Colour Vision

We see an object either because it produces light (it is *luminous*) or because it reflects light. Either way, light had to enter the eye, which is responsible for converting light into electrical signals that are then passed to the brain. The brain and the optic nerve work together to produce the image that we see.

The important part of the eye, as far as colour vision is concerned, is the *retina*: the cluster of light sensitive cells across the back of the eyeball (Figure 1).

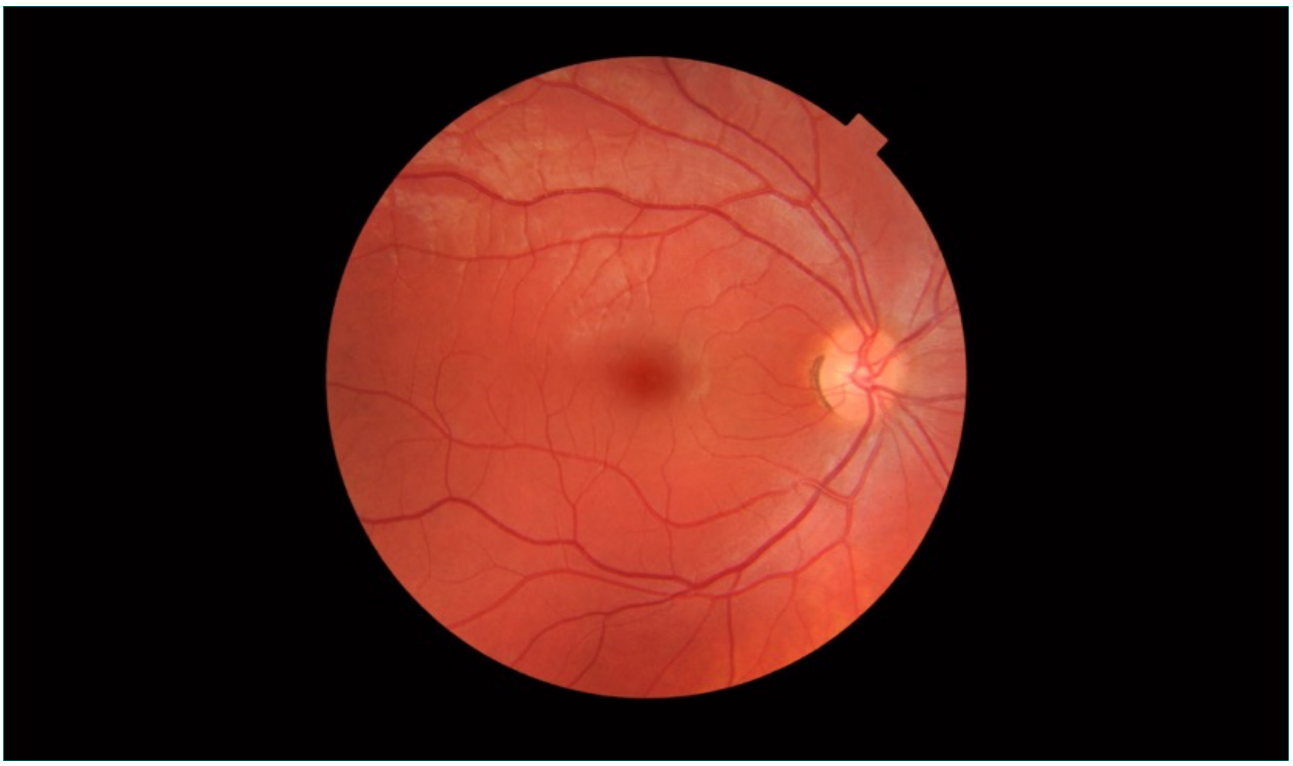

Figure 1: An image of the retina in the right eye of a human being.
(image credit: Häggström, Mikael [2014]. "Medical gallery of Mikael Häggström 2014". WikiJournal of Medicine 1 (2). DOI:10.15347/wjm/2014.008)

The retina contains two different types of cell, known as rods and cones because of the different shapes of the cells in cross section.

- Rods are very sensitive to light and so are good in dark conditions.
- Cones are not as sensitive to light, and so only function well during the day or in bright illumination. Cones come in three different types, which are broadly sensitive to different wavelengths (colours) of light.

Why do you think it is harder to see colours at night?

The three types of cone in the retina are sensitive to red, blue and green light. That means that if a beam of red light is shone into the eye, all the red-sensitive cones will send electrical signals to the brain (Figure 2). If green light is shone into the eye, then the green cones will 'fire'. The same is true of the blue cones sending signals from blue light.

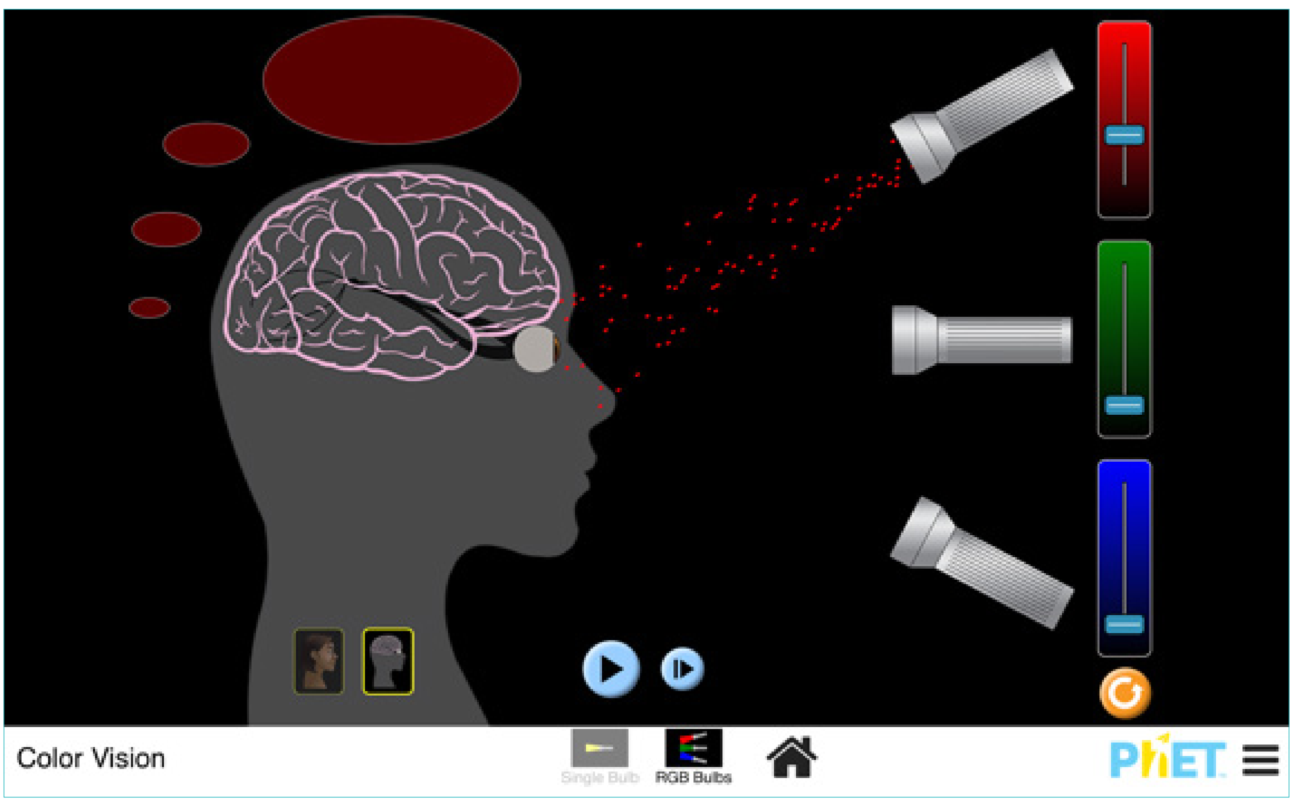

Figure 2: Red light shining into the eye causes the red-sensitive cones to fire and send signals to the brain. The blue light would stimulate the blue-sensitive cones and green light those that fire under green light.
(Screen shot from webpage: https://phet.colorado.edu/sims/html/color-vision/latest/color-vision_en.html)

Of course, there are more colours of light than just red, green and blue. So, what happens if we shine a yellow light into the eye?

Based on what we have done in previous lessons, how would we produce some yellow light?

A good way to produce yellow light is:

Yellow light will not cause any one of the types of cone to fire, but it will cause the red cones to fire off to some extent, and the green cones, depending on the exact shade (Figure 3).

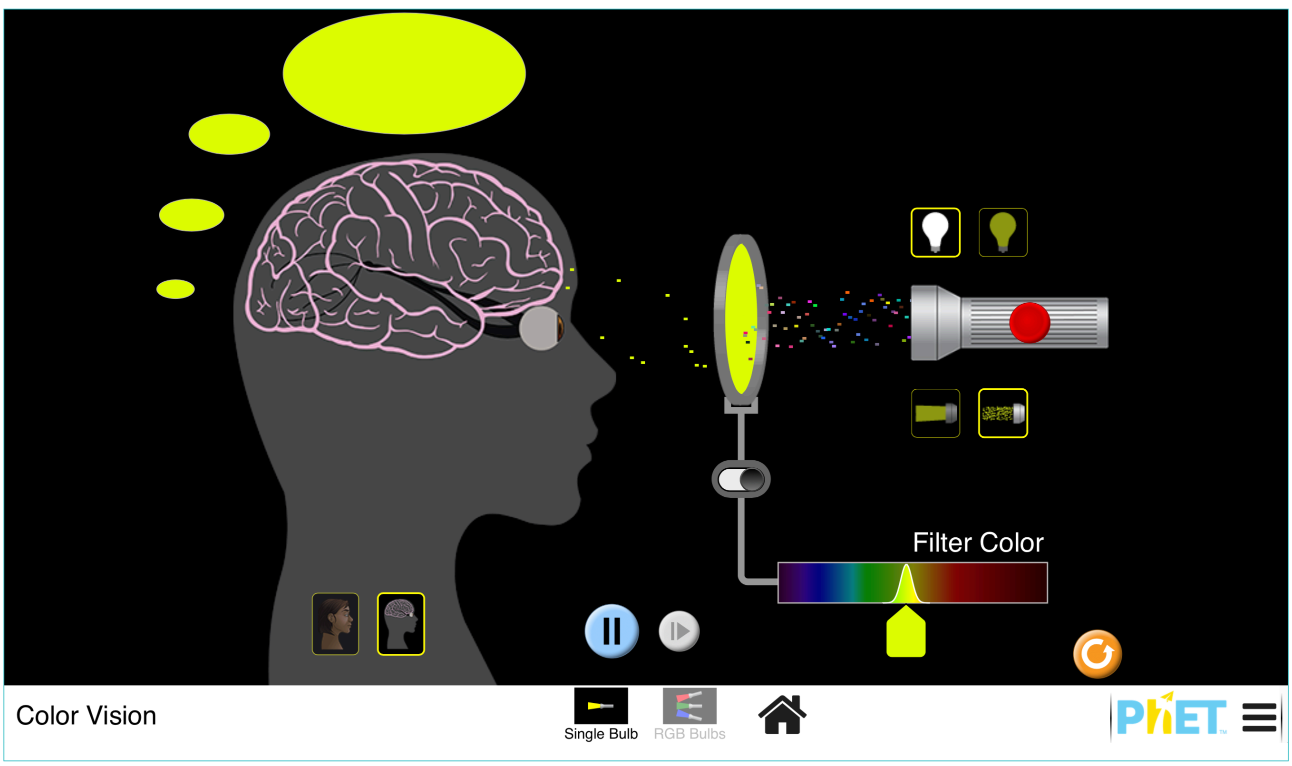

Figure 3: Arranging for yellow light to shine into the eye will cause the cones to fire to different extents and send a signal to the brain that we have learnt to interpret as yellow.
(Screen shot from webpage: https://phet.colorado.edu/sims/html/color-vision/latest/color-vision_en.html)

We have learnt to interpret this pattern of electrical signals sent to the brain from the retina as yellow.

The same would be true of any other colour, aside from red, green and blue. Another colour will cause a different pattern of electrical signals from the cones and we have grown to use these patterns to create the image of the colour in our brains.

Do you think that we ever really see any colours other than red, green and blue?

Fooling the brain

If yellow light produces a pattern of signals to the brain, some from the red cones, some from the green cones, then we should be able to 'fool' the brain into seeing yellow when really the only lights are red and green.

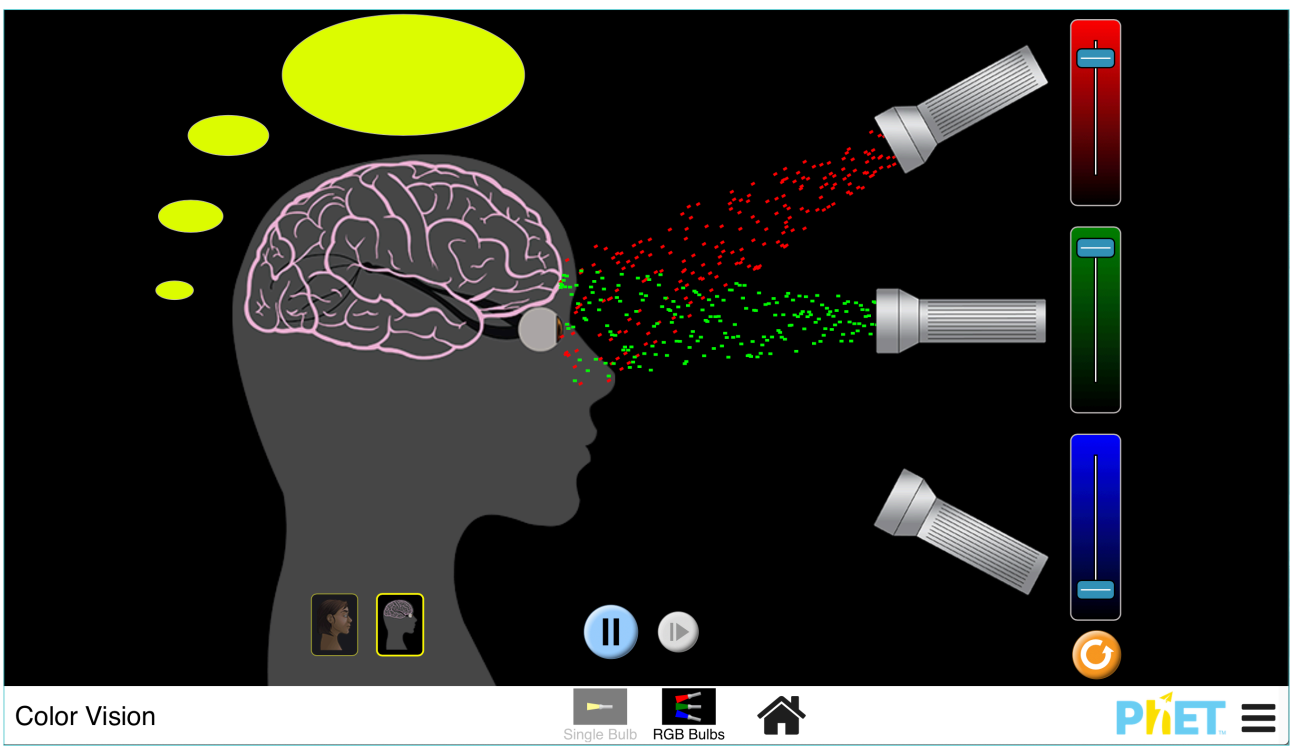

Figure 4: Fooling the brain into seeing yellow. A combination of red and green light shone onto the retina with the right brightness can produce the same pattern of signals that the pure yellow light did. The brain will not be able to tell the difference, so you see yellow. (Screen shot from webpage: https://phet.colorado.edu/sims/html/color-vision/latest/color-vision_en.html)

If we were to conduct an experiment like the one shown in Figure 4, and directed some red light and some green light into someone's eye, then we ought to be able to adjust the brightness of each light so that the pattern of electrical signals to the brain matches that produced by pure yellow light. The brain would then not be able to tell the difference: the person would see yellow.

Primary colours of light

Red, green and blue are known as the *primary colours* of light.

If you look up the definition of primary colours, it will probably tell you that combinations of the primary colours can make any other colour. This is illustrated in the colour mixing experiment shown in Figure 5.

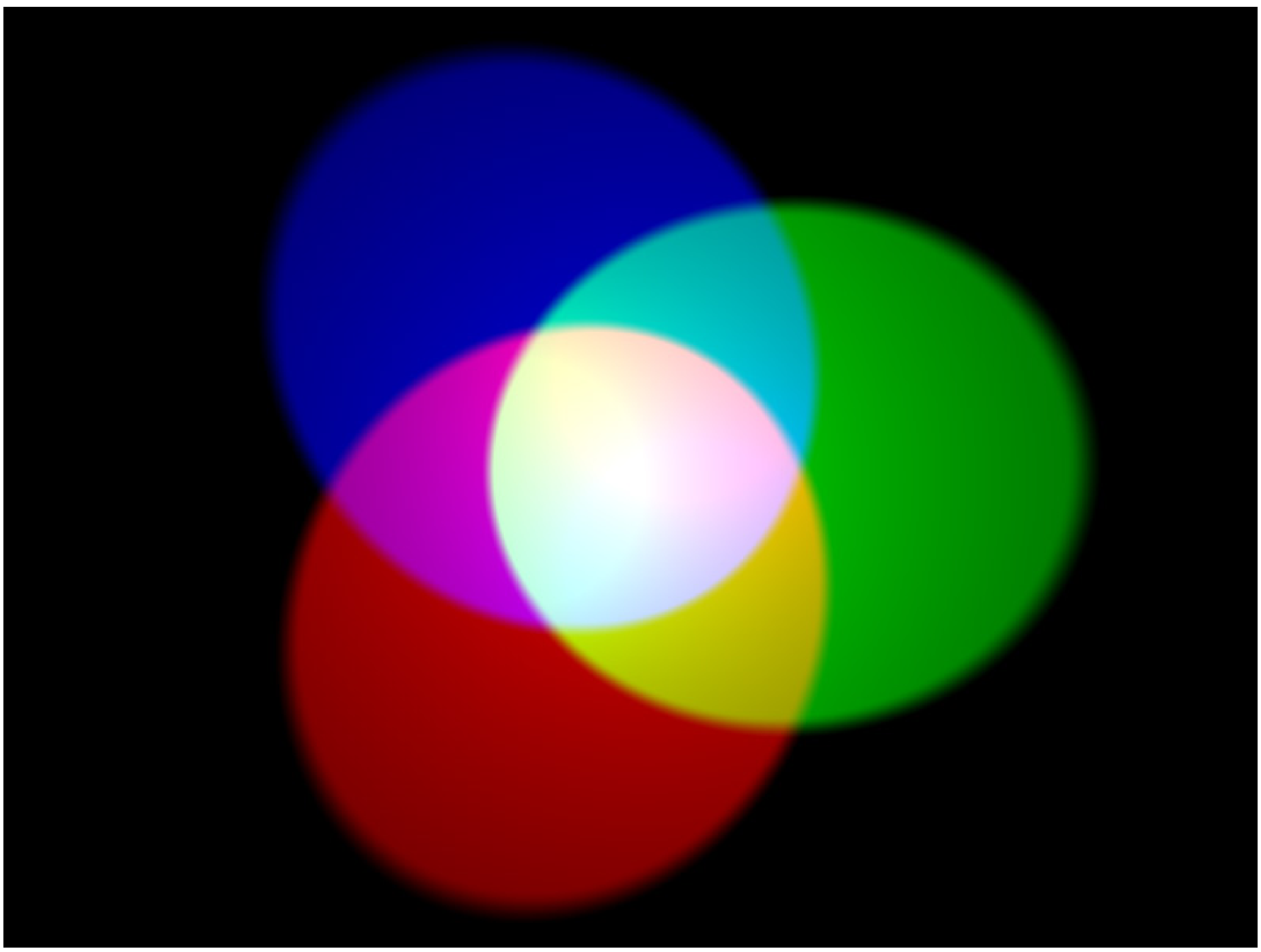

Figure 5: Red, green and blue light is directed onto a screen. Where the lights overlap, different colours can be seen. Where all three overlap, white light is produced. By adjusting the brightness of the different lights, different shades can be produced.

When beams of red, green and blue light are directed onto a screen, they will reflect back into our eyes. Where the lights overlap, combinations will reflect. However, we do not see an overlapping patch of green and red, for example; we see yellow. This is because that combination of green and blue light entering our eyes has happened to produce the same pattern of electrical signals that pure yellow light would have. **We see yellow, even though there is no actual yellow light entering our eyes.**

The fact that red, green and blue are the primary colours of light is due to the different cones in the retina, so it is more to do with *biology* than it is *physics*.

This also helps to explain how objects that reflect combinations of colours to our eyes can appear to be a specific shade of a single colour.

Notice that where the red, green and blue all overlap in Figure 5, white is seen. This explains what we noted in a previous lesson – white is what we see when all the colours are moving along together.

Important point

When we say something like 'red and green light makes yellow', we are actually talking about the combination of red and green entering the eye and making the same pattern of signals as yellow does. Sometimes people get confused and think that if you simply add the frequency of red light and the frequency of blue light together, then you would get the frequency of yellow light. This is not right! It is easy to see that it is not correct if you remember the sequence of colours in the rainbow (Figure 6).

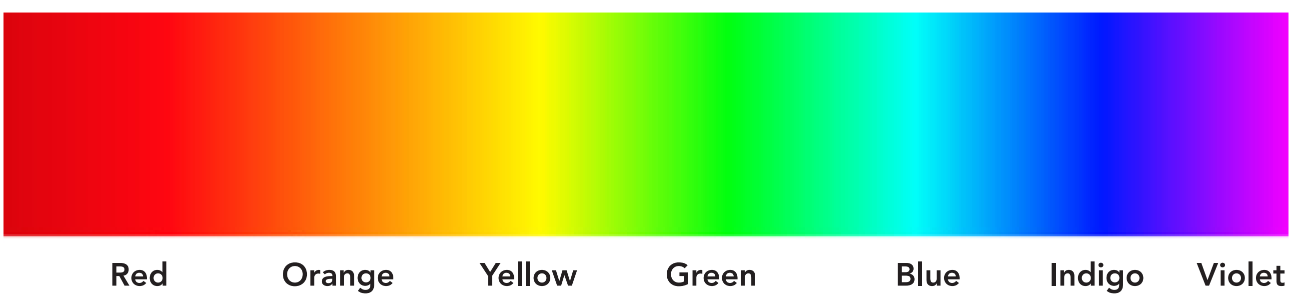

Figure 6: The colours in the rainbow – red is the low frequency end and violet is the high frequency end.

As blue (violet) is the high frequency end, and red the low frequency end, you could not simply add the value of the frequency of red to the value of the frequency of blue to get the value of the frequency of yellow, as blue is already a higher frequency (bigger number) than yellow!

Missing colours

In a previous lesson, we discussed the missing colours from the rainbow. We know that white light is what we see when a combination of red, green and blue lights enters the eye. The types of cone in the retina help to explain why that is. A white object reflects all colours of light into the eye, which is effectively the same thing. Black objects do not reflect any colours of light.

The most obvious missing colour from the rainbow is brown. This means that there is no frequency of light wave that corresponds to the colour brown. However, we see brown objects all the time.

The way that colour vision works in the eye explains this puzzle. A certain combination of red, green and blue stimulates the retina in a way that does not match other colours. The brain has learned to 'see' the colour brown when that pattern of light is seen. So, a brown book reflects the right combination of red, green and blue to be interpreted by the brain as brown.

Colour television

A lot of our modern technology uses combinations of red, green and blue to produce an image of any colour in the brain. If you look closely at the screen of a colour television, then you will actually see tiny red, green and blue LED lights (Figure 7). From a distance, these lights appear to merge, so that the light from them hits only a single patch on the retina. The computer inside the TV arranges for these dots to light up in the right combination to fool the brain into seeing the right patch of colour at any part of the screen.

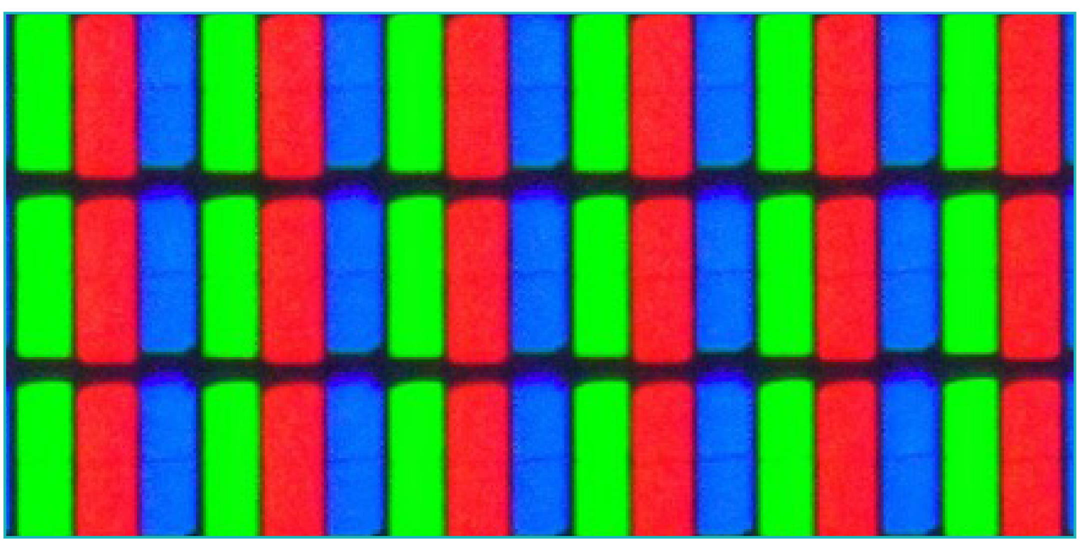

Figure 7: A close-up image of a small portion of a full HD 1080 LED TV screen showing the red, green and blue LEDs that are used to simulate any colour in the brain.

Can you think of any other piece of technology that uses a combination of the three primary colours to stimulate the brain into seeing any other colour?

Colour blindness

Someone who is colour-blind is not able to tell the difference between certain colours. The most common type is called red/green colour blindness. Someone who is red/green colour-blind finds it hard to tell the difference between those specific colours. However, the effect on their vision is not just specific to those colours. Various objects with colours that are not simply red and green also reflect red and green light as part of the combination that gives them their specific colour. So, a red/green colour-blind person would have difficulty with these colours or shades as well.

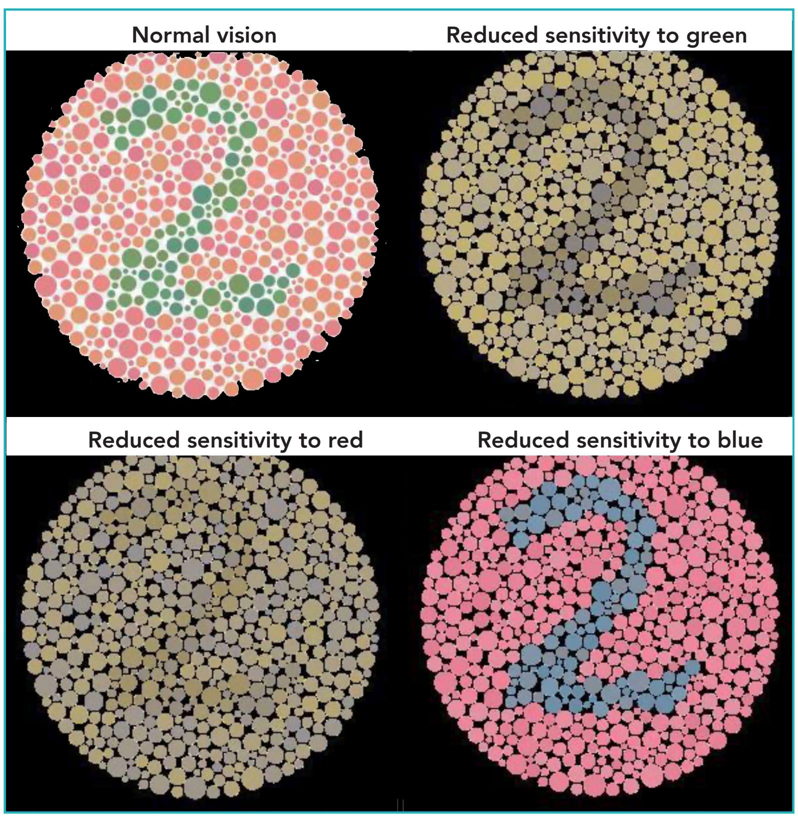

Figure 8: Different types of colour blindness.

(image credit: Eddau processed File: Ishihara 2.svg by User:Sakurambo, distributed under Creative Commons Attribution-share alike 3.0 International Licence https://creativecommons.org/licenses/by-sa/3.0/deed.en and modified to include different titles)

Figure 8 shows a simulation of what different types of colour blindness would mean when looking at a pattern of dots. The image in the top left is what a non-colour-blind person would see. The top right is the same collection of dots as seen by someone with a reduced sensitivity to green light. The bottom left image is that for a person with reduced sensitivity to red light, and the bottom right is the dots as seen by someone with a lower sensitivity to blue light (this is very rare):

- reduced sensitivity to red or green: known as red / green colour-blind and have difficulty distinguishing between reds, greens, browns and oranges; they also commonly confuse different blues and purples;
- reduced sensitivity to blue: the world appears as red, pink, black, white, grey and turquoise.

Knowing what we have discovered about the retina in this lesson, what do you think causes colour blindness?

What is colour?

We started this topic by asking the question 'what is colour?'. By now, you should realise that there is no simple answer to the question!

Scientifically, colours are different frequencies of light, but not all colours correspond to a frequency!

White is how the brain interprets all the frequencies together.

Black is how the brain interprets an absence of light reaching the eye.

Brown is a 'made-up' colour produced by the brain in response to a combination of red, green and blue.

Do you think that brown is a 'real' colour?

If you think that brown is not 'real' then consider how we see yellow or can use red, green, blue to make yellow. Are these colours more real than brown?

Lesson summary

- We can see things when light enters our eyes.
- Light-sensitive cells in the retina send electrical signals to the brain.
- Rod-shaped cells in the retina are very good at detecting light, even in dark conditions, but they cannot tell the difference between different colours.
- Cone-shaped cells in the retina come in three different types: sensitive to red, green and blue light.
- A coloured light, such as orange, will cause the green and red cones (for example) to fire in a pattern that depends on the exact shade. The brain interprets this pattern as orange.
- Directing a combination of red and green light to overlap on the retina can cause the same pattern of signals as orange light, so the brain sees this combination as orange.
- Colour television uses red, green and blue LED lights to fool the brain into seeing any colour.
- Someone who is colour-blind is less sensitive to certain colours of light.