The eye and sight

This chapter introduces the basic features of the human eye and the important concepts of depth of vision and accommodation. The function of the two different light-sensitive cells in the eye, called rods and cones, is discussed, and their role in vision under different conditions is analysed. The role of cones in colour vision is also discussed. Primary colours are introduced, and colour addition and subtraction discussed. The chapter ends with a brief note on the role of colour in perception.

Objectives

By the end of this chapter you should be able to:

- make an annotated *diagram of the eye*;
- explain the *function* of the main parts of the eye;
- outline the differences in the *density of rods and cones* across the retina;
- define *scotopic vision* and *photopic vision*;
- account for the *differences in scotopic and photopic vision*;
- understand the terms *primary colour* and *secondary colour*;
- understand the difference between *addition and subtraction of colours*;
- solve simple problems with *colour mixing*;
- understand the role of light in the *perception* of objects.

The structure of the human eye

The human eye is a remarkable 'instrument'. Figure A1.1 shows the basic features of the human eye. The eye is almost spherical in shape, with a diameter of about 2.5 cm. Light enters the eye through the **cornea** (a transparent membrane), where most of the refraction takes place. The index of refraction of the cornea is about 1.37, substantially different from the index of refraction of air (1.00).

In between the cornea and the eye lens is a liquid-filled chamber called the **aqueous humour**. The liquid filling the chamber is clear, mainly water with small amounts of salts. Its

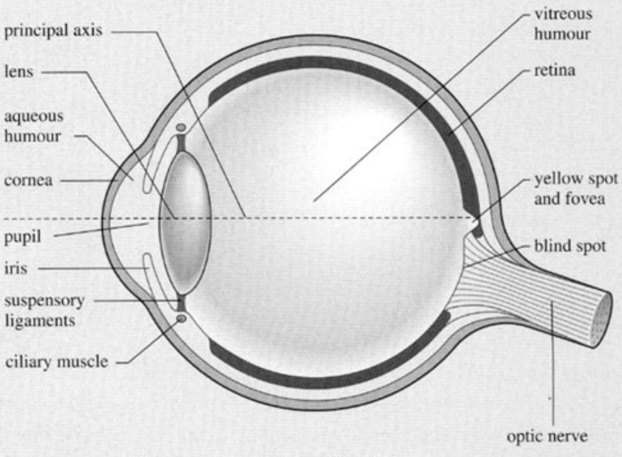

Figure A1.1 The human eye.

index of refraction is 1.33, essentially equal to that of water. This chamber is separated into two parts by the **iris** (the coloured part of the eye). At the centre of the iris is the **pupil**, an aperture through which the light enters the eye **lens**. The pupil can increase or decrease in diameter in order to adjust to varying intensities of light. The eye lens is attached to the **ciliary muscle** by ligaments – the ciliary muscle controls the curvature of the lens.

Light passing through the lens then enters a second chamber filled with a jelly-like substance called the **vitreous humour**. The light finally reaches the back surface of the eye, the **retina**. The retina is covered with light-sensitive cells that record the arrival of light. There are two types of light-sensitive cells on the retina, called **rods** and **cones**. Light reaching the rods and the cones is converted into tiny electrical signals in nerve fibres attached to these cells. The nerve fibres all converge to the **optic nerve**, which transmits the electrical signals to the brain. Close to the beginning of the optic nerve, and essentially on the principal axis of the eye, is an area called the **fovea**, a spot of diameter of about 0.25 mm, where vision is exceptionally acute. This is filled with cones, each connected to a different nerve fibre (unlike elsewhere on the retina, where many different cones are connected to the same fibre).

The distribution of rods and cones is not constant along the surface of the retina. At the fovea we have many cones but no rods. The density of cones at the centre of the fovea reaches 150 000 per mm^2. The rods are mainly found at the edges of the retina (i.e. away from the principal axis of the eye), whereas the concentration of the cones increases as we approach the principal axis.

Depth of vision

Figure A1.2 shows a converging lens and a set of rays, all parallel to the principal axis of the lens, incident on the lens. The rays refract and all pass through the same point on the principal axis of the lens. This point is called the **focal point** of the lens, and its distance from the optical centre of the lens is called the **focal length**.

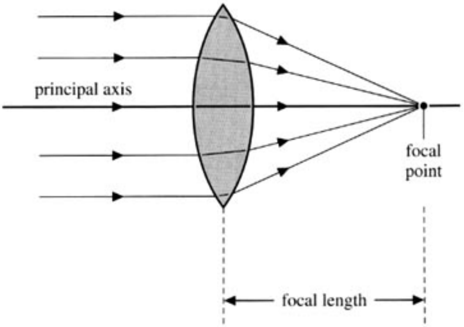

Figure A1.2 Focal point and focal length of a converging lens.

The eye cannot, at the same time, focus on two objects at two different distances from the eye. But if you focus on an object, O, far from the eye and straight ahead, so that the object is seen clearly, other objects closer and further than that object will also be seen clearly enough, even though the eye is not exactly focusing on them. If the furthest object that can be seen acceptably clearly is O_1 and the closest is O_2, then the distance O_1O_2 is called the **depth of vision** (or depth of field) (see Figure A1.3).

▶ The *depth of vision* is the range of object distances from the eye within which objects, or points on an object, can be seen acceptably clearly.

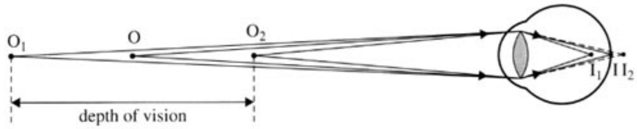

Figure A1.3 Diagram showing what is meant by depth of vision.

The depth of vision depends on the distance to the object. The further the object is from the eye, the larger the depth of vision. If the object is put close to the eye, the depth of vision is greatly reduced. However, if brighter light is used, the depth of vision will increase. This is because in brighter light the iris will reduce the pupil diameter. Figure A1.4 shows an increased depth of vision in the presence of a smaller aperture.

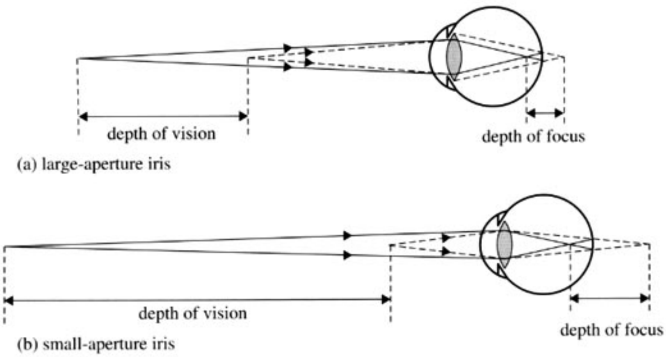

Figure A1.4 A reduced pupil diameter means that the rays entering the eye can be brought to focus.

Accommodation

The term **accommodation** refers to the ability of the eye lens to change its focal length. This is done by contractions of the ciliary muscle. When the muscle is relaxed, the eye has the shape shown in Figure A1.5(a) and the eye is said to be *unaccommodated*. The lens has its greatest focal length and the eye can focus on distant objects without fatigue. By contrast, when the muscle is contracted, the lens has the shape shown in Figure A1.5(b), its focal length is the least and the eye is said to be *accommodated*. The eye can then focus on nearby objects. This is an active process, leading to fatigue.

The nearest distance at which an object can be seen clearly, without undue strain on the eye, is called the *near point* of the eye. For a normal healthy eye, this distance is about 25 cm. The *far point* is the furthest distance the eye can focus on clearly. For a normal healthy eye, this is infinity.

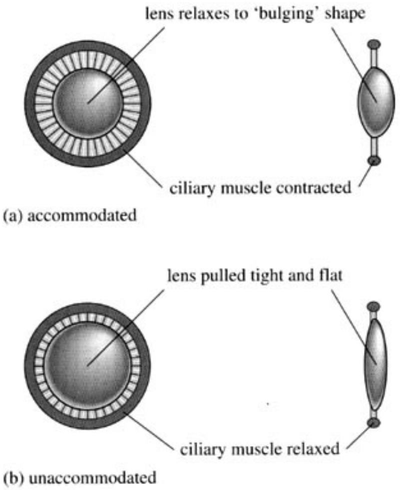

Figure A1.5 Changes in the eye lens in the case of an accommodated and an unaccommodated eye.

Scotopic and photopic vision

There are major differences in the functioning of the rods and the cones. Even though the rods have different responses to different wavelengths of light, the rods do not transmit this difference in a way that the brain can interpret as a difference in colour. They are, however, sensitive to light of low intensity, because many different rods are connected to the same nerve fibre. This means that, even if the intensity of light in any one rod is low, the signal given to the nerve fibre will be the sum of the individual signals and therefore can be large. A disadvantage of connecting different rods to the same nerve fibre is that in this way we lose on detail in the image.

▶ Vision in which the rods are the main detectors of the incident light in the eye is called *scotopic* vision.

The cones, on the other hand, do distinguish different colours. There are three types of cone, each sensitive to a different colour. Fewer of them are connected to the same fibre, and this allows for more detailed images. The cones are only sensitive when the intensity of light is high (i.e. in bright light). This is why in very low-intensity light (in the dark) it is not possible to distinguish colours. Thus if you look at a galaxy through a large telescope, you will see a black-and-white image; you will not see the brilliant colours that published photographs of galaxies have in books and on posters.

▶ Vision in which the cones are the main detectors of the incident light in the eye is called *photopic* vision.

These facts are summarized in Table A1.1.

Scotopic vision	Photopic vision
Rods are used	Cones are used (mainly)
Used at night and when there is very little light available	Used during the day and when there is a lot of light available
Distinguishes shapes but not colours	Distinguishes shapes and colours
Distinguishes little detail	Distinguishes a lot of detail

Table A1.1 Differences between scotopic and photopic vision.

Example question

Q1

Explain why in low-intensity light it is easier to obtain a clear image of an object by looking at the object a bit sideways rather than directly at it.

Answer

Since the intensity of light is low, vision takes place mainly through the rods and not the cones. The highest concentrations of the rods are away from the principal axis, and so we look a bit sideways at the object for light to fall on the rods.

Figure A1.6 shows the relative sensitivity of cones and rods to light of different wavelengths. (Recall that rods do not distinguish colour.) We see that rods are more sensitive than cones for blue light.

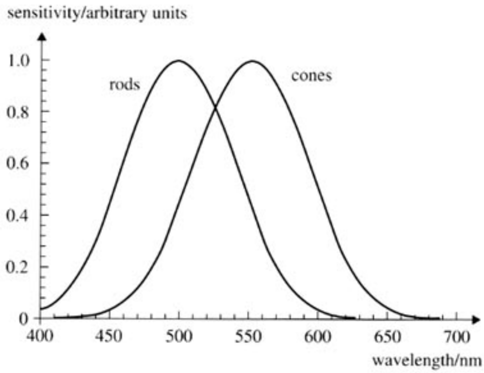

Figure A1.6 Overall relative sensitivity of cones and rods as a function of the wavelength of light.

Example question

Q2

Use the spectral response graph in Figure A1.6 to answer this question. An object reflecting red light of wavelength 640 nm is viewed in

(a) low-intensity light and

(b) high-intensity light.

Describe what the observer sees.

Answer

(a) In low-intensity light, vision is through rods. Light of wavelength 640 nm is beyond what the rods can detect, and so the object cannot be seen.

(b) In high-intensity light, the cones are used, and the object can be seen clearly.

Colour

The perception of colour is made possible by the fact that there are three types of cone cell, each type being sensitive to either blue, green or red light. This was suggested by Thomas Young as long ago as 1800. Figure A1.7 shows the spectral response curve for each type of cell. Adding together the three curves B, G and R for the cones produces the overall spectral response of the cones as already shown in Figure A1.6.

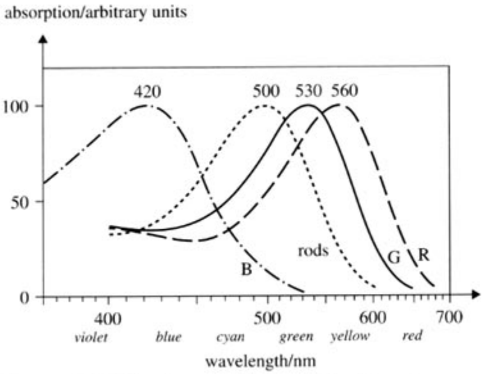

Figure A1.7 Relative sensitivity of the three types of cone cell.

It can be seen from Figure A1.7 that light of wavelength 550 nm will excite only the green- and red-sensitive cones. The combination of green and red (in equal quantities) gives yellow light, and so this is the colour that the brain understands for this wavelength of light.

Colour blindness

Colour blindness is a general term referring to people with deficiency in the perception of colour. It affects men more frequently than women. Complete colour blindness is rare. Since colour is perceived by the cone cells, colour blindness is associated with non-functioning cone cells or insufficient numbers of one or more types of cone cell. It can also be due to brain or nerve damage. The most common form of colour blindness involves the red and green cone cells, and the inability to distinguish between red and green colours. If one type of cone cell is non-functioning, the colours that can be perceived are only those that can be made by combining the colours to which the other two types of cone cell are sensitive. If two types of cone cell are not functioning, then the person is completely colour blind in the sense that he or she cannot distinguish between any two coloured objects.

Colour addition

It is an amazing fact that, by mixing light of just three colours, we can make a *very wide* range of other colours. Three is the minimum number of colours needed. With two colours, for example green and red, we cannot make blue. If we take the three colours to be blue (B), green (G) and red (R), the combination

$$X = bB + gG + rR$$

gives any desired colour, where b, g and r are the relative intensities of the blue, green and red light used in the mixture. The three colours used (in this case, blue, green and red) are called **primary colours**. (But others might also be used as primaries – see page 477.) In practice, this means that if you shine blue, green and red lights of various intensities onto a white screen, the colour X would appear where the three coloured beams overlap.

> ▶ *Primary colours* are colours which, when overlapped, give a wide range of other colours. No one primary can be made with the other two. Adding three primary colours of light, say B, G and R, in equal amounts gives white light, $W = B + G + R$.

To get the colour $X = bB + gG + rR$, the three primary colours are mixed with relative intensities b, g and r.

> ▶ Obtaining a colour of light by overlapping different amounts of three primary colours is called *colour addition.*

Adding the primaries (here taken as blue, green and red) two at a time results in the three **secondary colours**, of cyan, magenta and yellow:

$B + G = C$, cyan (bluish green, i.e. turquoise)

$B + R = M$, magenta (reddish purple)

$R + G = Y$, yellow

It follows that adding a specific primary colour to a secondary colour results in white light, W:

$$C + R = W \quad (\text{because } C = B + G)$$
$$M + G = W \quad (\text{because } M = B + R)$$
$$Y + B = W \quad (\text{because } Y = R + G)$$

The primary colour added to the secondary colour to give white light is called the **complementary colour** of the secondary; for example, red is complementary to cyan.

Example question

Q3

What colour of light is obtained when we overlap equal intensities of magenta with yellow?

Answer

We get

$$\begin{aligned} M + Y &= (R + B) + (R + G) \\ &= (R + B + G) + R \\ &= W + R \end{aligned}$$

This is red.

As mentioned earlier, there is no unique choice of the three primary colours. Blue, green and red are normally used because they give a very wide range of colours by colour addition. They correspond to the three sets of cones present in the eye. This system is also used in colour television and digital cameras. But other systems can be used as well. For example, consider the choice of red (R), yellow (Y) and blue (B) as the primaries. A wide range of colours is obtained by using colour addition with these three, but unfortunately it is not possible to obtain green light by adding any combination of these three. However, a mixture of yellow (Y) and blue (B) can be made identical to a mixture of red (R) and green (G). That is to say

$$yY + bB = gG + rR$$

This means that

$$gG = yY + bB - rR$$

$$G = \frac{y}{g}Y + \frac{b}{g}B - \frac{r}{g}R$$

In this way we have managed to get green out of the three primaries Y, B and R, but this time the coefficient of red is negative.

In other words, if we allow for negative coefficients in the mixture, any three colours can be used as primaries, and there is therefore no unique choice of primaries. (Notice that the standard choice of primaries, red, green and blue, also requires negative coefficients in order to obtain certain colours. There is, in fact, no choice of three primaries from which all other colours may be obtained with only positive coefficients in the mixture.)

Notice that the presence of negative coefficients in the mixture $yY + bB + rR$ is sometimes referred to as colour subtraction. The proper meaning of colour subtraction, however, is discussed below.

Colour subtraction

The term **colour subtraction** refers to white light being transmitted through a coloured filter. The transmitted light has the colour of the filter because the filter removes (subtracts) a certain colour from the white light. The three primary filters used are yellow, magenta and cyan filters (see Figure A1.8).

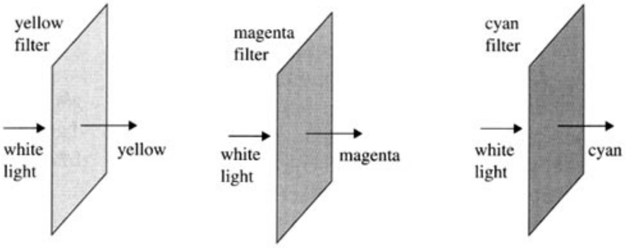

Figure A1.8 The three primary filters, yellow, magenta and cyan, remove blue, green and red colour, respectively, from white light.

White light transmitted through a yellow filter has the blue removed, so that the transmitted light has a colour given by

$$\begin{aligned} W - B &= (B + G + R) - B \\ &= G + R \\ &= Y \end{aligned}$$

i.e. yellow, as expected of a yellow filter.

Similarly, a magenta filter removes green, and a cyan filter removes red. In other words, the three filters each remove their respective complementary colour.

If light is transmitted through a magenta filter *and then* through a yellow filter, the transmitted colour will be

$$\begin{aligned} W - B - G &= (B + G + R) - B - G \\ &= R \end{aligned}$$

i.e. red.

If white light is transmitted through the three primary filters of yellow, magenta and cyan, the light will be absorbed and the three filters will look black where they all overlap. This is because

$$W - B - G - R = (B + G + R) - B - G - R = 0$$

Perception of colour and light

The perception of colour has, as we have seen, its physiological basis in the functioning of the cone cells in the eye. But the overall perception of colour extends into the realm of psychology. This has been exploited by architects, designers, interior decorators, advertisers and others, to create effects based on the perception of colour. Thus, a room painted in bright red or yellowish colours gives a sense of a busy, hurried place. Another painted in soft, pastel colours gives the impression of a relaxed, calm place. Soft reddish or orange colours create a 'warm' atmosphere, whereas bluish and violet colours give the impression of a cold or cool place. Small rooms can be made to 'look' bigger by painting them in light, soft colours, and a low ceiling can be 'raised' by painting it with a colour that is lighter than that used for the walls. A floor will look smaller if painted in dark colours rather than light colours.

Another effect is the inclusion of shadows. Deep shadows give the impression of a solid, massive object, whereas light shadows, or the absence of them, give the impression of a light and 'airy' structure.

Questions

1 (a) Make an annotated diagram of the human eye.
(b) Explain the function of the parts you have annotated.

2 (a) Explain why you cannot see clearly under water.
(b) Why can you see clearly if you are wearing a diving mask?

3 (a) Describe the function of cones and rods in vision.
(b) State the distribution of cones and rods on the retina.

4 Many different rod cells are connected to the same nerve fibre. State and explain one advantage and one disadvantage of this in the context of the eye's ability to see.

5 (a) State what is meant by (i) depth of vision and (ii) accommodation.
(b) Outline why the depth of vision increases when the eye's aperture is reduced.
(c) Hence explain the effect on the depth of vision of an increase in the intensity of light.

6 Define what is meant by (a) scotopic vision and (b) photopic vision.

7 Suggest why it is difficult to observe colour in low-intensity light even though the outline of an object can be clearly seen.

8 Explain why in high-intensity light an object can be seen most clearly by looking directly at the object but as the intensity is reduced the object is most clearly seen when it is observed off the eye's principal axis.

9 (a) What is meant by colour blindness?
(b) State and explain whether colour blindness is associated with damage to rod cells or cone cells.

10 The density of cones on the fovea is 150000 cones per square millimetre. The fovea may be taken as a circle of diameter 0.25 mm.
(a) Calculate the average separation of cones in the fovea.
(b) The diameter of the eye is about 2.5 cm. Calculate the angle subtended at the pupil of the eye by the separation between two cones calculated in (a).
(c) Diffraction at the eye's aperture limits the resolution of the eye, i.e. whether two distinct objects are actually seen as distinct. The minimum angular separation between two objects that can be seen as distinct is given by $\theta \approx 1.22\frac{\lambda}{d}$, where λ is the wavelength of light used and d is the diameter of the aperture. Calculate θ by taking $\lambda = 5.5 \times 10^{-7}$ m and a pupil diameter of $d = 1.5 \times 10^{-3}$ m.
(d) By comparing the values obtained in (b) and (c), state and explain whether there would be any improvement in the resolution of the eye if the cones were closer to each other.

11 (a) Explain why the depth of vision is increased when looking at a page of text through a hole in a piece of cardboard.
(b) Suggest why there is a limit to the increase in the depth of vision that can be achieved in this way.

12 (a) Sketch graphs to show the variation with wavelength of the relative sensitivity of cones and rods.
(b) Use your graphs to explain why reducing the intensity of light shifts the wavelength at which the eye is most sensitive towards *blue wavelengths.*

13 (a) State what is meant by primary colours.
(b) How many primary colours are there?
(c) Explain why the choice of primary colours is not unique.

14 Using the spectral response curve of Figure A1.7 in the text, explain the colour perceived when light of wavelength (a) $\lambda = 400$ nm and (b) $\lambda = 680$ nm is incident on the eye.

15 State what is meant by (a) colour addition and (b) colour subtraction.

16 Determine the colour of light obtained when (a) cyan and yellow and (b) cyan and magenta are added with equal intensities.

17 Determine the colour of white light that is transmitted first through a magenta filter and then through a cyan filter.

18 What two primary filters (cyan, magenta and yellow) must be used so that white light will emerge green?

19 (a) Determine the colour obtained when cyan, yellow and magenta are added with equal intensities.
(b) Determine the colour obtained when white light is transmitted through overlapping cyan, yellow and magenta filters.

20 Comment on the statement: 'Colour is a construction of the mind and not the property of an object.'

21 Name one of your favourite buildings and describe how the use of colour makes the building special.

22 The three grey dots in Figure A1.9 are identical. Do they *look* equally bright? How do you explain your answer?

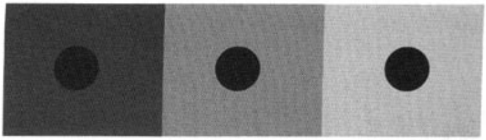

Figure A1.9 *For question 22.*