The Importance of Light in our Lives[1]

An overview of the fascinating history and current relevance of Optics and Photonics

Lecture Notes

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[1] This subject is included in the University of Cantabria's Senior Program.

Figure 0. Simulation demonstrating the difference between human vision and cat vision. Source: Nickolay Lamm. License: Permission given explicitly by the author `http://bit.ly/1blQ9tz`

The Importance of Light in our Lives

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THE IMPORTANCE OF LIGHT IN OUR LIVES

Course Structure

This course is divided into 8 chapters and aims to provide an introduction to the main concepts of optics and photonics: from the use of the first magnifying glasses to the use of laser in a multitude of present-day devices and applications.

- **Chapter 1: The Historical Evolution of Optics and Photonics**

  With reference to the discoveries of key personalities such as Archimedes, Newton or Einstein, this chapter traces the fascinating history of the evolution of Optics through to Photonics, with the invention of the omnipresent laser and optical fiber.
- **Chapter 2: What is Light? Waves and Particles**

  This chapter aims to provide a clear and simple explanation of one of the "mysteries" that have most greatly concerned and occupied hundreds of scientists throughout the centuries: What is Light? Is it a wave or a particle?
- **Chapter 3: Sun, Light and Life: how the Sun and photosynthesis work**

  Life on our planet would not exist without the Sun and the energy it provides every second. Likewise, photosynthesis or the conversion of inorganic substances to organic compounds in plants, takes place thanks to the energy of light.
- **Chapter 4: The light that revolutionized the digital era: the laser and optical fiber**

  Today's society would not be the same if, back in 1958, the laser had not been invented and, thereafter, optical fiber. The Internet, the great communications phenomenon that has revolutionized our lives, is simply light (laser) travelling around the world through optical fiber. We will briefly review the invention of the laser, optical fiber and their fundamentals.
- **Chapter 5: Measuring the world using light: from biomedicine to civil work**

  Light not only serves for high speed communication via the Internet, but can also help us in a variety of applications: from precisely delimiting cancer cells to real-time monitoring of a bridge or dam. This chapter provides a brief explanation of some important examples that help us to better understand this "hidden" facet of light.
- **Chapter 6: The phenomenon of vision: how humans and animals see**

  This introduction to the world of light would not be complete if we were not to explain how one of the most incredible parts of our body works: the eye and the sense of sight. Furthermore, we will explore the differences between our sense of sight and that of other members of the animal kingdom.
- **Chapter 7: Photonics: current situation and future perspectives**

  This final chapter reviews some of the most recent advances in the world of optics and photonics and other possible future applications of this field of knowledge, which is fundamentally important today and will undoubtedly continue to be so in future decades.
- **Chapter 8: Experiments with light that you can do at home**

  Finally, we suggest a series of simple experiments that students can do to help assimilate the concepts explained during the course.

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Chapter 6

The phenomenon of vision: how humans and animals see

The sense of vision is absolutely fascinating, allowing us and many species belonging to the animal kingdom to interact with our surroundings in a variety of ways. This chapter will provide a s**hort review of how the human eye works** and also take a look at the **vision of other species** to analyze the many differences that exist.

6.1. The structure of the human eye

The **human eye** is no more than a sensor system which allows us to interact with our surroundings. Perhaps we should first of all define the concept of **sensor**:

A sensor is a device which converts physical or chemical magnitude into another magnitude, normally electric, and tries to quantitatively measure the phenomenon.

Is it right to define the eye as a sensor? Clearly it is: **the eye converts photons** (or beams of light), with information about our surroundings, **into electric signals that are then interpreted by our brains**. But, how does this process take place? **??** is a simplified diagram of this process: light rays that reflect off an object reach the eye, where certain components like the crystalline lens, allow those rays or beams of light to be correctly “focused” on the retina. The retina is the sensor or transducer where the image is formed and the optical signal (photons) is converted into an electric signal (electrons).

A detailed picture of the structure of the human eye is provided below.

Below is a description of the main parts of the eye:

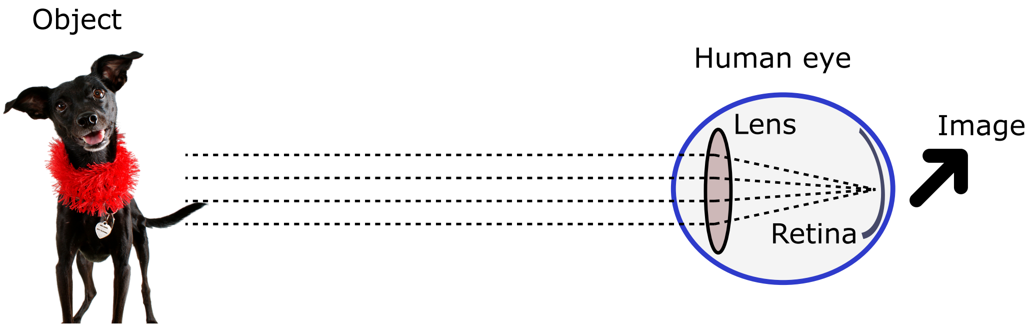

Figure 1. Simplified diagram of the phenomenon of vision and the human eye. Source: Author's own work.

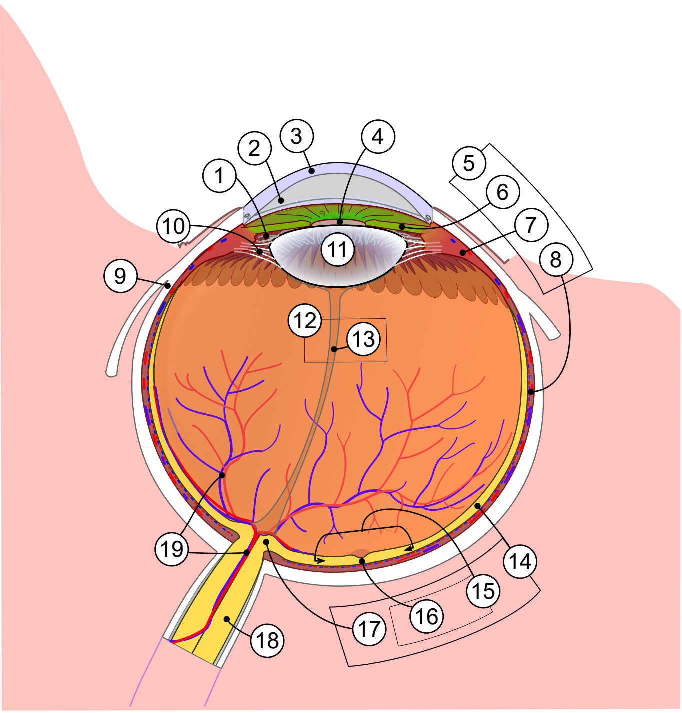

Figure 2. Schematic diagram of the structure of the human eye. Components: 1. Posterior chamber 2. Anterior chamber 3. Cornea 4. Pupil 5. Uvea 6. Iris 7. Ciliary body 8. Choroid 9. Sclera 10. Suspensory ligament of lens 11. Lens 12. Vitreous humor 13. Hyaloid canal 14. Retina 15 Macula 16. Fovea 17. Optic disc 18. Optic nerve 19. Retinal blood vessels. Source: Wikimedia. License: Public Domain. `http://bit.ly/2j9TBSH`

The cornea is a transparent hemisphere covering the front of the eye whose role is to let the light in and to protect the iris. The cornea is the first refractive surface for light rays entering the eye, its refractive index being 1.377[1].

Pupil and iris : the iris controls the amount of light entering the eye, by means of muscles that regulate the opening of the pupil (see Figure 3), the central orifice of the iris measuring about 3 millimeters in diameter.

The aqueous humor is a liquid that circulates around the lens, the iris and the cornea and which

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[1] If you cannot remember what the refractive index is, please look through the previous chapters again to correctly understand this important concept.

has different functions, like keeping eye pressure at normal level[2], nourishing and cleansing the cornea and the lens and also contributing to the refraction of light (with a refractive index of 1.337) although to a lesser extent than the lens.

The crystalline lens works like a bi-convex lens which enables focusing objects situated at different distances. This focusing process, called **accommodation**, is achieved thanks to an increase or decrease in the lens curvature and thickness (see Figure 4). The crystalline lens has a refractive index of 1.413.

The vitreous humor is, like the aqueous humor, a liquid which in this case occupies the space between the lens and the retina. Its two main functions are to maintain the shape of the eye and to ensure that the retina has a uniform surface for the best possible reception of images. The refractive index of the vitreous humor is 1.336.

The retina is the eye's sensor or transducer, which enables converting light into electrical impulses that are then interpreted by the brain.

The fovea is the area of the retina where the light rays are focused and this area is particularly responsible for color vision.

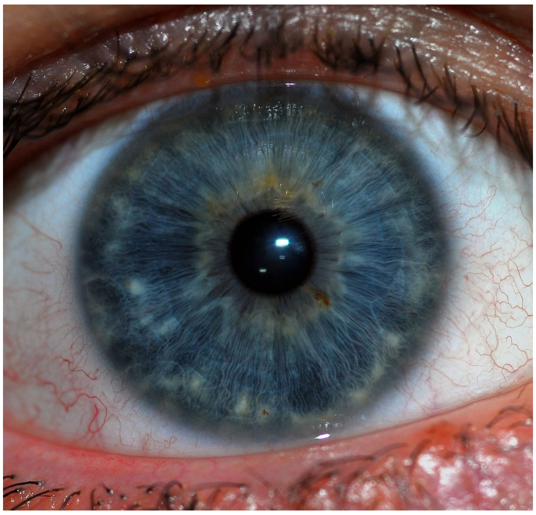

Figure 3. Close-up view of a blue human iris. Source: Wikimedia. License: CC-BY-SA 3.0. `http://bit.ly/2zkziNa`

6.2. Cones and rods: real eye sensors

As already discussed, the retina is the part of the eye that really enables vision, by converting light into electrical signals which are then conveyed to the brain. But how does this conversion process really take place? The retina consists of a series of cells that send the signals generated, but the key to the process of vision is in specialized retina cells called **photoreceptors** (or light receptors). There are two types of photoreceptors, cones and rods:

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[2] Excess intraocular pressure due to insufficient drainage of the aqueous humor is the cause of glaucoma.

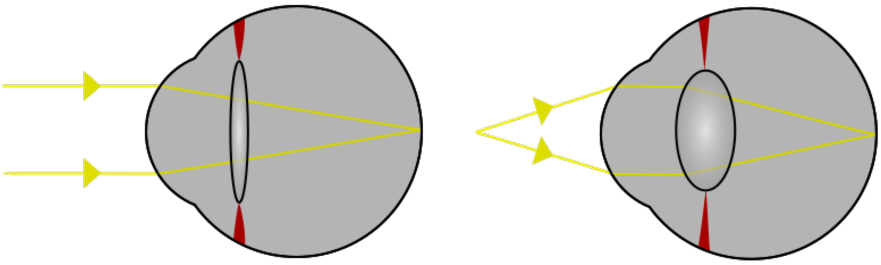

Figure 4. Diagram of the functioning of the crystalline lens and the accommodation process. Source: Wikimedia. License: CC-BY-SA 2.5. `http://bit.ly/2AeboTq`

Rods are greater in number (amounting to about **120 million**) and are more sensitive to light, in other words, they **enable us to see in dim light**. They are, therefore, responsible for enabling us to perceive details and forms in the dark, but they do not allow us to see colors. They are also associated with detecting movement and peripheral vision, as they are mainly situated in the area surrounding the fovea, which is the area of the retina on which light falls when we look directly at something and where there is a predominance of cones.

Cones are the photoreceptors **responsible for perceiving colors** and they are situated in the area of the retina where the image is projected when we look directly at an object, more precisely in the fovea and the surrounding macula. Here there are about 6 to 7 million cones.

As regards cones, it is interesting to note that there are **3 types of cones associated with the colors red, green and blue**. The other colors are formed by mixing those three "primary" colors, as occurs with conventional screens or televisions (which use an RGB system: Red, Green and Blue). Different studies have concluded that the spectral response of these cones is as shown in Figure 5, where we can see the 3 curves corresponding to the red, green and blue cones and the curve corresponding to the rods (the dotted line). The horizontal axis indicates the wavelength associated with each color1. The alternative terms S (*Short*), M (*Medium*) and L (*Long*) for blue, green and red cones respectively are also given, which come from their wavelengths.

Question 2.1: RGB screens

Find out and explain **in your own words** how the colors shown on television screens (for example LED screens) or computer monitors are formed.

Question 2.2: Color in printers

Find out and briefly explain **in your own words** how colors are formed in conventional printers: is the RGB system also used here?

Interestingly, the "blue" cones are only 2 % of the total amount of cones and are located outside the central fovea area where the red and green cones are. Although these cones are more sensitive, this fact alone does not explain how the different colors are appreciated with a similar sensitivity. It is believed that there is a system in the brain which "amplifies" the signals coming from the blue cones so that the final result is balanced.

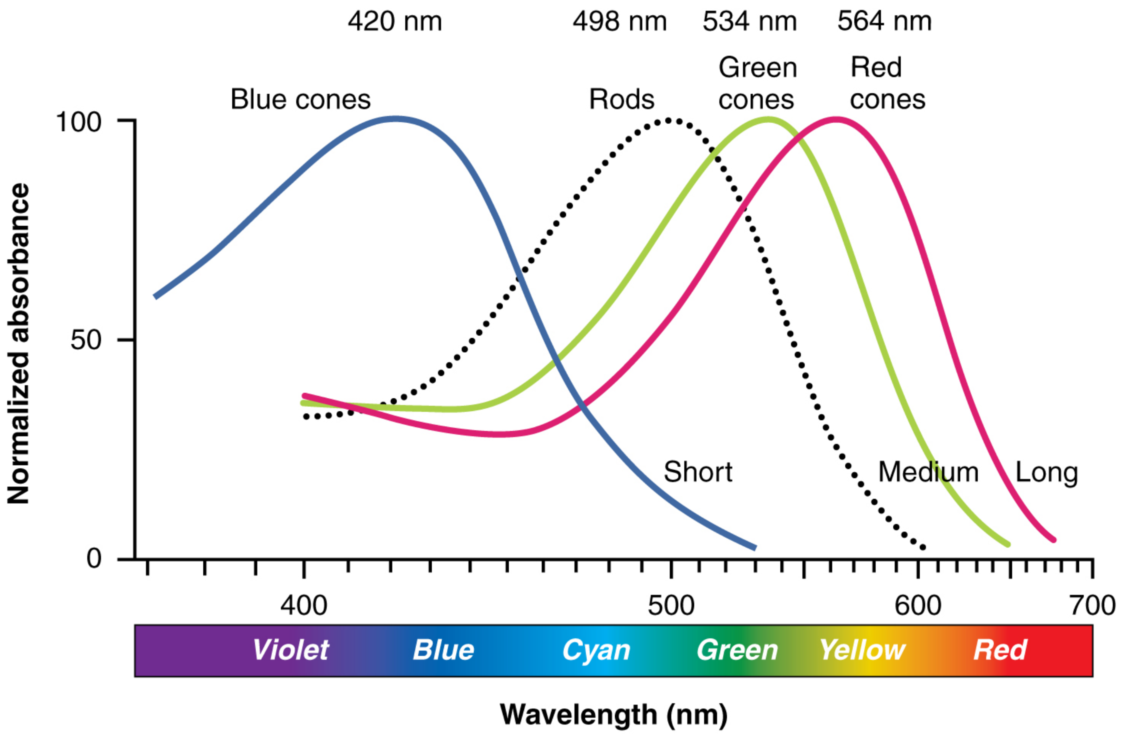

Figure 5. Representation of the response associated with blue, green and red cones (photoreceptors). Source: Wikimedia (original image modified). License: CC-BY-SA 3.0. `http://bit.ly/2hNbvu8`

Important 2.1: Deep blue

The visual perception of objects with a deep blue color is less clear than the perception of objects which are red and green. This can be seen in the images shown at the following link[a] and is due to the fact that the blue cones are located outside the fovea, which is the area where we focus our “direct” vision.

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[a] `http://bit.ly/2zdtjpn`

6.3. Vision defects

Having explained how the human eye works, it is now time to take a closer look at how **normal vision** takes place and what happens when the process is altered due to a number of different reasons.

A normal eye provides a perfect image on the retina of a distant object. When the object gets closer, the lens deforms so that the image of the object, which is not in focus, is still formed on the retina (this process is called **accommodation**, as already shown in Figure 4). This lens deformation is at its maximum when the object is situated at distance d_m (called **least distance of distinct vision**), which varies with age. For adult people, a normal d_m distance is considered to be about 25 cm, being 15 cm at the age of 30 and 7-8 cm in children.

6.3.1. Vision defects: myopia, presbyopia, hyperopia and astigmatism

Myopia is caused by excess convergence in the eye's optical system, forcing the image to be focused in front of the retina, as shown in Figure 6. It is precisely this "lack of focus" that makes distant objects appear blurry.

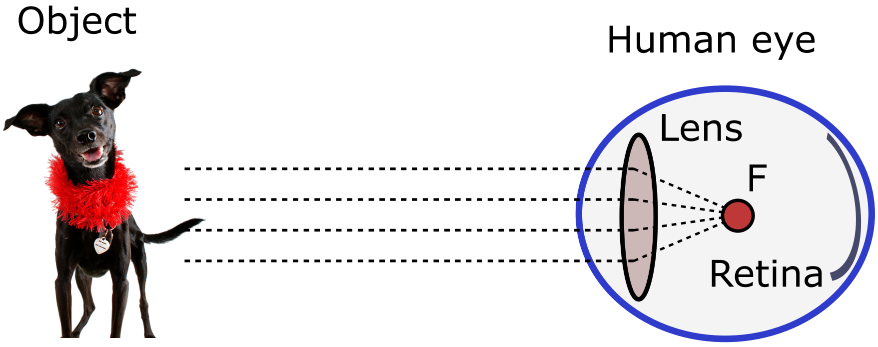

Figure 6. Schematic diagram of myopia. Source: Author's own work.

However, over the years the lens' ability to adapt lessens and it loses part of its original flexibility (what is known as **presbyopia**). Thus, the least distance of distinct vision d_m increases, what is known as tired eyes (see Figure 7), resulting in difficulty to see nearby objects clearly. It mainly affects adult people, to be precise more than 80 % of people over 45 years of age and almost 100 % of people over 65 years of age.

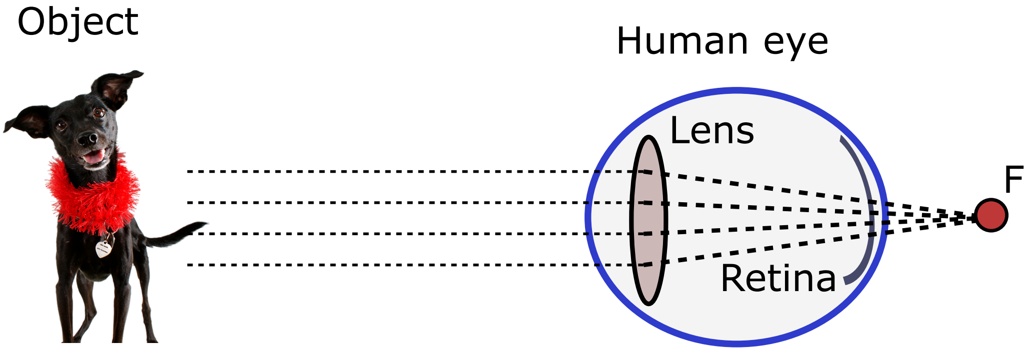

Figure 7. Schematic diagram of presbyopia. Source: Author's own work.

Hyperopia has very similar symptoms to presbyopia, but affects younger people due to the fact that is not caused by deterioration in the flexibility of the lens, but to the eye's incorrect refraction of light, again resulting in a focal point beyond the retina, as shown in Figure 7. Contrary to presbyopia, with hyperopia there may be a significant hereditary factor.

Finally, **astigmatism** is a vision defect where non-uniform refraction takes place in the eye, therefore two focal points are generated, one in front of and one behind the retina, instead of one on the retina as occurs in a "healthy" eye. The main symptom of astigmatism is blurred vision, both of nearby and distant objects, as well as difficulty in perceiving small detail in images. Figure 8 is a diagram showing the focal point of an image in an eye with astigmatism (left), and the effect that astigmatism has on vision (right).

Generally speaking, these vision defects can be solved or improved using lenses, although surgery may be necessary in some cases.

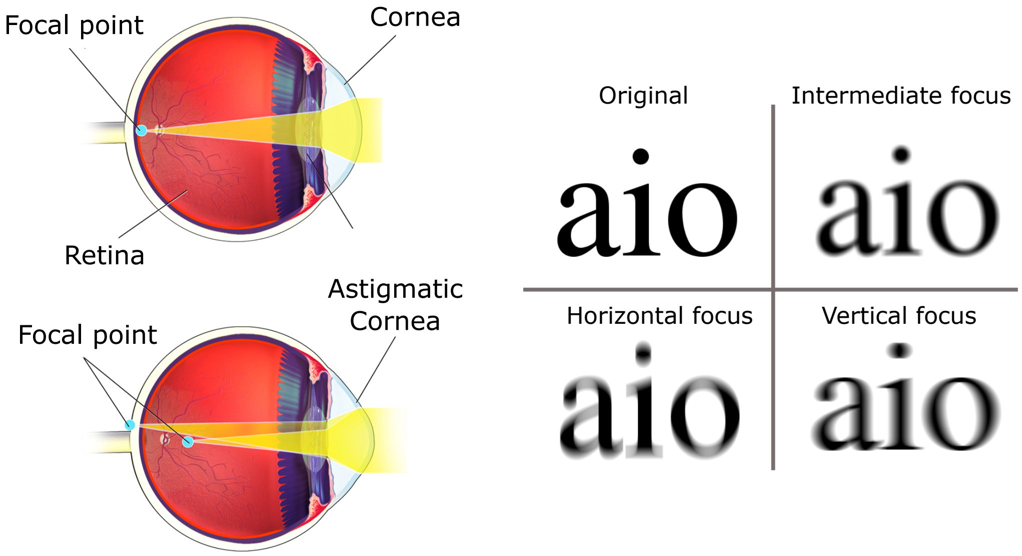

Figure 8. Schematic diagram of astigmatism (left) and the effect of astigmatism on vision (right). Source: Wikimedia. License: CC-BY-SA 4.0 (left); BSD ((C) Jean-Jacques Milan.)

6.4. Returning sight to the blind: the bionic eye

Scientific development over recent years has made it possible to return sight to people who, due to disorders like *retinitis pigmentosa*, have become blind. This major breakthrough, in which Spain is at the cutting edge thanks to the **Barraquer Ophthalmology Centre**, involves using a device called the *Argus II Retinal Prothesis System*, which works as follows:

A small camera housed in the patient's glasses captures the images of their surroundings.

A transmission system sends these images to a device implanted in the patient's retina.

A chip with electrodes substitutes the function of cones and rods, thus allowing the transmission of electrical pulses to the patient's brain, where they are interpreted.

Following this complicated operation, the patient must carry out a long period of rehabilitation (see Figure 10) to retrain their system of sight. In fact, the patient must have been able to see at some point in their life in order for their brain to use their visual memory. Sight is not completely restored, but it is possible for patients to recognize lights, shapes and people, which is great step forward for a blind person.

6.5. 3D vision glasses: how do they work?

Nowadays, **3D glasses** are commonly used in movie theatres, providing a different visual experience, as if certain objects were coming out of the screen towards us, the spectators. However, very few people are actually aware of the simple principle behind them.

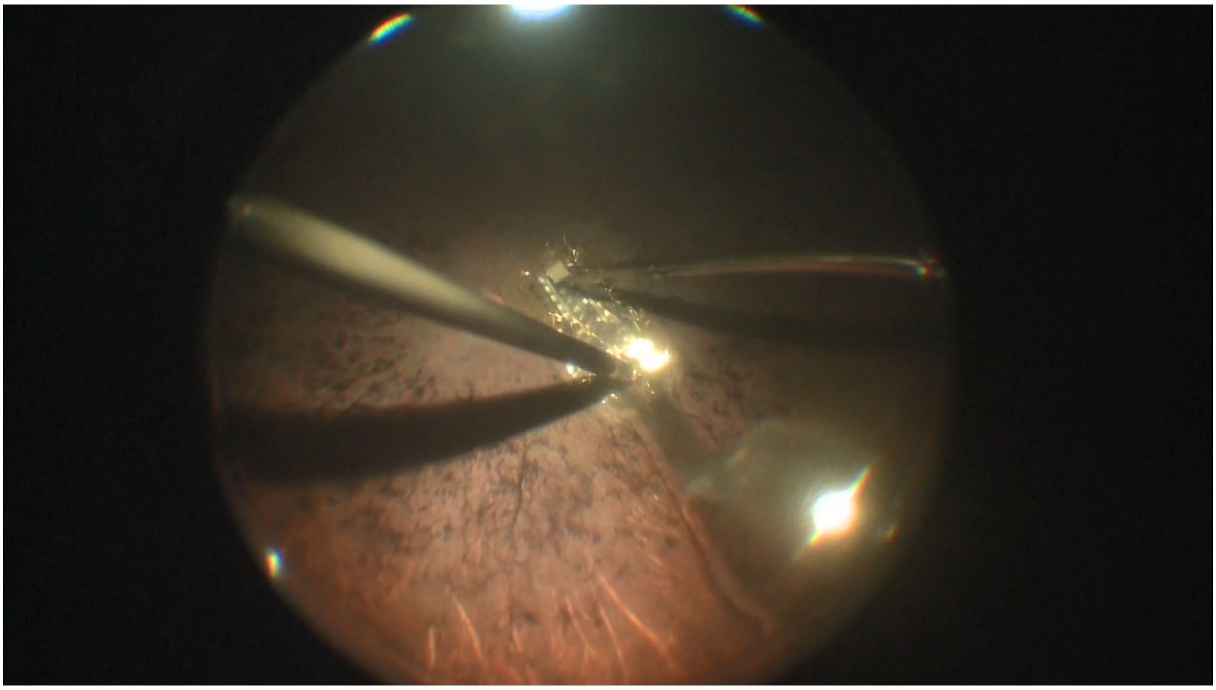

Figure 9. Image of the surgical procedure to implant the chip in the patient's retina. Source: Barraquer Clinic (Dr. Jeroni Nadal).

Figure 10. Picture of a patient during the rehabilitation process following his operation at the Barraquer Clinic. Source: Barraquer Clinic (Dr. Jeroni Nadal).

To explain how 3D glasses work, we must first explain a phenomenon called the polarization of light. At this point in the course, we are well aware that Light can be understood as a wave (more precisely, as an electromagnetic field that propagates like a wave). The polarization of light is simply that electromagnetic field's direction of vibration. For example, "ordinary" light, such as sunlight or light from a conventional bulb, is not polarized, but instead vibrates in all directions. However, if a "polarizing filter" is used, then the light is polarized: in the example in Figure 11, the light would be vertically polarized.

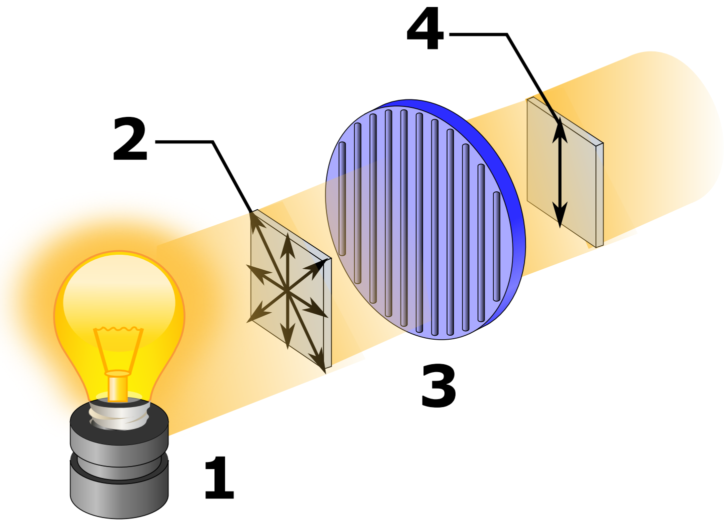

Figure 11. The polarization of light: using a vertical polarizing filter. Source: Wikimedia. License: CC-BY-SA 3.0. `http://bit.ly/2AeYuDN`

This is precisely the system used in 3D glasses. The left lens has a horizontal filter incorporated and the right lens has a vertical one. This way, each eye receives different information corresponding to interleaved **frames**[1]. This system is based on our **stereoscopic vision**, which basically means that, as our eyes are separated, each one generates a slightly different image. Our brain then processes them and is capable of differentiating the distances between the different objects that appear on the screen, thus creating the sensation of depth.

In fact, the forerunner of these 3D glasses is the **stereoscope**, invented by Sir Charles Wheatstone in 1840 (see Figure 12), which is still used today in some publications.

Question 5.1: Polarized sunglasses

As well as the 3D glasses used in movie theatres, there are various models of sunglasses that are "polarized". Find out and explain **in your own words** what benefits there are to incorporating a polarization filter into sunglasses.

Important 5.1: Polarization: mobile and sunglasses

If you have a mobile telephone and sunglasses (polarized) and have used them at the same time, you might have experienced the strange effect produced when you rotate your mobile. Look for information about this phenomenon and explain it in your own words[a].

[a] Clue: look at **??**.

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[1] *Frame* is the term which refers to each one of the static images that make up a video or sequence.

Figure 12. Stereoscope (above) and stereoscopic card from 1899 (below). Source: Wikimedia. License: CC-BY-SA 2.5 (above) http://bit.ly/2AFqFwL; Public domain (below). `http://bit.ly/2zNTOWQ`.

6.6. The animal eye

Having analyzed in detail the structure of the human eye, we are now going to devote a section of this chapter to the **peculiarities of vision in some animal species**. We do not intend to make an in-depth analysis in each case, but to simply point out some interesting facts and the most significant differences.

6.6.1. Horse vision

One of the main peculiarities of equine vision is that it covers almost 360°, to be specific about 350°, as a horse's eyes are located on the sides of its head. This arrangement makes it possible for horses to easily detect possible predators. However, horses have two "blind" spots, one just in front (they are capable of seeing from 2 meters directly in front of them, but not before that) and another one just behind. It is thus advisable to approach a horse laterally, so that it can see you, otherwise it may get a fright and react violently.

Horses have **dichromatic vision** (as opposed to human trichromatic RGB vision); this means that they distinguish two colors as they have **two kinds of cones, green and blue**. However, the

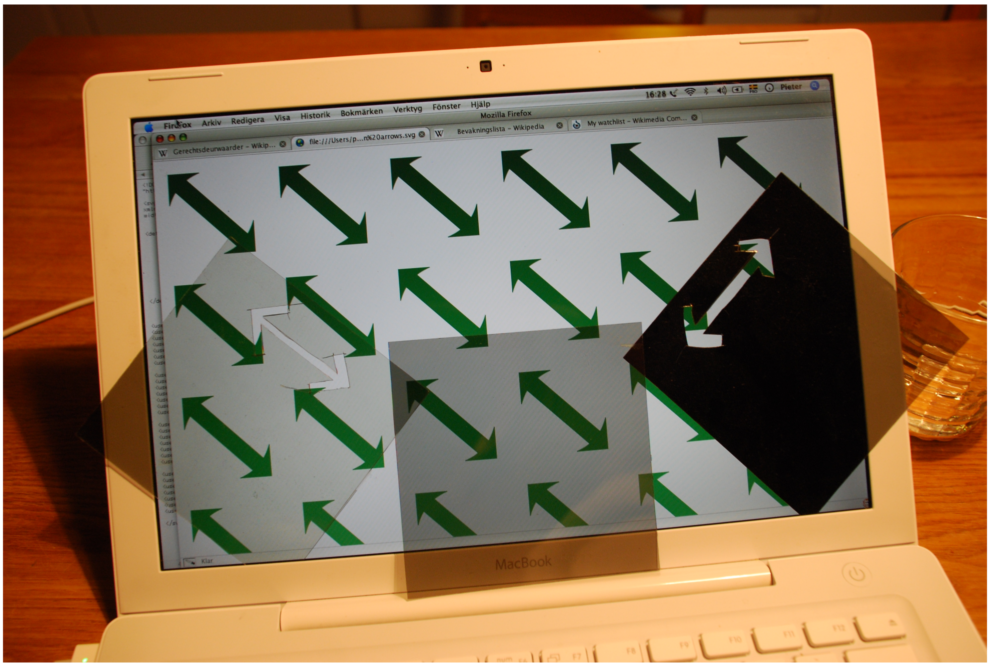

Figure 13. Computer screen with two polarization filters. Source: Wikimedia. License: Public domain. `http://bit.ly/2BuIgoi`

Figure 14. Close-up of a horse's eye. Source: Wikimedia. License: CC-BY-SA 3.0. `http://bit.ly/2BlNjXi`

rod/cone proportion is much greater than ours (20:1), providing a high sensitivity in dim light and excellent nocturnal vision. Horses are highly sensitive to movement, which could imply a predator attack. Movement is usually detected by peripheral vision which, being less sharp, means that a horse may bolt in the face of any movement detected in this field of vision.

Important 6.1: Horses, obstacles and colors

Equine vision is taken into account when designing the obstacles in certain trials, which use colors that can be easily identified by these animals.

6.6.2. Cat vision

One remarkable characteristic of cats' eyes is that the geometry of their pupils varies, in order to automatically adjust to the amount of light available. That is why their pupils sometimes look round and other times look vertically elongated (see Figure 15).

As occurs with horses, cats have a lot more rod photoreceptors than cone photoreceptors, which means that their vision is good in dim light. Moreover, cats have a **reflective membrane behind the retina**, called the ***tapetum lucidum***, which reflects the light, increasing their sensitivity by approximately 44%. This membrane is the reason why **cats' eyes glow in the dark** or when you take a photo of them (see Figure 16).

Figure 15. Different images of cats' eyes. Source: Wikimedia. License: CC-BY-SA 3.0.

Figure 16. *Tapetum lucidum* in a cat. Source: Wikimedia. License: CC-BY-SA 3.0. `http://bit.ly/2AHf0xt`

However, it is not true that cats cannot perceive colors. Instead they are believed to have **dichromatic vision** (like horses) which enables them to distinguish blue-violet and green- yellow.

Figure 17 shows two compositions by the graphic artist Nikolay Lamm[1] who, with the help of several professionals, has hypothesized what cats may perceive visually as compared to humans. In the first example, we can see how during the day cats perceive images with less color detail which are more "saturated", due to the large amount of rods (as opposed to cones) that they have. On the other hand, in low-light conditions at night, cats are much more capable of perceiving the details of a scene, which is precisely thanks to this large amount of rods.

The vision of dogs is similar to that of cats as regards the proportion of rods and cones, dichromatic vision and the tapetum lucidum.

Figure 17. Simulation demonstrating the difference between human vision and cat vision. Source: Nickolay Lamm. License: Permission given explicitly by the author. `http://bit.ly/1blQ9tz`

6.6.3. Bird vision

Whereas in other animals, like dogs, vision defects are compensated for by the enhancement of other senses, like the sense of smell, in birds, **sight is their strongest sense**. Logically, there are differences depending on the bird species, birds of prey being those with the best vision.

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[1] You can look at his work at the following link: `http://nickolaylamm.com/`

Birds, like other vertebrates apart from mammals, have **4 kinds of cone-type photoreceptors, involving the colors red, green, blue and also ultraviolet (UV)**. Indeed, birds are capable of seeing UV radiation and are believed to have evolved this way in order to better locate their prey, as the urine of certain prey species strongly reflects this radiation. About 50 % of birds have a second fovea, which helps them to focus lateral images better.

Figure 18. An owl's eyes. Source: Wikimedia. License: CC-BY-SA 2.0. `http://bit.ly/2jwHWxt`

As well as having a greater number of photoreceptors, **their optical nerve is also larger and a larger part of their brain is devoted to processing images** (as occurs in dogs with the part dedicated to processing scents, compared with humans). The greater number of photoreceptors, specifically cones, enables birds to make a very good distinction between colors, thus being able to detect a green insect on a leaf. Finally, birds' visual detection of movement is much better than that of humans owing to the fact that, amongst other factors, **their visual system is capable of capturing 100 images per second, as opposed to 25 in the human eye**.

6.6.4. Snakes: thermographic vision

There are a lot of similarities in the vision of snakes to that of other vertebrates, although **there is one fundamental difference in the way that they focus**. In the section on human vision, we saw how a process of accommodation takes place, however snakes do not modify the curvature of the lens to focus, but instead **move the lens forward and backward**. The majority of snakes have cones and rods. Furthermore, some species like rattlesnakes are **capable of detecting infrared radiation**. As discussed earlier on in the course, infrared radiation is associated with the heat of objects, therefore this characteristic is tremendously useful for detecting potential prey. This infrared vision is possible thanks to extremely sensitive thermoreceptor cavities, capable of detecting temperature variations as subtle as 0.001°C.

6.6.5. Insect vision

The majority of adult insects have **a pair of compound eyes and three simple eyes called *ocelli***, which are normally situated at the top of their heads between the compound eyes and, being simple, are only able to distinguish differences in the intensity of light received.

Figure 19. Close-up of a snake's eye. Source: Wikimedia. License: CC BY-ND 2.0. `http://bit.ly/2zA0in0`

Figure 20. Eyes of a Holcocephala fusca Robber fly. Source: Wikimedia. License: CC BY-SA 2.0. `http://bit.ly/2j2FsqV`

The compound eyes are composed of units called ***ommatidia*** which act like an independent eye, the final image being the sum of what each unit contributes. The number of ommatidia or units in a compound eye varies according to the species, and can range, for example, between 6 and 1000 in different kinds of ants; a domestic fly has about 4000; a bee has about 6000; butterflies have between 10,000 and 30,000, depending on the species; and dragonflies have more than 40,000[1]. It is believed that the vision process in insects results in images that are more "grainy" and less sharp than in humans.

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[1] Fuente: www.investigacionyciencia.es `http://bit.ly/2jwnfkW`

6.7. Conclusions

This fascinating chapter has provided a review of the **process of vision**. Beginning with **human vision**, we have analyzed the **structure of the eye** and described the vision process, pointing out some typical sight defects and providing information about vision with 3D glasses or the possibility of restoring sight by using cameras and retinal implants.

A short description has also been given of the particularities of **vision in other animals** such as horses, dogs and cats, birds, snakes and insects.

List of Figures