Vision

5

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Learning Objectives

- Seeing is not just receiving visual information.
- Seeing involves a process in which images are modified and interpreted by complex retinal and cerebral activities.
- Watching is a conscious and attentive form of seeing; e.g., the viewer knows what he sees.
- Seeing must be learned.
- Stereoscopic binocular single vision is the highest level of seeing.

Introduction

Aristotle (384–323 BCE) stated that of all our senses the eye is the most important. The recent observation that “about one-third of the human brain is dedicated to the mission of vision” [1] seems to confirm his statement after almost 2500 years. Until the year 1600, the so-called emission theory to explain how the eyes work prevailed. Perhaps based on the observation that cats show bright yellow-green eyes in the dark, Greek scientists and many others after them believed that eyes emitted beams that were constantly scanning the surroundings. Around 1600, it was Keppler who discovered that it is the other way around: Light beams enter the eye (immission theory), and the world is depicted on our retina. However, the difference between the meaning of the words seeing and watching illustrates that passive and active aspects are involved. Images projected on the retina need to enter numerous neural networks before they get a meaning. Already Descartes argued that visual images are processed as codes by our central nervous system [2].

Over the centuries, vision, as compared to other senses, only gained importance. At present, most human beings spend perhaps more than half the time they are awake looking at some kind of display: working, studying, relaxing, shopping, gathering information, exchanging personal information, reading, and anything; all can be done with smart devices and our eyes (and fingers). My personal screen time this week was 4.5 h a day, and this concerned just my desktop, not my other devices.

What Is Seeing?

Seeing is not only the ability to distinguish details, which allows us to read and write; it is also the perception of a three-dimensional field that offers

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us a position in spatial planning. With extremely fast eye movements (up to 700° per second), we scan our surroundings. Less than 2% of what we see is imaged in detail. Anything seen beyond this area is blurred. These parts of our visual field are being filled in with (visual) information by our brain based on previous experiences. The brain compares new images with those it has assembled during our life and focuses on what is new or different. In this way, our visual apparatus is a very economic and fast-responding system: Our attention is constantly drawn to those details that are new or do not fit in our previous perceptions [1].

The subjective aspect of seeing explains why sometimes two individuals see different things, although they look at the same thing. Even more fascinating is that a healthy, normal seeing individual alternatingly can see two different images when looking at one object. It appears impossible to see both images at the same time. Look at Fig. 5.1, what do you see: a duck or a rabbit?

What we actually see are differences in black and white, lines, and shapes resulting in figures that are saved in our visual memory system. These resulting figures can be interpreted as either a duck or a rabbit. Different neural networks compete for what appears in our awareness: the duck or the rabbit (Fig. 5.1).

Visual Pathways

Light beams are firstly refracted on our cornea, the window of our eye, secondly by our lens and next focused on our retina. Photons then travel through the transparent layers of the retina to the second deepest, the layer of the rods and cones. Here, they evoke an electrical signal, which is processed and sent backward to the second superficial layer, the nerve fiber layer, which eventually forms the optic nerve.

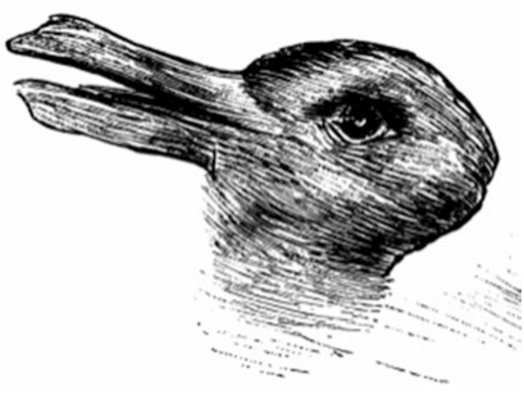

Fig. 5.1 Duck or rabbit? (Wikipedia—this image is in the public domain)

The visual information travels along the optic nerve to the optic chiasm, the lateral geniculate nuclei, and finally along the optic radiation to the primary visual cortex in the occipital lobes of our brain. Here, the images from both eyes are merged (if there is sufficient similarity) into a single, stereoscopic, three-dimensional percept. The globes or eyeballs can be regarded as a during the evolution pushed-forward part of our brain.

The visual system not only comprises afferent pathways as described above. The geniculate nuclei and the primary visual cortex connect with a broad network of cerebral regions, which in turn connect with the superior colliculus in the brainstem. From here, efferent fibers run to the dilatator and sphincter muscles of the iris, which results in a pupil size inversely proportional to the amount of light that falls on the eye. This reflex can be simply tested with a penlight in a semi-dark environment, with the person being examined looking into the distance. Because of mutual connections, not only the illuminated eye shows narrowing of the pupil, also the pupil of the fellow eye shows an identical contraction, which is called consensual reaction. A relative afferent pupil block (RAPD) indicates that something is wrong along this reflex arc, e.g., a tumor compressing the optic nerve or any other part of the optic pathways. In anterior uveitis (or iridocyclitis), the pupil cannot dilate as the iris is “glued” to the lens.

From nuclei in the midbrain, three oculomotor nerves (cranial nerves III, IV, and VI) innervate six eye muscles (per eye): four straight and two oblique muscles. A miraculously refined coordination system allows simultaneous movements of our eyes in all directions to a limit of about 50°. This coordination system is easily disturbed: Consuming a little too much alcohol already can result in blurred vision.

The retina is composed of ten layers. The most posterior is the pigment epithelium. Anteriorly lies the layer of the rods and cones. The human eye contains approximately 120 million rods and 7 million cones. The bipolar cells transmit the signals from the rods and cones to the more anteriorly located ganglion cells. A single bipolar cell may receive signals from several rods, which helps to intensify the light and movement sensitivity. In the center of the retina, called the macula lutea, the red- and green-sensitive cones are one-to-one connected to ganglion cells, which helps to create sharp vision. Amacrine and horizontal cells are dispersed between the bipolar cells and increase signal contrast. Horizontal cells transmit signals from cones and rods to other cones and rods and to several ganglion cells. Amacrine cells disperse signals from a bipolar cell to several ganglion cells. The axons of the ganglion cells transport the modified signals to the brain. Finally, Müller's cells compose a framework for the other cells.

The cones and rods contain light-absorbing pigments, for which composition vitamin A plays an important role. Vitamin A deficiency leads to hemeralopia: night blindness [2]. The rods contain the pigment-containing protein rhodopsin, which is sensitive to most forms of visible light. Rhodopsin cannot distinguish between different colors, which explain why we cannot see colors at night time when there is insufficient light to stimulate the cones. The rods of patients suffering from complete color blindness (or day blindness) are overstimulated during daytime with light. The rods are completely saturated and cannot see differences in brightness anymore. Night blindness is not always easily recognized. Day and night blindness are extremely rare.

Seeing Must Be Learned

Similar to playing the violin or golf, seeing must be learned. This occurs during the first seven years of life, provided that a clear image can be projected on the retina. When the pupil is covered by the eyelid (blepharoptosis), when the optical media (cornea, lens, vitreous) are not clear, or when the eyes are not straight, this learning process is impeded and the eye becomes amblyopic (i.e., lazy eye). In contrast to other learning processes, the ability to learn seeing comes to a complete halt at the age of about seven. Moreover, during those seven years, what has been learned already can be lost again if something happens that prevents the projection of a clear image on the retina. The earlier in life such an event takes place, the worse the visual outcome. The fact that input of the whole body is required for the development of proper seeing is demonstrated in the next experiment. Inside a cylinder with vertical black and white bars, one kitten was allowed to walk, whereas the other kitten was carried around in a box. Both kittens received exactly the same visual input, but only the kitten that was allowed to walk by itself developed normal vision [3].

Visual Acuity

Usually, the first thing that will be measured when you visit an optometrist or ophthalmologist with the complaint that you "see less" is visual acuity. This is a function of the macula lutea, the center of the retina in which the concentration of cones is maximal and, therefore, where the ability to see images in great detail is optimal. The outcome of this examination depends on the quality of your macula, but also of the refractive abilities of your eye. It was the Dutch ophthalmologist Frans Cornelis Donders (1818–1889), whose studies of pathology and physiology established the base for the correction of nearsightedness, farsightedness, and astigmatism. In nearsightedness (or: myopia), the focal point of the reflected image of the outside world lies in front of the retina, which explains why the image is not sharp. Myopic patients are corrected with concave lenses. In patients with farsightedness or hypermetropia, the focal point lies behind the retina. Without help, a young hypermetropic patient can create a sharp image by accommodating, e.g., by making his lens rounder. However, constant accommodation—for seeing nearby and in the distance—imposes an extra effort, and this may lead to fatigue and/or burning eyes or other nonspecific complaints. With aging, the ability of the human lens to become rounder decreases and nearby objects cannot be seen sharp anymore. This is called presbyopia. Presbyopia is superimposed on myopia and hypermetropia. Hypermetropic or presbyopia patients are corrected with convex lenses. People who are not myopic or hypermetropic are called emmetropic. The aging process of the human lens causes emmetropic people to look for reading glasses around the age of 45. Astigmatism, finally, is an imperfection of the curvatures of the cornea or (less frequently) of the lens. It can be corrected by aspheric, toric lenses.

Visual acuity is tested using derivatives of the Snellen optotypes. Herman Snellen (1834–1908) was Donder's successor as director of the "Ooglijders Gasthuis" in Utrecht. Compare an O and a C, depicted in black on a white background. When one is able to see the opening in the C as a distinct area (and assuming one is familiar with the Latin alphabet), one can conclude to see a C. This is the principle of Snellen's optotypes. With the Snellen chart, showing optotypes in decreasing size, the visual acuity (or the resolving power of the eye) is measured (Fig. 5.2).

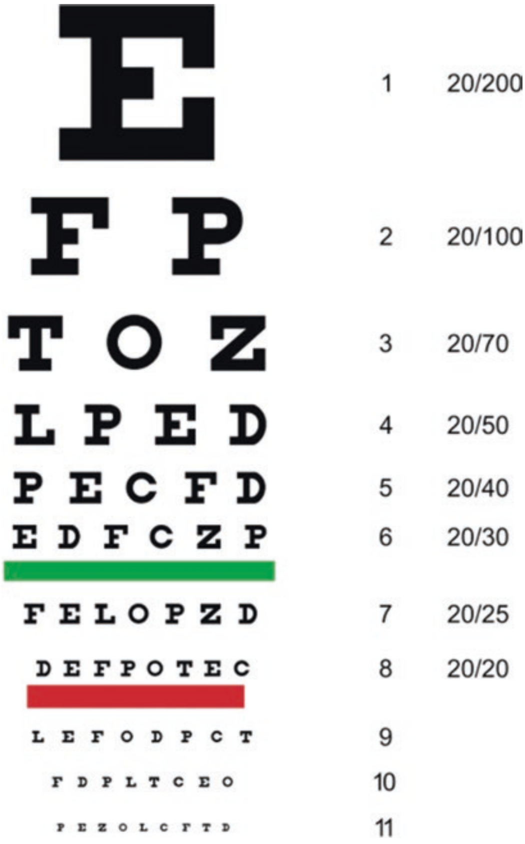

Fig. 5.2 Snellen chart (Wikipedia—Creative Commons Attribution-Share Alike 3.0 Unported license)

Color Vision

Light is defined as the part of electromagnetic radiation that is visible to the human eye and covers wavelengths between 400 nm (violet) and 750 nm (red). Objects that completely absorb light of all visible wavelengths appear as black, whereas objects that almost completely reflect light beams of all wavelengths are experienced as white. Strictly speaking, therefore, color is no intrinsic physical characteristic of objects. The sensation of color is created by our eyes and brain to make a distinction between objects possible. Color facilitates detecting borders of objects. While rods are 1000 times more sensitive to light than cones, they do not discern colors as the pigment-containing protein rhodopsin cannot discriminate between different wavelengths. In contrast, cones contain different pigment-containing proteins that transform light into electrical signals. There are three types of human cones, responding to different wavelengths: blue-sensitive (short wavelengths), green-sensitive (medium wavelengths), and red-sensitive (long wavelength). Sixty-five percent of our cones are red-sensitive, 33% are green-sensitive, and only 2% are blue-sensitive. Already located in the retina, circuits of cells make mixing of colors possible, which eventually leads to the ability to distinguish more than 100 different colors (if circumstances are optimal). More than 99% of all colorblind people are suffering from a red–green color vision deficiency. The X-linked recessive red–green deficiency affects up to 8% of males.

In most orbital diseases, color vision hardly plays a role. The exception is Graves' disease. Loss of color vision, especially over the blue axis, is an early manifestation of dysthyroid optic neuropathy (DON) [4]. Color vision is mostly tested with Ishihara's red–green pseudoisochromatic color plates. Although Ishihara's test is theoretically not the most sensitive test for patients with developing DON, it was found that almost all patients suspected of having DON responded abnormally to this test [5].

Seeing in Darkness

The human eye is able to see objects that are hardly illuminated and also things that receive more than one billion times more light (from the sun) [2]. However, it cannot see such objects at the same time. The human eye is gifted with a high potential of contrast sensitivity within a narrow range of light intensities [2]. In order to achieve this, the eye is able to adapt itself to the brightness of the light. Seeing under low-intensity light circumstances is called scotopic vision. Photopic vision is seeing under daylight circumstances. Cones are only stimulated when the light intensity surpasses a certain minimum and react immediately. Rods are far more light-sensitive, but need an adaptation time of minutes when light intensity decreases suddenly, e.g., when entering a dark room. Rods produce differences in gray, but no colors. Sharp vision disappears at night time.

Visual Field

The visual field is the total area that can be seen without moving one's head and eyes. It is grossly oval with its horizontal diameter larger than its vertical. The visual field of one eye covers that of the other eye for a large part. Only the center of the visual field allows binocular vision; in other parts, there is just monocular vision. The visual field warns of fixed or moving objects in the periphery and is thus of paramount importance in traffic circumstances. When fixating an object, we can distinguish a left and a right part of the visual field. The right part of the visual field of the right eye is projected on the nasal part of the retina, crosses the chiasm, and is then projected on the left hemisphere. The visual field is usually tested, each eye separately, with a Goldman (Chap. 6) or Humphrey perimeter. The fully developed classical visual field defects, such as homonym, heteronym, or bitemporal hemianopsia, are rare in orbital diseases. Instead, we find enlargement of the blind spot or cecocentral and paracentral defects, for instance, in patients with an optic nerve sheath meningioma or DON [6]. Typical eye diseases that are related to visual field defects are glaucoma and the family of inherited disorders of the photoreceptors called retinitis pigmentosa.

Stereoscopic Vision

When we fixate an object with both eyes, each eye sees that object from a different angle. In people with straight eyes, the two images are projected on corresponding retina points and are fused into one single image in the brain. We call this sensory fusion. The result is a sense of depth perception. A point in space further away from the fixated point is depicted nasally from the fovea (binasal disparity) and is therefore experienced as further away from the eye. A point closer to the eye than the fixated point is depicted temporarily from the fovea (bitemporal disparity) and is therefore appreciated as closer to the eye (Fig.5.3). Hence, stereoscopic seeing requires a geometrical construction, built up by two pupils and a fixation point. Prior to sensory fusion, the eyes have to be directed at the focus of attention. This is called motor fusion. Sensory and motor fusion are complementary. Binocular single vision and diplopia are extensively discussed in Chap. 6. Stereoscopic seeing enables evaluation of distances between two objects. Stereoscopic seeing, however, is limited. Beyond a distance of approximately five meters, this system adds little to monocular seeing because the differences in the angles between the two eyes become too small to be detected by our brain.

With only one eye, a limited form of stereoscopy is possible. This is called psychophysic stereoscopy. It is based on the (known) size of objects, the parallax, and accommodation state of our eyes.

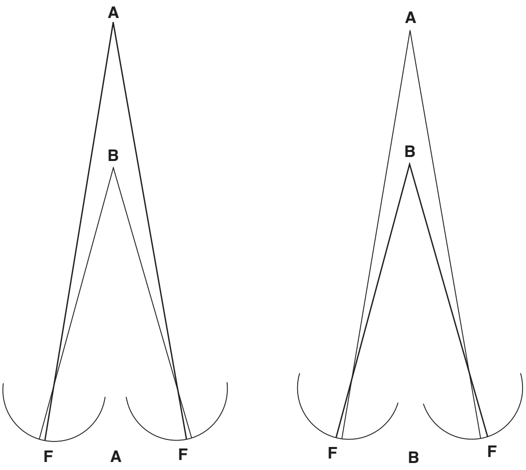

Fig. 5.3 Stereoscopic vision. On the left side, point A is being fixated. Point B, closer by, is being depicted on the retina with temporal disparity. On the right side, point B is being fixated. Point A, at a more remote distance, is being depicted with nasal disparity

For most daily activities, psychophysic stereoscopy suffices. For instance, individuals who have only one functional eye are allowed by law to drive a passenger car. In contrast, cataract surgery requires double-eyed stereoscopic vision. Stereoscopic depth perception is considered the ultimate level of seeing. Not every individual reaches this level. As mentioned before, seeing must be learned and ocular developmental disorders (e.g., squint) may prevent an individual from reaching the highest level of seeing. However, many individuals are not aware that they have no binocular single vision, nor are they aware that they have one amblyopic eye, and, nevertheless, they live happily.

Facial Recognition

Facial recognition is an extremely important characteristic of animals that live together in groups, such as primates. Humans have developed a refined facial recognition system, which allows a young baby already to recognize its mother’s face. The center of the retina (e.g., the macula lutea) and occipital brain center(s) are essential for facial recognition. Patients with advanced stages of macular degeneration (the most frequent cause of impaired vision in the Western world) lose the ability to recognize faces, which in turn may lead to social isolation.

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