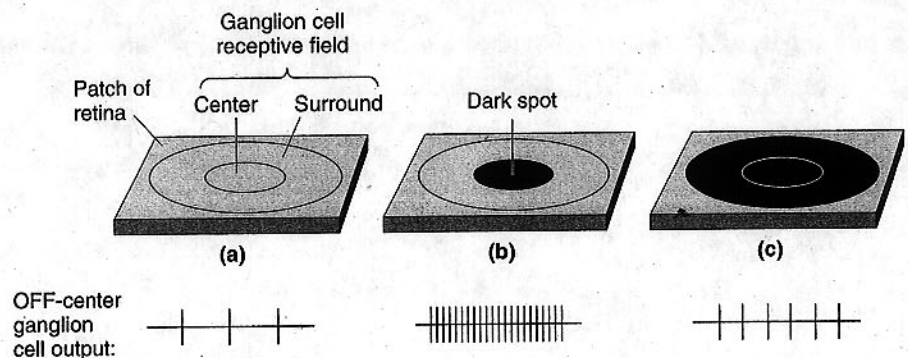


FIGURE 9.23

**A center-surround ganglion cell receptive field.** (a, b) An OFF-center ganglion cell responds with a barrage of action potentials when a dark spot is imaged on its receptive field center. (c) If the spot is enlarged to include the receptive field surround, the response is greatly reduced.

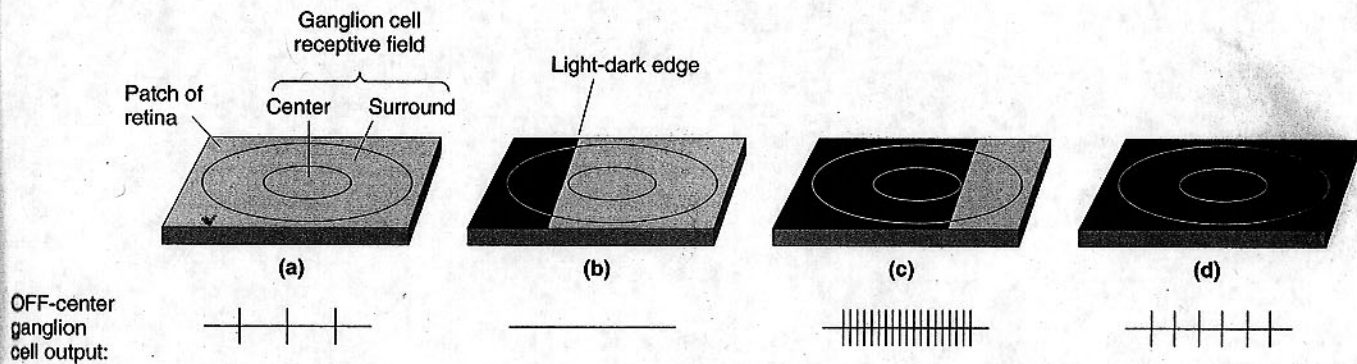


FIGURE 9.24

**Responses to a light-dark edge crossing an OFF-center ganglion cell receptive field.** The response of the neuron is determined by the fraction of the center and surround that are filled by light and dark. (See text for details.)

9.24c). In this way, the difference in illumination at a light-dark edge is not faithfully represented by the difference in the output of ganglion cells on either side of the edge. Instead, *the center-surround organization of the receptive fields leads to a neural response that emphasizes the contrast at light-dark edges.*

There are many visual illusions involving the perception of light level. The organization of ganglion cell receptive fields suggests an explanation for the illusion shown in Figure 9.25. Even though the two central squares are the same shade of gray, the square on the left background appears darker. Consider the two ON-center receptive fields shown on the gray squares. In both cases, the same gray light hits the receptive field center. However, the receptive field on the left has more light in its surround than the receptive field on the right. This will lead to a lower response and may be related to the darker appearance of the left gray square.

## Types of Ganglion Cells

Most ganglion cells in the mammalian retina have a center-surround receptive field with either an ON or an OFF center. They can be further categorized based on their appearance, connectivity, and electrophysiological properties. In the macaque monkey retina and human retina, two major types of ganglion cells are distinguished: large **M-type ganglion cells** and smaller **P-type ganglion cells**. (M stands for *magno*, from the Latin for

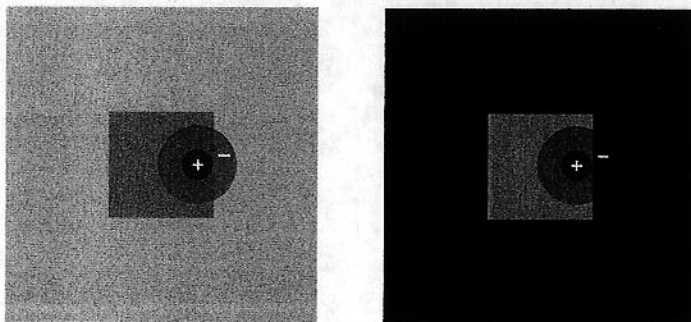


FIGURE 9.25

**The influence of contrast on the perception of light and dark.** The central boxes are identical shades of gray, but because the surrounding area is lighter on the left, the left central box appears darker: ON-center receptive fields are shown on the left and right of the figure. Which would respond more?

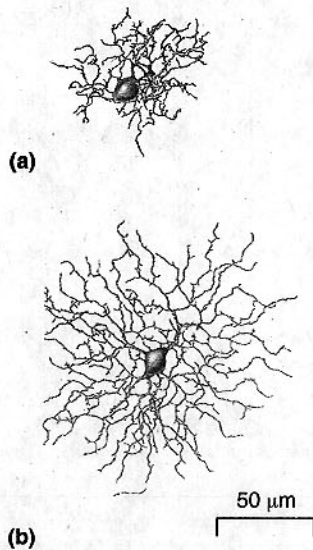


FIGURE 9.26  
**M-type and P-type ganglion cells in the macaque monkey retina.** (a) A small P cell from the peripheral retina. (b) An M cell from a similar retinal location is significantly larger. (Source: Watanabe and Rodieck, 1989, pp. 437, 439.)

"large"; P stands for *parvo*, from the Latin for "small.") Figure 9.26 shows the relative sizes of M and P ganglion cells at the same location on the retina. P cells constitute about 90% of the ganglion cell population, M cells constitute about 5%, and the remaining 5% is made up of a variety of **nonM-nonP ganglion cell** types that are less well characterized.

The visual response properties of M cells differ from those of P cells in several ways. They have larger receptive fields, they conduct action potentials more rapidly in the optic nerve, and they are more sensitive to low-contrast stimuli. In addition, M cells respond to stimulation of their receptive field centers with a transient burst of action potentials, while P cells respond with a sustained discharge as long as the stimulus is on (Figure 9.27). We will see in Chapter 10 that the different types of ganglion cells appear to play different roles in visual perception.

**Color-Opponent Ganglion Cells.** Another important distinction between ganglion cell types is that some P cells and nonM-nonP cells are sensitive to differences in the wavelength of light. The majority of these color-sensitive neurons are called **color-opponent cells**, reflecting the fact that the response to one wavelength in the receptive field center is canceled by showing another wavelength in the receptive field surround. Two types of opponency are found, red versus green and blue versus yellow. Consider, for example, a cell with a red ON center and a green OFF surround (Figure 9.28). The center of the receptive field is fed mainly by red cones; therefore, the cell responds to red light by firing action potentials. Note that even a red light that bathes the entire receptive field is an effective stimulus. However, the response is reduced because red light has some effect on green cones (recall the overlap of the red and green sensitivity curves in Figure 9.20) that feed into the green OFF surround. The response to red is only canceled by green light on the surround. Shorthand notation for such a cell is  $R^+G^-$ , meaning simply that it is excited by red in the receptive field center, and this response is inhibited by green in the surround. What would be the response to white light on the entire receptive field? Because white light contains all visible wavelengths, both center and surround would be equally activated, thereby canceling the response of the cell.

Blue-yellow color opponency works the same way. Consider a cell with a blue ON center and a yellow OFF surround ( $B^+Y^-$ ). Blue light drives blue cones that feed the receptive field center, while yellow light activates both

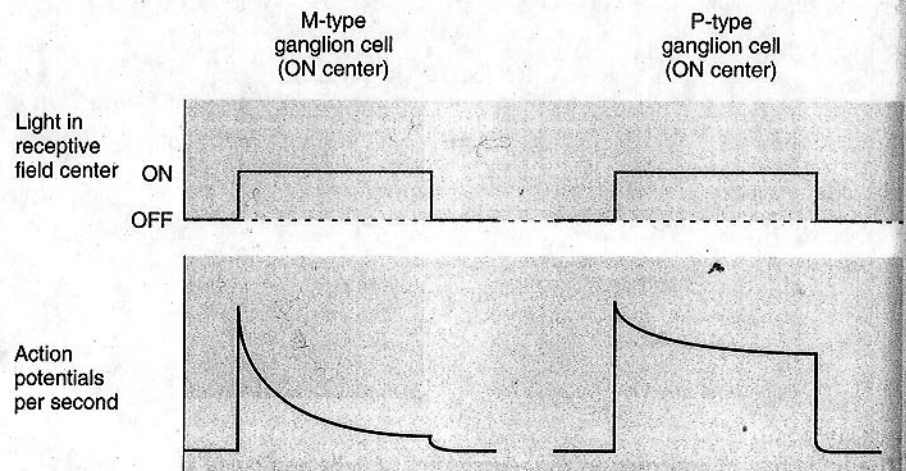


FIGURE 9.27  
**Different responses to light of M-type and P-type ganglion cells.**

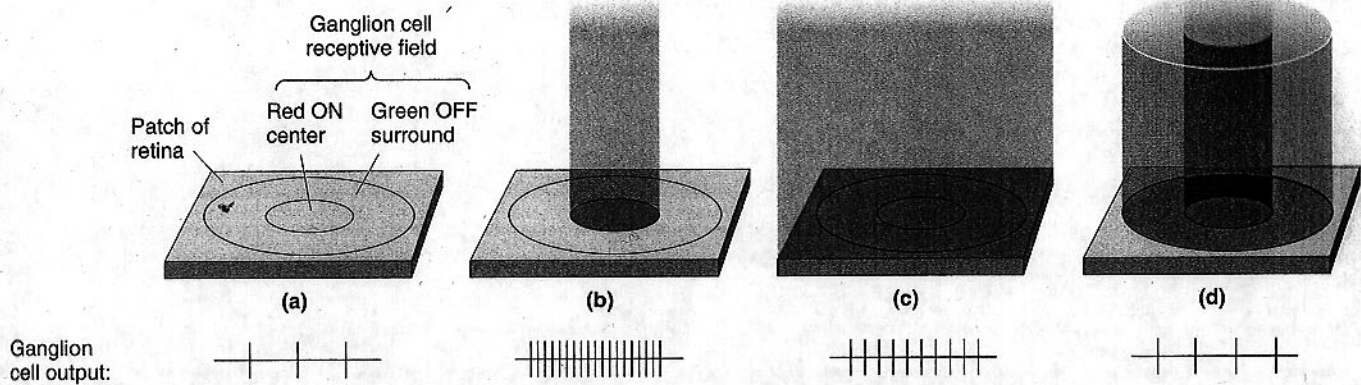


FIGURE 9.28  
A color-opponent center-surround receptive field of a P-type ganglion cell.

red and green cones that feed the surround. Again, diffuse blue light would be an effective stimulus for this cell, but yellow on the surround would cancel the response, as would diffuse white light. The lack of color opponency in M cells is accounted for by the fact that both the center and surround of the receptive field receive input from more than one type of cone.

Perceived color is based on the relative activity of ganglion cells whose receptive field centers receive input from red, green, and blue cones. Demonstrate this to yourself by fixating on the cross in the middle of the red box in Figure 9.29 for a minute or so. This will have the effect of light-adapting some of your red cones. Then look at the white box. The activation of the green cones by the white light is unopposed, and you see a green square. Similarly, if you fixate on the blue box, you will see yellow when you shift your gaze to the white box. Thus, it appears that the

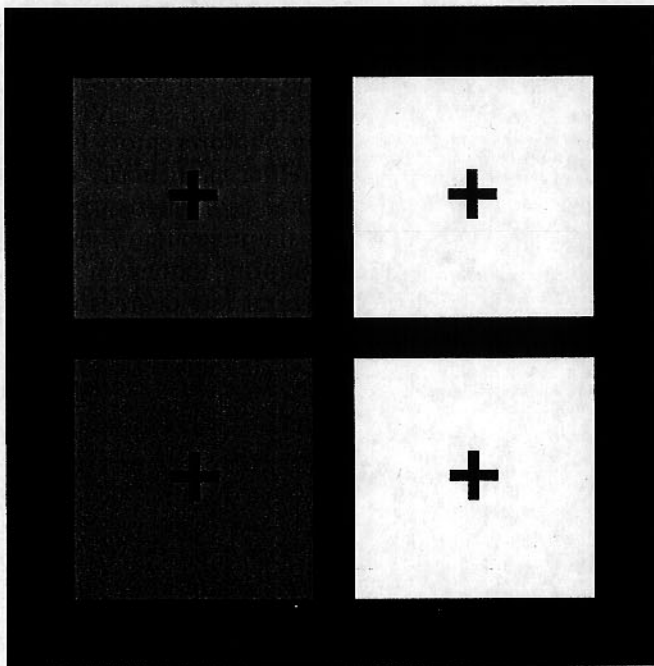


FIGURE 9.29  
**Color opponency revealed.** Fixate on the cross in the red box on the left for 60 seconds, then shift your gaze to the cross in the white box. What color do you see? Try it again with the blue box.

ganglion cells provide a stream of information to the brain that is involved in the spatial comparison of three different opposing processes: light versus dark, red versus green, and blue versus yellow.

### Parallel Processing


One of the important concepts that emerges from our discussion of the retina is the idea of **parallel processing in the visual system**. Here's why. First, we view the world with not one but two eyes that provide two parallel streams of information. In the central visual system, these streams are compared to give information about *depth*, the distance of an object from the observer. Second, there appear to be independent streams of information about light and dark that arise from the ON-center and OFF-center ganglion cells in each retina. Third, ganglion cells of both ON and OFF varieties have different types of receptive fields and response properties. M cells can detect subtle contrasts over their large receptive fields and are likely to contribute to low-resolution vision. P cells have small receptive fields that are well suited for the discrimination of fine detail. P cells and nonM-nonP cells are specialized for the separate processing of red-green and blue-yellow information.

### ▼ CONCLUDING REMARKS

In this chapter, we have seen how light emitted by or reflected off objects in space can be imaged by the eye onto the retina. Light energy is first converted into membrane potential changes in the mosaic of photoreceptors. It is interesting to note that the transduction mechanism in photoreceptors is very similar to that in olfactory receptor cells, both of which involve cyclic nucleotide-gated ion channels. Photoreceptor membrane potential is converted into a chemical signal (the neurotransmitter glutamate), which is again converted into membrane potential changes in the postsynaptic bipolar and horizontal cells. This process of electrical-to-chemical-to-electrical signaling repeats again and again, until the presence of light or dark or color is finally converted to a change in the action potential firing frequency of the ganglion cells.

The information from the 125 million photoreceptors is funneled into 1 million ganglion cells. In the central retina, particularly the fovea, relatively few photoreceptors feed each ganglion cell, whereas in the peripheral retina, thousands of receptors do. Thus, the mapping of visual space onto the array of optic nerve fibers is not uniform. Rather, in "neural space," there is an overrepresentation of the central few degrees of visual space, and signals from individual cones are more important. This specialization ensures high acuity in central vision but also requires that the eye move to bring the images of objects of interest onto the fovea.

As we shall see in the next chapter, there is good reason to believe that the different types of information that arise from different types of ganglion cells are, at least in the early stages, processed independently. Parallel streams of information—for example, from the right and left eyes—remain segregated at the first synaptic relay in the lateral geniculate nucleus of the thalamus. The same can be said for the M-cell and P-cell synaptic relays in the LGN. In the visual cortex, it appears that parallel paths may process different visual attributes. For example, the distinction in the retina between neurons that do and do not convey information about color is preserved in the visual cortex. In general, each of the more than two-dozen visual cortical areas may be specialized for the analysis of different types of retinal output.



## KEY TERMS

**Introduction**

vision (p. 278)  
retina (p. 278)

**Properties of Light**

refraction (p. 280)

**The Structure of the Eye**

pupil (p. 280)  
iris (p. 280)  
cornea (p. 280)  
sclera (p. 280)  
extraocular muscle (p. 280)  
conjunctiva (p. 280)  
optic nerve (p. 280)  
optic disk (p. 281)  
macula (p. 281)  
fovea (p. 281)  
aqueous humor (p. 282)  
lens (p. 282)  
ciliary muscle (p. 282)  
vitreous humor (p. 282)

**Image Formation by the Eye**

diopter (p. 283)  
accommodation (p. 284)  
pupillary light reflex (p. 287)  
visual field (p. 288)  
visual acuity (p. 288)  
visual angle (p. 288)

**Microscopic Anatomy of the Retina**

photoreceptor (p. 288)  
bipolar cell (p. 288)  
ganglion cell (p. 288)  
horizontal cell (p. 288)  
amacrine cell (p. 288)  
ganglion cell layer (p. 290)  
inner nuclear layer (p. 290)  
outer nuclear layer (p. 290)  
layer of photoreceptor outer segments (p. 290)  
inner plexiform layer (p. 290)  
outer plexiform layer (p. 290)  
rod photoreceptor (p. 290)  
cone photoreceptor (p. 290)

**Phototransduction**


dark current (p. 293)  
cyclic guanosine monophosphate (cGMP) (p. 293)  
rhodopsin (p. 294)  
transducin (p. 294)  
phosphodiesterase (PDE) (p. 294)  
Young-Helmholtz trichromacy theory (p. 296)  
dark adaptation (p. 296)  
light adaptation (p. 298)

**Retinal Processing**

OFF bipolar cell (p. 299)  
ON bipolar cell (p. 299)  
receptive field (p. 299)  
center-surround receptive field (p. 300)

**Retinal Output**

M-type ganglion cell (p. 303)  
P-type ganglion cell (p. 303)  
nonM-nonP ganglion cell (p. 304)  
color-opponent cell (p. 304)  
parallel processing (p. 306)



## REVIEW QUESTIONS

1. What physical property of light is most closely related to the perception of color?
2. Name eight structures in the eye that light passes through before it strikes the photoreceptors.
3. Why is a scuba mask necessary for clear vision under water?
4. What is myopia, and how is it corrected?
5. Give three reasons explaining why visual acuity is best when images fall on the fovea.
6. How does the membrane potential change in response to a spot of light in the receptive field center of a photoreceptor? Of an ON bipolar cell? Of an OFF-center ganglion cell? Why?
7. What happens in the retina when you "get used to the dark"? Why can't you see color at night?
8. In what way is retinal output *not* a faithful reproduction of the visual image falling on the retina?
9. In retinitis pigmentosa, early symptoms include the loss of peripheral vision and night vision. The loss of what type of cells could lead to such symptoms?

FURTHER  
READING

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