1 The formation of the perceived image

Content

The formation of the perceived image

First step: Generation of nerve impulses

The encyclopedia defines „seeing" as „the reception of light stimuli by the e*yes and the perception of the information content of these optical stimuli in the brain.*" In humans and vertebrates, light rays are refracted by the cornea, lens and vitreous body, resulting in an inverted actual image on the retina. The optic nerve transmits the relevant action potentials from the retina to the cerebral cortex, where they are processed.

„In Looking at an object we reach out for it. With an invisible finger we move through the space around us, go out to the distant places where things are found, touch them, catch them, scan their surfaces, trace their borders, explore their texture. It is an eminently active occupation." Rudolf Arnheim

The eye

Living beings' physical reactions to light are approximately 1.5 billion years old. Their early version most likely helped creatures convert physical activity from night to day, and light-sensitive cells on the skin that serve this purpose may still be observed in primitive single-celled animals today.

In a second phase, photoreceptors were placed in small pits to protect them from stray light and enhance the perception of moving shadows and potential danger. To shield these early eye pits from external objects, translucent membranes gradually formed over them, becoming thicker in the center and laying the groundwork for the creation of a lens. The first of these lenses may have only functioned to magnify light, and it took several million years for them to produce truly useful images. It was not until about 800 million years ago that eyes evolved, allowing living beings with various receptors to see both during the day and at night.

The eyes are essential to our vision today because they help the brain capture visual information. While the eyes resemble a camera in certain ways, they do more than just send a highly focused image to the brain; they also handle the first stage of the complex processing of acquired data.

The eyes are more than optical instruments. They perform the first stage of neurological processing of visual signals.

The human eye, as we know it now, is a roughly spherical object approximately 2.5 cm in diameter. The dense tissue of the **sclera** protects it from the outside, allowing light to enter only through the small transparent area of the cornea. The gelatinous mass of the so-called **vitreous humor** occupies the majority of the eye's interior, maintaining the entire structure's shape and protecting the sensitive portions. The **conjunctiva** covers the **cornea**, which is the eye's outermost functional unit. It refracts incident light most strongly and, when combined with the **lens**, produces a sharp image. The next structure inward is a tiny hollow filled with aqueous humor, which houses the **iris**. It is composed of thin connective tissue that contains the pigmented cells responsible for the eyes' various colors. However, this is merely a means to an end because, aside from the **pupil** (also known as the iris diaphragm) in the center, the iris must be completely lightproof. The **retina**, located at the back of the eye and responsible for reproducing the image seen, adjusts slowly to changes in luminance, so the iris serves as a protective diaphragm that closes quickly. It controls the pupil size between 2 and 8 millimeters, allowing it to reduce or increase the amount of incident light by two logarithmic units. Only after the iris makes an immediate adjustment do the sensory cells in the retina adapt to the new luminance. In addition to regulating light, the iris diaphragm is analogous to a camera aperture in that its constriction improves the depth of field during near vision. The trick of using an eye mirror is required to look through the pupil into the eye, as the observer's head constantly creates a shadow. Only when photographing with a flashlight can we frequently capture an unintended glimpse inside

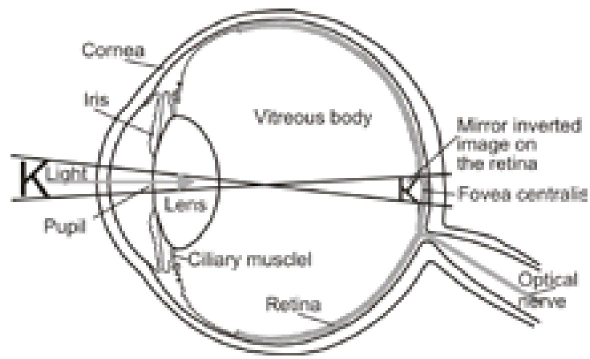

Figure 1: Cross section of the human eye

the eye. If the flash is too close to the lens's axis and the pupil is wide open due to poor ambient lighting, the retina, which is well supplied with blood, appears as a red reflection in the image. Flash units can mitigate this by either constricting the pupil with a series of pre-flashes that reflect minimal light back or by triggering the flash offset from the exposure axis.

The **lens** is located immediately behind the iris. It is responsible for the eye's adaptation to various object distances. For this purpose, the ciliary muscle on the right and left sides of the eye contracts or relaxes, and this movement is transmitted to the lens via the zonular fibers, which alter its curvature. If the object to be focused on is more than 6 meters away, the light rays fall nearly parallel onto the retina, resulting in a sharp image. When the object is closer, the image plane shifts behind the retina, and the rays no longer appear parallel. To enable near vision, the muscle contracts and, surprisingly, relaxes the zonular fibers, causing the lens to curve more sharply. This increased curvature causes the light to be refracted more strongly, and the image plane shifts forward sufficiently to allow the now-sharp image to fall back onto the retina. This adjustment, known as **accommodation**, prevents muscle vibrations from being transmitted to the ocular system. The lens, like an onion, is composed of layers. It grows over time as new cells adhere to its outer surface. Unfortunately, this growth process has the unintended effect of eventually restricting the flow of nutrients to the older cells inside, causing them to lose their suppleness. With age, the lens can no longer accommodate the optical system's adaptation to varying distances, and glasses or contact lenses must compensate for this loss.

The interaction of the cornea, iris, pupil, and lens produces a sharp, tiny, and upside-down image of our surroundings on the inner surface of the eye and the retina that lines it, similar to a camera obscura. For a long time, it was believed that the brain interpreted the image projected onto the retina as a whole using a kind of „inner eye." However, contemporary research has demonstrated that visual perception is far more sophisticated, involving intricate neural processing.

The retina

In evolutionary terms, the retina is an externally displaced portion of the brain's surface. It is only 0.1 millimeters thick and contains approximately 200 million closely packed, highly specialized nerve cells. The upside-down image of our environment falls onto it. The retina is a curved plane that corresponds to the curvature of the eyeball, giving it the advantage of being equidistant from the lens at all points and providing a sharp image everywhere. Furthermore, regardless of the light's angle of incidence, the curvature ensures consistency with the same fraction of the image scale.

The structure of the retina is notable for stacking its functional layers so that light reaches photosensitive cone and rod cells only after passing through the neuronal cells above them. This arrangement is analogous to inserting photographic film with the active side facing outward, which reduces contrast-degrading stray light. This is achievable without hazard because the neural plexus on top remains stationary, and our perception filters out such static impulses from our conscious view.

From back to front, the photoreceptors are followed by horizontal cells, then bipolar and amacrine cells, and finally ganglion cells. Each of these neuron types exists in several forms and performs functions beyond those listed here. For example, there are over a dozen different types of amacrine cells, as well as two major types of ganglion cells: small magnocellular cells and large parvocellular cells. Both are critical components of the „categorization of information“ process. Bipolar cells receive input signals directly from photoreceptors, and many of them connect to ganglion cells. Horizontal cells transmit data between individual receptors, while amacrine cells do the same for individual bipolar cells. This connectivity enables feedback (lateral inhibition) and the grouping of specific receptors or bipolar cells.

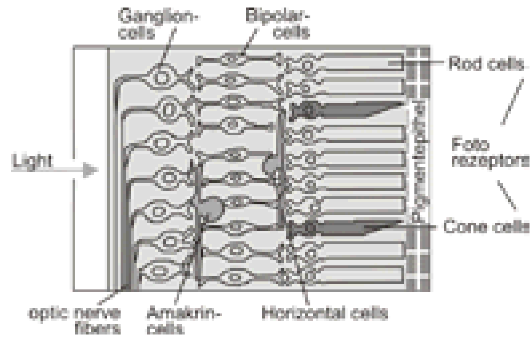

Figure 2: Cross section of the human retina

The photoreceptors in general

Light transports visual information, and the optics of the eye produce a two-dimensional representation of the surroundings and objects on the retina. Specialized sensors known as photoreceptors detect the incoming energy potential. At the current stage of evolution, each retina contains approximately 120 million highly specialized sensory cells that convert light into electrical signals and transmit information about the strength and chromaticity of the incident spectrum to the visual system. We distinguish between around 110 million **rod cells**, named for their distinctive shapes, and approximately 6 million **cone cells**.

The basic structure of both receptor types consists of three parts: the outer segment, the inner segment, and the synaptic body. To minimize the reception of reflected light, they are positioned upside down on the retina. The outer segment consists of approximately 1,000 stacked membrane discs, each containing photochemically active pigment. The key to vision is a combination of the large protein **opsin** and the small light-sensitive molecule **retinal**, a derivative of vitamin A. Because they absorb light, these pigments have a distinct color: a somewhat dark, opaque purple, known as

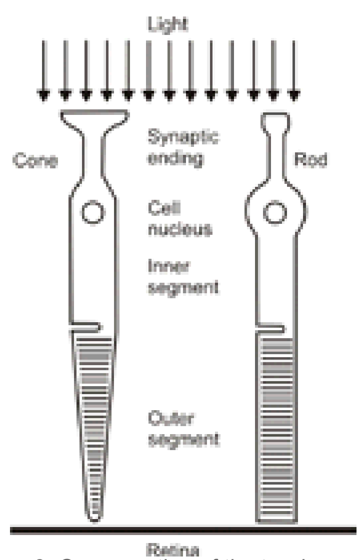

Figure 3: Cross section of the two human photoreceptor types

The formation of the perceived image

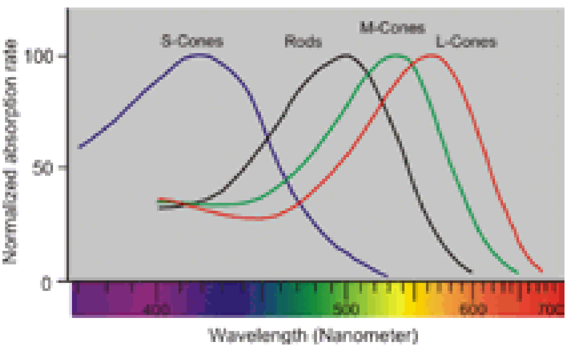

Figure 4: Normalized absorption spectra of the rod and cone cells; Bowmaker, Dartnall 1980

visual purple. When exposed to light, the pigment bleaches and becomes opaque white, rendering it ineffective for the visual process. The inner segment is responsible for regenerating these molecules. It renews depleted molecules, incorporates them into new membrane discs, and transports them to the outer segment, where they gradually reach the tip. Additionally, the inner segment houses the cell nucleus and the mitochondria (the cell‘s power plants), which support energy metabolism through protein synthesis. Finally, through the synaptic body, the receptor connects to downstream retinal cells.

All **rod cells** contain the photochemically active pigment **rhodopsin**, which makes them sensitive to wavelengths ranging from 440 to 620 nanometers (green-yellow). Each **cone cell** contains one of three distinct **iodopsin** pigments, which cover the spectral range from 400 nm (blue) to 700 nm (red), with a sensitivity maximum at 580 nm (yellow). The opsin‘s genetic code determines the wavelength range. Based on this classification, they are also known as **S cones** (short-wave, blue), ***M cones*** (medium-wave, green), and **L cones** (long-wave, red).

Let‘s take a closer look at **pigment bleaching**, as it is vital to the overall visual process. In darkness, the electrical potential difference between the inside and outside of the cell is -30 millivolts due to a continuous influx of sodium ions. During this stage, the synapse continuously releases messenger chemicals, thereby inhibiting the retinal cells from further processing. When exposed to light, the photochemically active pigment breaks down into its components: the protein opsin and the chromophore retinal. The free opsin alters the permeability of the cell membrane through a cascade of enzymes. The cell undergoes hyperpolarization when the ion channels close, preventing the influx of sodium ions, thus equalizing the potential and lowering the membrane potential to its resting value of -70 millivolts. As the receptor no longer releases messenger chemicals and ceases to inhibit the retina‘s downstream cells, these cells continue to transmit an excitation signal, resulting in the perception of brightness and color.

This is how vision works: light modifies the photopigments, triggering an electrochemical reaction that influences the activity of the synaptic connection and sends an impulse to the nervous system.