1
Structure and Function

In the following chapters of this book, we will deal with the examination and treatment of the human eye. As the majority of readers are expected to have an engineering or scientific background, we would like to provide a background in human ocular anatomy. This chapter shall also serve as an introduction and general reference for the more technical chapters. Of course, these chapters cannot claim to cover the entire anatomy and physiology of the eye, but they should be sufficient to gain an understanding of the interaction between the eye and the ophthalmic devices under consideration.

The human eye is a sophisticated sensory organ through which 80% of the sensory information we receive is processed. It is indeed our most important connection to the outside world. Any reduction or loss of vision means a major impairment of our quality of life.

In principle, the eye works like an artificial optical imaging system. To create an image, optical components focus light rays onto a photosensitive detector. But vision is more than just a projection of the surroundings onto a passive screen. The optical data is "preprocessed" by the photosensitive and neuronal tissue before it is sent to the brain for final "image analysis". Even with efficient preprocessing, the eye sends 10 × more data to the brain than all other sensory organs altogether. To analyze this huge amount of information flow with almost no latency[1], 30 different parts of the brain are involved simultaneously. During image processing, relevant information is filtered by recognition of known patterns.

The brain's important role for vision is illustrated in Figure 1.1. In Figure 1.1a, an animated image is shown as it would be directly projected onto photosensitive tissue. Here, a sharp image exists only in the center of the visual field. The eye now automatically changes the viewing direction in a fast manner and, for a moment, the margins of the image are sharply imaged as well. All the image segments are then merged by the brain so that the perceived field of sharp vision extends to the margins (Figure 1.1b).

1) The average period of latency to transmit a light stimulus from the retina to the visual cortex takes about 95–115 ms, and it takes about 300 ms to perceive the signal. However, the brain "simulates" a real-time perception.

Optical Devices in Ophthalmology and Optometry, First Edition. Michael Kaschke, Karl-Heinz Donnerhacke, and Michael Stefan Rill.

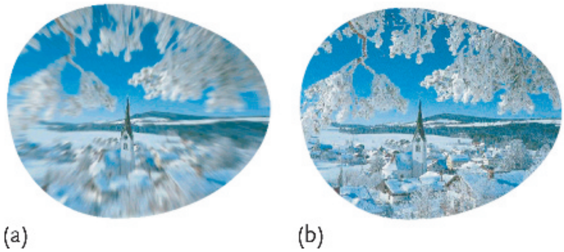

Figure 1.1 Image processing by the brain. (a) Simulated "raw" image as it would be detected by photosensitive tissue. (b) Due to fast changes of the viewing direction and preprocessing of the "detected data", the perceived field of clear vision is considerably extended. Taken with permission from [1].

We can trick the brain's hard-wired processing algorithms by looking at visual illusions (Figure 1.2). It is an interesting and currently not fully answered question how much visual illusions are based purely on innate factors, or to what extent they are also based on experience and adaption.

1.1 Anatomy of the Human Eye

The human eye can be divided into the *anterior* and *posterior segments* (Figure 1.3b and c, respectively). The anterior segment (Figure 1.4) is the optical window to the environment. It mainly consists of optical components, such as the cornea, eye lens, and iris. The posterior segment of the eye (Figure 1.5) is referred to as the *fundus*. It is connected to the visual cortex of the brain via the optic nerve (Figure 1.6).

Sclera and cornea The spherical outer shell of the human eye consists of the white, opaque *sclera*. It serves as a mechanical support and protects the eye from injuries caused by mechanical force. The collagen fibers in the sclera are randomly distributed. Consequently, the incident light is strongly scattered (Section 9.2) so that the tissue appears white and opaque, which is why this part is also called "the whites of the eyes".

In the anterior segment of the eye, the sclera passes into the transparent *cornea*. The cornea is composed of multiple functional layers (Figure 1.7) and is covered by the 4–7 μm thick *tear film*. The tear film consists of a viscous, aqueous fluid that smooths the surface roughness of the corneal surface. A smooth surface reduces light scattering (Section 9.2), and thus improves the clarity of vision. The corneal *epithelium* is a 50 μm thick chemical barrier of the outer cornea which protects the eye against water, large molecules, and toxic substances. This is followed by *Bowman's membrane* which is a thin layer (8–14 μm) above the 500 μm thick *stroma*. The stroma is composed of approximately 250 stacked collagen layers termed *lamellae*. Each lamella has a thickness of about 2 μm and contains ordered, cylindrical-

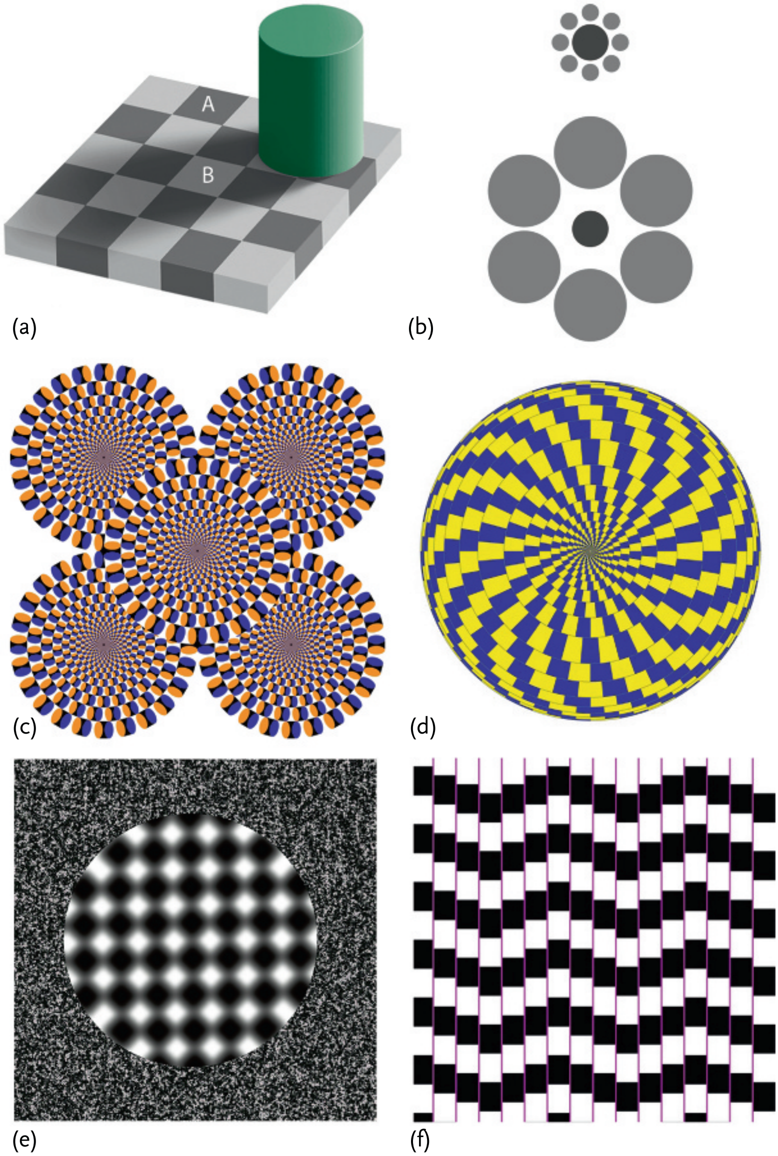

Figure 1.2 Visual illusions which trick the image processing capability of the brain. (a) The checkerboard field A seems to be darker than B although the gray scales are equal in both cases. (b) The big dark dot at the top appears larger than the lower one, even though both dots are exactly the same size. (c) The circles seem to rotate. (d) Does the image show spirals? A closer look reveals that the structures are closed rings. (e) Fixate the pattern in the center. When moving your head, the circle seems to move independently from the background. When bringing your head closer, the pattern inside the circle seems to approach. (f) The lines appear to be bent although they are perfectly straight. See also [2].

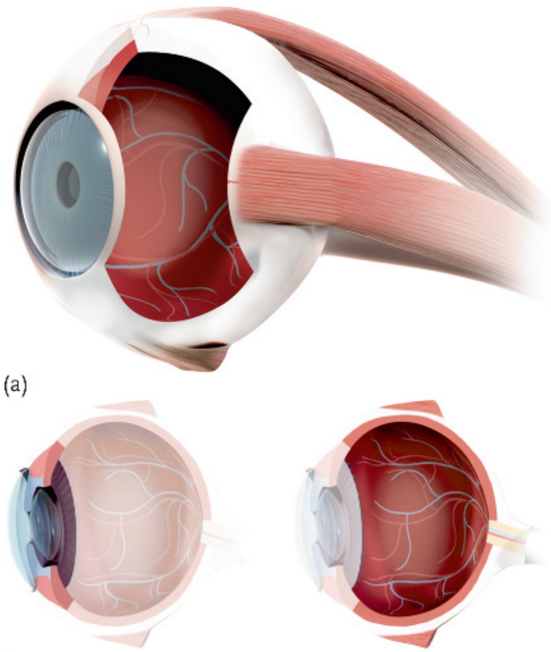

Figure 1.3 Anatomy of the human eye. (a) Oblique view of the human eye ball. (b) Side view of the eye with highlighted anterior segment. (c) Side view of the eye with highlighted posterior segment.

shaped collagen *fibrils* with diameters of 25–35 nm and a spacing of 20–50 nm [3]. Underneath the stroma we have the *Descemet's membrane* (approximately 10 μm thick) which forms the basement layer of *endothelial cells*. The innermost corneal layer is the 5 μm thick *endothelium*. It is composed of hexagonal cells arranged in a honeycomb lattice and allows leakage of nutrients to the upper layers of the cornea. At the same time, the endothelium actively pumps water out of the cornea to keep it clear and transparent.

Uvea, choroid, iris, and ciliary body The *uvea* forms the middle shell of the eye. In the posterior part of the eye (Figure 1.5), the uvea forms the so-called choroid, that is, a blood-rich tissue supplying nutrients to the retina (Section 1.2). The *choroid* has a total thickness of 350–450 μm. In the anterior segment (Figure 1.4), the uvea has evolved into the *iris*. In optical terms, the iris is an adjustable aperture stop whose diameter can be modified by two antagonistic muscles (*sphincter* and *dilator pupillae*). The hole of the iris is called the *pupil*. Note that the "anatomic pupil" does *not* correspond to the optical entrance or exit pupils (Sections 2.1.1 and A.1.4). The color of the iris depends on the amount of pigmentation in the anterior limiting layer of iris and stroma.

Between iris and choroid, the uvea has formed into the *ciliary body* which has two important functions. On the one hand, it produces the aqueous humor. On the

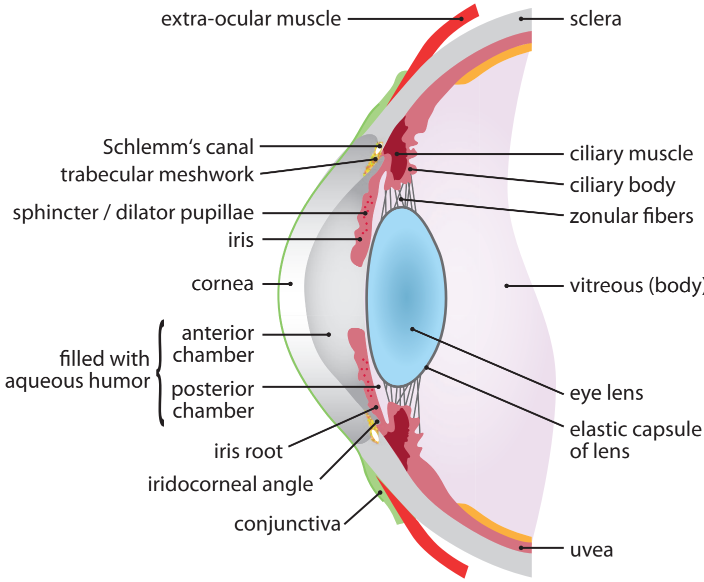

Figure 1.4 Scheme of the eye's anterior segment (see also Figure 1.3b). The depicted eye components are not to scale.

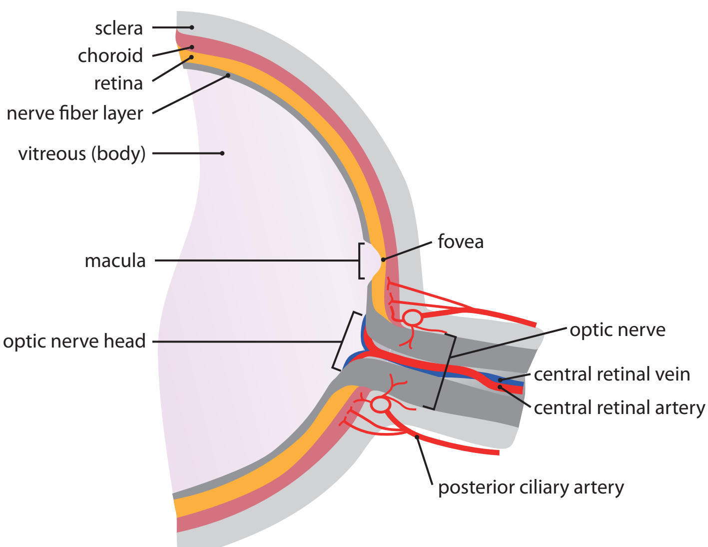

Figure 1.5 Scheme of the eye's posterior segment (see also Figure 1.3c). The depicted eye components are not to scale.

other hand, it comprises the ciliary muscle which may relax the tension on the eye lens so that near vision is possible (Section 2.1.4).

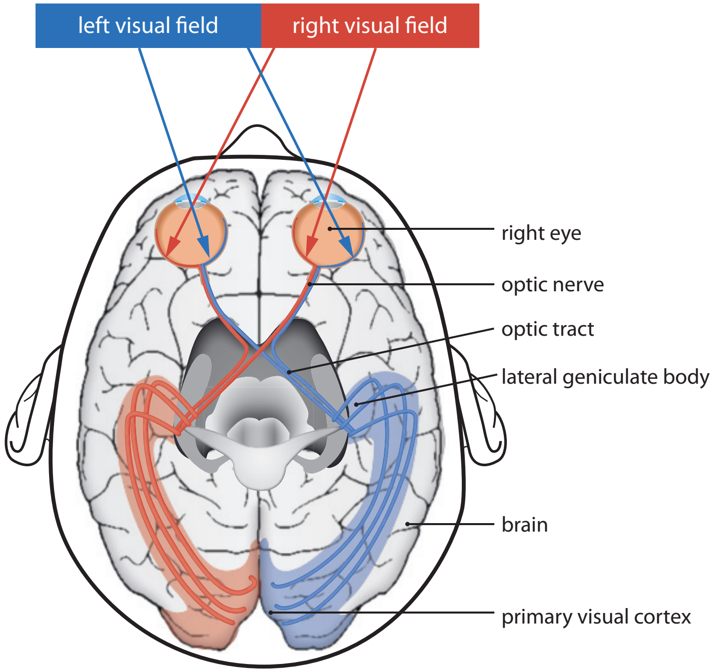

Figure 1.6 Transverse cross-section of the visual pathway including the primary visual cortex. The left and right areas of the retina are connected to different parts of the visual cortex. Hence, if one side of the visual cortex is impaired, the visual information of both eyes can still be used.

Eye lens Similar to the cornea, the eye lens is a transparent tissue which contains no nerve fibers or blood vessels. The required nutrients are supplied by the aqueous humor, which is a clear fluid. The eye lens is embedded into an elastic capsule which is again attached to the ciliary body via *zonular fibers*. The capsule is composed of collagen and varies from 2–28 μm in thickness. The lens itself consists of an *epithelial layer*, which is only located in the anterior part of lens, and the *lens fibers*. The cells of the epithelium are located between the lens capsule and the outermost layer of lens fibers. Lens fibers form the bulk of the interior of the lens. They are long (up to 12 mm), thin, and transparent cells whose diameter ranges between 4 and 7 μm. The eye lens consists of two kinds of fiber. The inner core, the so-called *nucleus*, is formed by primary lens fibers. The nucleus is surrounded by the *cortex* which is formed by secondary lens fibers. The major purpose of the lens is the refractive change (i.e. accommodation; Section 2.1.4) to focus nearby objects.

Eye chambers The interior of the eye is divided into three chambers. The space between cornea and iris is called the *anterior chamber*, and between iris and eye lens we have the *posterior chamber*. The remaining space between lens and retina is referred to as the *vitreous*. The anterior and posterior chambers are filled with aque-

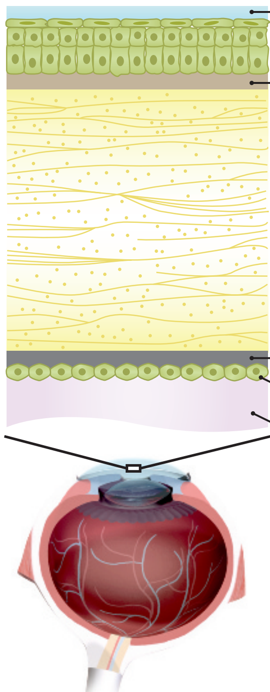

Figure 1.7 Detailed view of the corneal layer structure. The layer thicknesses are not to scale. Corresponding mean values are shown in parentheses. For reference, the cross-section of the whole eye is also shown. Adapted from [4].

ous humor which contains nutrients for the eye lens and inner cornea. The aqueous humor is produced by the epithelial cells of the ciliary body in an amount of approximately 2.4 mm^3/min and dispensed to the posterior chamber. It then flows continuously through the pupil to the *trabecular meshwork*, where it is eventually drained through *Schlemm's canal* (Figure 1.4). The relationship between production and discharge of aqueous humor determines the *intraocular pressure*, which is slightly higher than atmospheric pressure and approximately matches the intercranial pressure. The vitreous is filled with a transparent, colorless, gelatinous mass. In contrast to the aqueous humor, the vitreous does not flow through the eye.

Retina The inner layer of the human eye is referred to as the *retina*. The retina is an upstream part of the brain which "detects" light and converts the stimulus to neuronal signal, which are then transmitted by the optic nerve to the visual centers of the brain, where the image is eventually "formed". The retina will be highlighted in detail in the following section because of its high structural and functional complexity as well as its importance for vision.

Most parts of the eye are optically not accessible. When looking at the eye, we can only see the colored iris with the pupil and the white sclera. For optical imaging and structural analysis of the other parts, special optical techniques are required which we will discuss in Part Two of this book.

1.2
Retina: The Optical Sensor

The retina has evolved from the central nervous system and is actually part of the brain. It consists of approximately 127 million photoreceptors which convert incident light to electrical signals by a light-induced chemical reaction. These signals are than to some extent preprocessed by the retinal neural network and the ganglion cells. The nerve fibers of the approximately 1.2 million ganglion cells (called axons) merge on the *optic nerve head* (also called *optic disk*) into the optic nerve (Figure 1.5). From there, the neuronal signals are transmitted to the *primary visual cortex* of the brain (Figure 1.6).

1.2.1
Retinal Structure

The human retina is a multilayered tissue with a total thickness of about 180 μm in the fovea and between 200 and 400 μm elsewhere. The retinal structure is schematically shown in Figure 1.8. The retina contains two types of photoreceptors which are named after their shape: *rods* and *cones* (Figure 1.9). The photoreceptors are separated into three subregions, that is, outer segment, inner segment, and synaptic terminal. The outer segment is built up of a densely-packed stack of membranes which include the chromophores rhodopsin (rods) or iodopsin (cones)[2]. This part of the receptor is amazingly sensitive to incident light. If the eye is totally adapted to a dark environment, five to eight photons can be perceived when they hit the membrane within 20 ms[3]. The inner segment of a photoreceptor consists of the cell nucleus, mitochondria, and the endoplasmic reticulum. The synaptic terminal is a fiber-like extension of the nerve cell which conducts electric nerve impulses to the horizontal and bipolar cells of the retinal neural network. After some preprocessing there, these electrical signals are then conducted via the axons of the ganglion cells to the brain.

The spatial distribution of the photoreceptors across the retina is highly nonuniform (Figure 1.10b). The density of the about 6–7 million cones is highest in the fovea. The peak density of the about 120 million rods is located at about 15° from the eye's optical axis. In the fovea, no rods are present. Cones are only used under

2) Each pigment molecule consists of two components, a large protein molecule (*opsin*) and a small molecule derived from vitamin A (*retinal*). The latter is responsible for light absorption.

3) Light perception (also referred to as *transduction*) takes place in less than 1 ms. During this short period, the retinal molecule changes its shape and dissociates from its binding site on the opsin. This process, known as *bleaching*, is the only step in vision which depends on light. Then, an electrically conductive sodium ion (Na^+) channel is closed. As long as the channel is open in the dark, the excitatory neurotransmitter *glutamate* is steadily released.

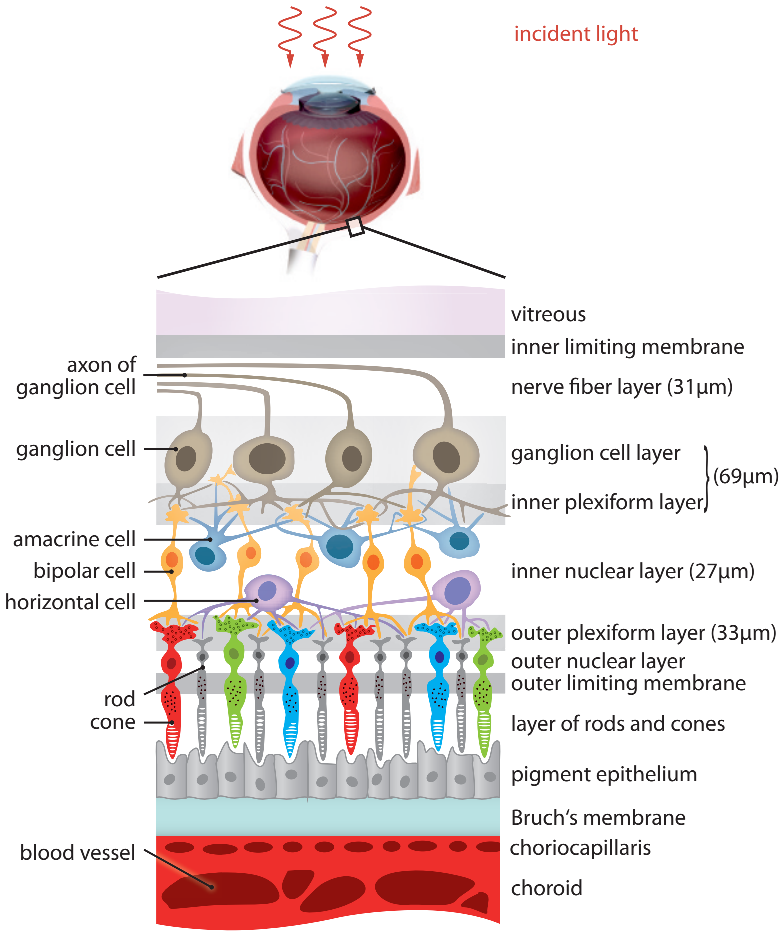

Figure 1.8 Cross-section of the functional retinal layers. At the top, the cross-section of the whole eye is added as a reference. The layer thicknesses and the relative distance (and density) of the photoreceptors are *not* to scale. Measured (mean) thickness values [5] of some retinal layers are shown in parentheses. The different colors of the cones refer to their distinct spectral absorption of light (Section 2.3). *S*, *M*, and *L* cones are shown in blue, green, and red, respectively. Adapted from [4].

sufficient ambient light conditions, that is, *daylight* or *photopic vision* (Section 2.1.6). In this case, three types of cones are used with different spectral absorptions so that we are able to perceive colors (Section 2.3). *S*, *M*, and *L* cones (color coding in Figure 1.8) contain pigments which absorb in the blue, green, and red spectral range, respectively. The human eye is thus *trichromatic* in daylight. The nervous system combines the signals of all types of cones and assigns a respective color.

In contrast to cones, rods are needed when the ambient light conditions are poor, that is, *night* or *scotopic vision* (Section 2.1.6). All rods contain the same chromophore so that the color impression decreases progressively with the light level.

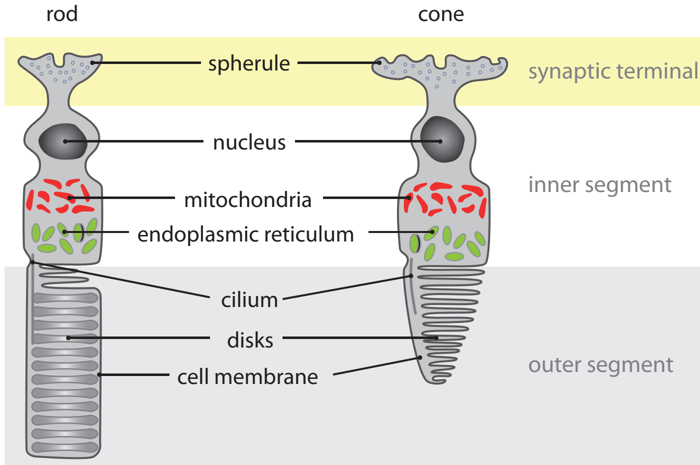

Figure 1.9 Segmentation and structure of retinal photoreceptors.

To achieve sufficient light sensitivity, the output signal of about 100 rods is combined on the way to the brain. As a consequence of this sampling the spatial resolution (Section 2.1.5) for scotopic vision is much lower compared to photopic vision, as in the fovea the density of cones is highest (Figure 1.10b), and each cone is connected to one nerve fiber.

1.2.2
Functional Areas

The *macula* (anatomic fovea centralis) is located in the center of the retina and is about 1.5 mm in diameter (Figures 1.5 and 1.10a). The most central part of the macula, called fovea (anatomic foveola), has a depression with a diameter of about 0.35 mm located at a field angle of approximately 5° from the eye's optical axis (Section 2.1.3). In this region we find the highest density of cone photoreceptors (Figure 1.10b). As a consequence, visual acuity and resolution for photopic vision (Section 2.1.5, Figure 2.8) have their maximum values in this region.

In the fovea, the cone nerve fibers are spread radially from the center and nearly parallel to the surface of the retina and form the so-called *Henle fiber layer* (Info Box 6.5). The first connection between the cone fibers and the bipolar cells of the neuronal network occurs outside the fovea. Consequently, there are no tissue layers such as inner plexiform, ganglion cell, and nerve fiber layers (Figure 1.8) above the foveal cones, which could result in an impaired image quality due to scattering of light (see Section 9.2) by these layers. For the same reason, the central part of the macula (500 μm in diameter) contains no retinal capillaries (so-called *foveal avascular zone*). Since rods are not present in the fovea, this area is basically night-blind. The sharpest vision in the case of scotopic vision is achieved at about 15° from the eye's optical axis because there we find the highest of the rod density (Figure 1.10b).

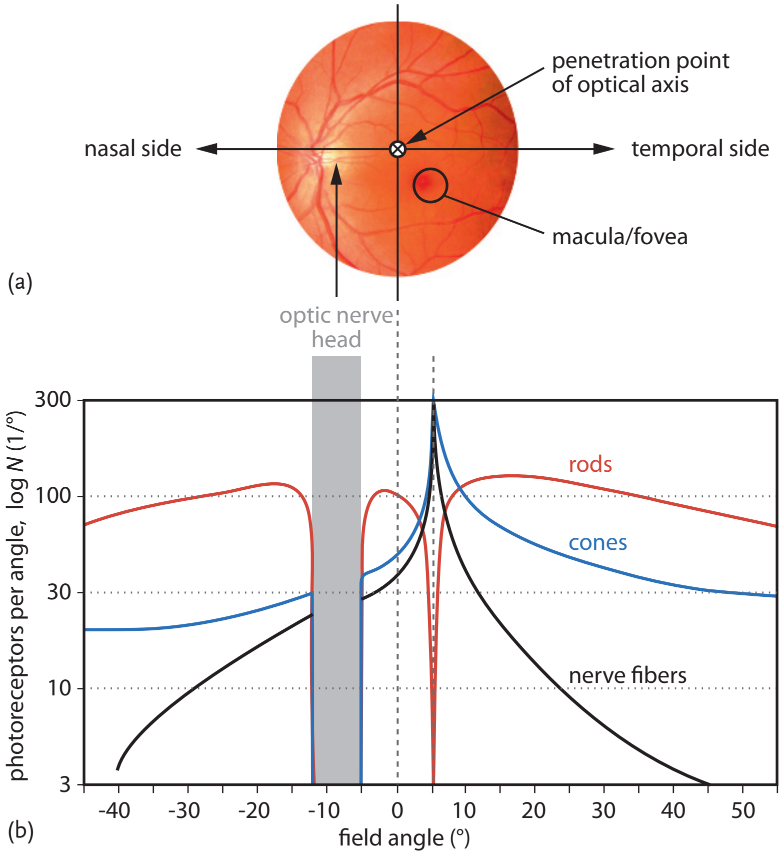

Figure 1.10 (a) Image of the eye fundus as a reference for the diagram in (b). The penetration point of the optical axis as well as the locations of fovea and optic nerve head are highlighted. (b) Distribution of photoreceptors and nerve fibers in the retina relative to the optical axis (0°). The logarithm of the number of photoreceptors *N* per degree of field angle is taken as the vertical axis. Data taken from [1].

It is worth noting that the human retina is an inverted detector (Figure 1.8). Incident light is converted to an electric signal by photoreceptors which form the lowest layer. After being preprocessed, the electric signal is transmitted by nerve fibers of the ganglion cell layer that form the top layer (towards the vitreous). This kind of structure has the advantage that photoreceptors can be directly supplied with nutrients by the choroid. At one common exit point, the nerve fibers are connected to the brain and, thus, have to penetrate all other layers (*not* shown in Figure 1.8). Here, at the optic nerve head, the retina is 600 μm thick, but does not comprise any photoreceptors (Figure 1.10b). The optic nerve head is located about 10° nasally relative to the optical axis and 1.5° upwards relative to the fovea (Figure 1.10a).

1.3 Recommended Reading

Further details about the anatomy, structure, and function of the human eye are presented in [1, 4, 6–10]. Further examples of visual illusions can be found in [11].

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