Science in School
The European journal for science teachers

ISSUE 70 – November 2024 **Topics** Biology | Chemistry | General science | Physics

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Colour magic: additive mixing and coloured shadows

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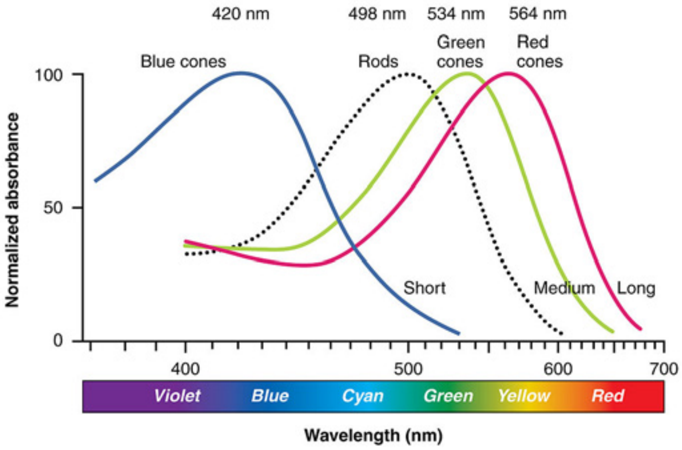
With flying colours: Try some simple but striking experiments to illustrate temporal additive colour mixing, and create and mix coloured shadows.

Generally, very little time is dedicated to the study of light and colour in secondary curriculums, so students lack basic knowledge of this branch of physics when they leave school. In the past, demonstrations of additive colour mixing relied on overhead projectors combined with red-, green-, and blue-coloured transparencies. Today, a more common approach is to use red, green, and blue light-emitting diode (LED) projectors. Here, we introduce other low-cost possibilities, for instance, coloured stickers. We also investigate coloured shadows by illuminating a white surface with three coloured lights and introducing an object in between.

These activities are suitable for students aged 11–16.

Colour mixing

According to the theory of colour vision, developed by Thomas Young and Hermann von Helmholtz in the 19th century, we experience colour thanks to three different types of receptor cells (now known as cones) in our retina, each of which is most sensitive to red, green, or blue wavelengths of light. Young chose three principal colours because he found that he could produce any colour of the spectrum (as well as white) by a mixture of three overlapping lights set to appropriate intensities. He also found that this could be achieved with a range of wavelengths; this means there is a certain degree of arbitrariness to the definition of the three primary colours.[1]

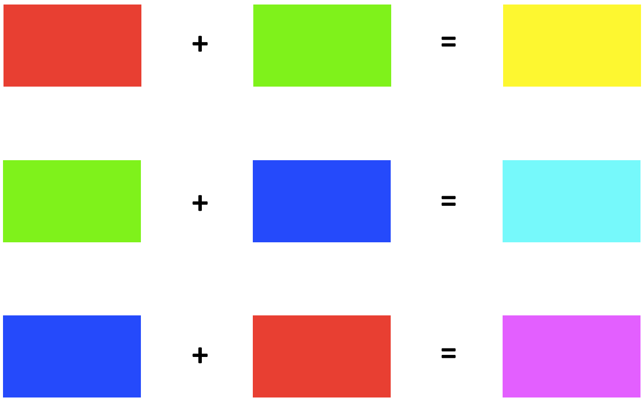


Modern-day experimentally determined responsivity spectra of the three types of human cone cells (normalized)

Image: Anatomy & Physiology, 2023, OpenStax

The Young–Helmholtz theory has led to the development of the so-called red, green, blue (RGB) model. The RGB model was applied in the first experiments of early colour photography, and it is used today to produce colour in computer, television, and mobile phone displays.

In additive colour mixing, combining the three primary colours, red, green, and blue, in equal proportions yields white, whereas mixing any two primary colours in equal proportions yields the so-called secondary colours: yellow, cyan, and magenta. When the additive mixture of two colours produces white, these colours are said to be complementary that is, cyan and red, magenta and green, and yellow and blue.



Additive mixing of two primary colours (red, green, blue) produces the so-called secondary colours (yellow, cyan, magenta).

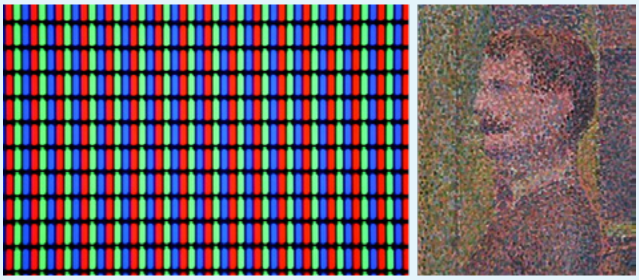
Image courtesy of the author

Additive mixing

Additive mixing can be demonstrated in a straightforward manner by projecting different overlapping coloured lights onto a screen. We call this simple additive mixing. However, due to our eyes' limited reaction time and spatial resolution, we also perceive colour mixing in other less-obvious circumstances:

(1) **Temporal additive colour mixing** refers to the perception of colours mixing when these are viewed in quick succession. This is a consequence of our eyes' limited temporal resolution and a phenomenon known as retinal persistence, that is, the persistence of our perception of an object even after light coming from it has ceased to enter our eyes. In practice, this persistence is of the order of 0.1 s. Examples of temporal additive colour mixing are based on the thaumatrope, as demonstrated in Activities 1–3.

(2) **Spatial additive colour mixing** refers to the perception of colours mixing when these are sufficiently small and sufficiently close to each other. As a consequence of our eyes' limited spatial resolution, for a certain size range and viewing distance, our eyes cannot make out individual colours and perceive a mixture instead. A good example of this phenomenon involves digital displays, in which the colour of each pixel is determined by the relative intensity of three minuscule lights of red, green, and blue; or pointillism, a painting technique in which the artist uses small distinct dots of colour to create an image.



Left: Microscope image of a liquid-crystal display (LCD) phone screen, showing a blank, white image. The red, green, and blue light that makes up each pixel is visible. This screen has 424 pixels per inch, meaning that each pixel is around 60 microns. For comparison, a sheet of paper is about 100 microns thick. Right: Detail from *Circus Sideshow (Parade de cirque)* by the pointillist artist Georges Seurat.

Images: LCD screen: Dome Poon/Fickr, CC BY-NC-ND 2.0. Seurat's painting: Image courtesy of Metropolitan Museum of Art, Public Domain

Activity 1: Thaumatrope with coloured stickers

In 1826, John Ayrton Paris invented the thaumatrope, a toy consisting of a disc with an image on each side, which, when revolved rapidly using twisted strings, created the illusion that both images were superimposed. This device is also called a Faraday Wheel, after British physicist Michael Faraday, who later used it to investigate the phenomenon of retinal persistence.[2]

This first activity explores the temporal additive mixing of two primary colours using cardstock paper and a stick. Students will be able to see for themselves that additive colour mixing does not yield the colours expected from childhood experience of mixing paint or clay. They will also be able to observe the phenomenon of retinal persistence.

An alternative is to build a setup with a motor to spin the sticks; this is more helpful for whole-class discussions.[3, 4] See the supporting material for details of how to build the motor setup for an optional alternative activity. Another simple alternative to Activity 1 can be found in Ref. [5].

This activity takes approximately 20 minutes, not including making the cards.

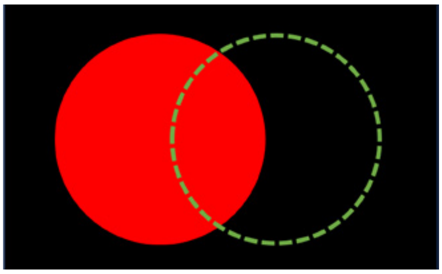
Materials

- Student worksheet: How we perceive colour
- Square of cardstock paper, 6 cm × 6 cm, ideally black
- Red, green, blue, and yellow stickers, 15 mm in diameter
- Wooden rods or skewers with a split in one end to hold the cards
- Glue

Procedure

Prepare the cards

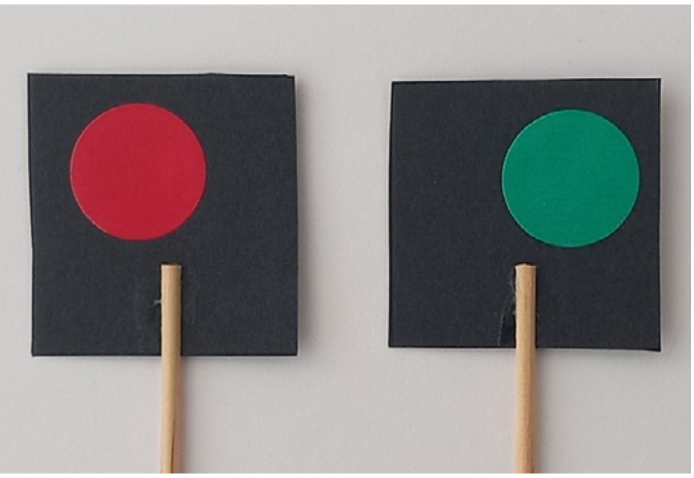
1. Choose two colours, for instance, red and green, and stick one on each side of one of the cardstock squares. The stickers should be placed off-centre, so the front and back stickers have some overlap.



Schematic showing the position of the stickers on either side of the card

Image courtesy of the author

2. Insert the cards into the split in the wooden rod or skewer and glue in place. Make cards for every different colour combination.
3. Once the glue has dried, you can take the rod in your hand and roll it back and forth between your palms.

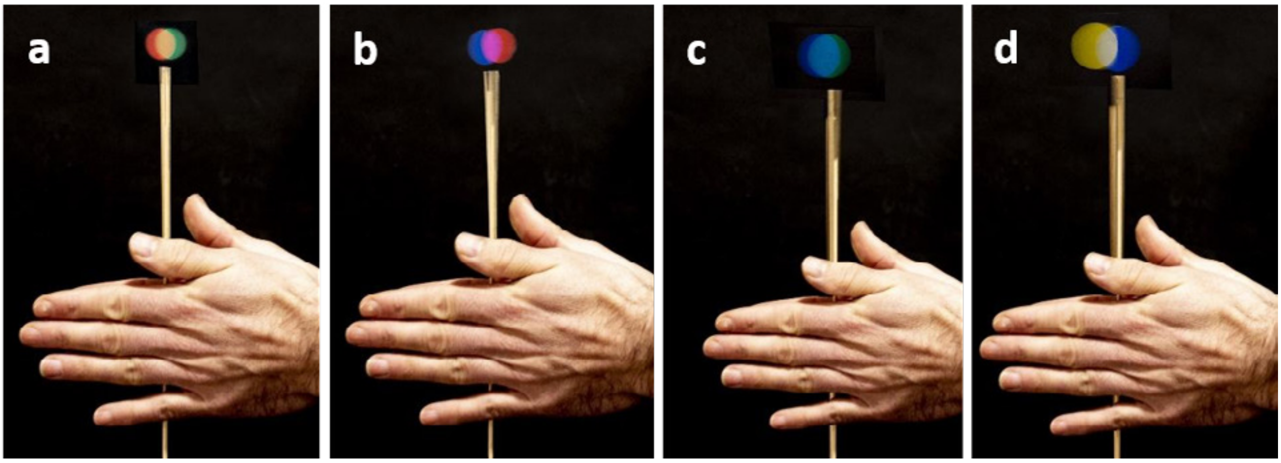


Cards and wooden rods

Image courtesy of the author

Activity

1. Go through the introduction on the worksheet for how we perceive colour. Make sure students understand the difference between additive colour mixing (mixing light) and subtractive colour mixing (mixing pigments), as well as the three cone types in the eye and what colours of light stimulate them.
2. Have students pick a card with primary colours. They can do this independently or take turns coming to the front to show the whole class.
3. Ask them to predict what they will see when card is spun. What kind of mixing do they expect?
4. Ask students to spin the card fast by rolling the rod between their palms and then describe what they see. Is it the same or different from the result they'd expect when mixing paint? How can they explain this? See the discussion section.
5. Repeat with other primary-colour pairs, always making a prediction first.
6. Repeat with two complementary colours (yellow + blue). Ask students to make a prediction first and then explain the result (white).
7. Try spinning slower and faster. How does this affect the result; does it work better at faster or slower speeds? What can this tell us about how long retinal persistence lasts?



Temporal additive mixing: a) green + red = yellow; b) red + blue = magenta; c) blue + green = cyan, d) blue + yellow = white

Image courtesy of the author

Discussion

It is important for students to realize that in additive colour mixing we speak of mixing light of different colours. When mixing paints (i.e., pigments), it is subtractive colour mixing that occurs, that is, each of the mixed materials absorbs (subtracts) certain wavelengths of the incoming (white) light. Students are typically more familiar with subtractive colour mixing due to their experience of mixing different colours of paint or clay, so this point should be clearly made.

As holder and card rotate, we observe temporal additive mixing of the two colours on the card: red and green flash in quick succession, activating the cones sensitive to those two primary colours in our retina. When mixing two complementary colours, such as blue and yellow, we see white in the overlapping area. The light reflected from the yellow sticker activates the cones that are sensitive to red and green, whereas the light reflected from the blue sticker activates the cones sensitive to blue light.

Activity 2: Multicoloured LED ball

This activity uses an LED ball that flashes red, green, and blue sequentially at a frequency high enough for it to appear white when at rest. As in Activity 1, the phenomena of additive colour mixing and retinal persistence are explored. The activity takes around 10 minutes.

Materials

- Multicoloured LED ball with tether (LED Poi)

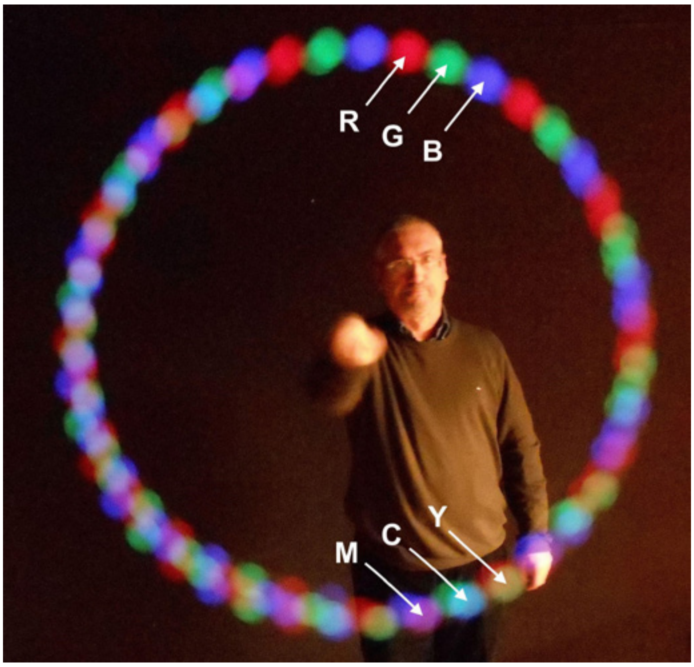
Multicoloured LED ball and tether

Image courtesy of the author

Procedure

1. Turn off the lights in the room and switch on the LED ball.
2. Keeping the ball still, ask students what colour they see (it should be white, or near white).
3. Next, making sure you have enough space to do so, swing the ball around on its tether to observe the separation of colours.

4. Again, ask students what they see, and ask them to explain why colours are observed now and not when the ball is at rest. Hint: what kind of LEDs do they think are inside the ball based on the result?
5. Vary the speed at which you swing to control the overlap of colours, asking the students for feedback ("What do you see now?" "Should I spin faster or slower?").
6. How many colours can they see in total?
7. Optional: you can have the students photograph the swinging ball with a longer exposure to better observe the individual colours (red, green, blue) and their mixtures (cyan, magenta, yellow).



The top of the circumference clearly shows green (G), blue (B), and red (R) light; the bottom shows overlapping colours, magenta (M), cyan (C), and yellow (Y).

Image courtesy of the author

Discussion

The LED ball contains three high-intensity LEDs (red, green, blue), which, when switched on, flash sequentially at high frequency. However, when the ball is at rest, we perceive a steady white light due retinal persistence. The ball is not quite white but has a pinkish glow, because the red LED is somewhat more intense than the green and blue LEDs.

When the ball is swung around on its tether, however, it is possible to observe all three colours individually, as the ball is in a different position each time the LEDs flash. If we reduce the speed of the ball, the red, green, and blue lights begin to overlap and we observe magenta, yellow, and cyan.

Activity 3: Coloured shadows

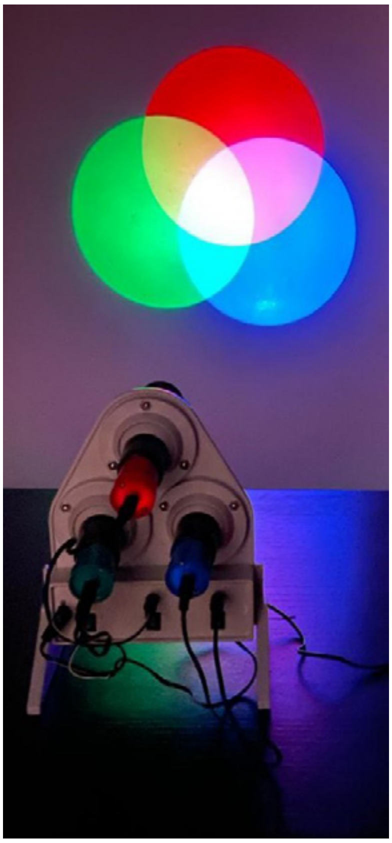
If we ask students what colour shadows are, most will respond that shadows are black. However, shadows may take different colours, as we see in this activity,[4] which takes around 20 minutes to complete.

Materials

- Three LED lamps (red, green, and blue)
- Projector screen (or white wall)
- Object to generate shadow (e.g., a rod)

Procedure

1. Set up the three LED lamps on a table facing the screen or wall. The colours should overlap in pairs to produce the secondary colours, and the three colours should overlap in the centre to produce white (it may be necessary to switch off the lights). Ask students to name each colour visible on the screen and name the primary colours it is composed of.



LED projector setup

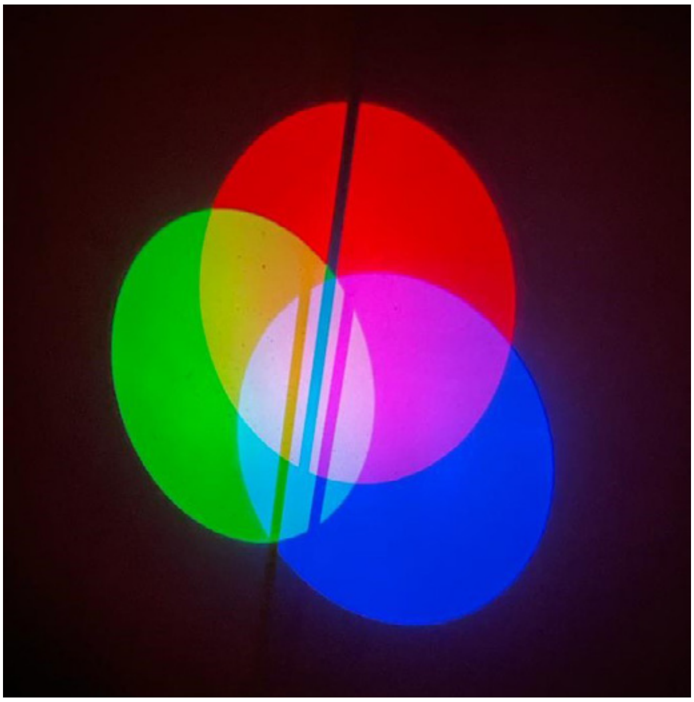
Image courtesy of the author

2. Place a rod (or other object) between the lamps and screen to create a shadow in the white area. Three shadows will appear. Adjust the position of the rod to play with the overlap of the three shadows. In each case, ask students to identify the colour of the shadow in the

different regions (areas with different coloured background) and to name the primary colours it is composed of, thereby identifying which of the LEDs is being blocked by the rod.
3. Begin with a position farther from the screen, so that three shadows are visible.
4. Next, move the object closer to the screen, so that the three shadows begin to overlap.
5. Lastly, move the object even closer so that all three shadows overlap to produce true darkness.

Discussion

Due to the slightly different positions of each of the three LEDs, the rod generates three shadows. Each of these shadows forms as the object blocks one of the three lights. In each case, the shadow's colour corresponds to the combined effect of the two lights that have not been blocked by the object.

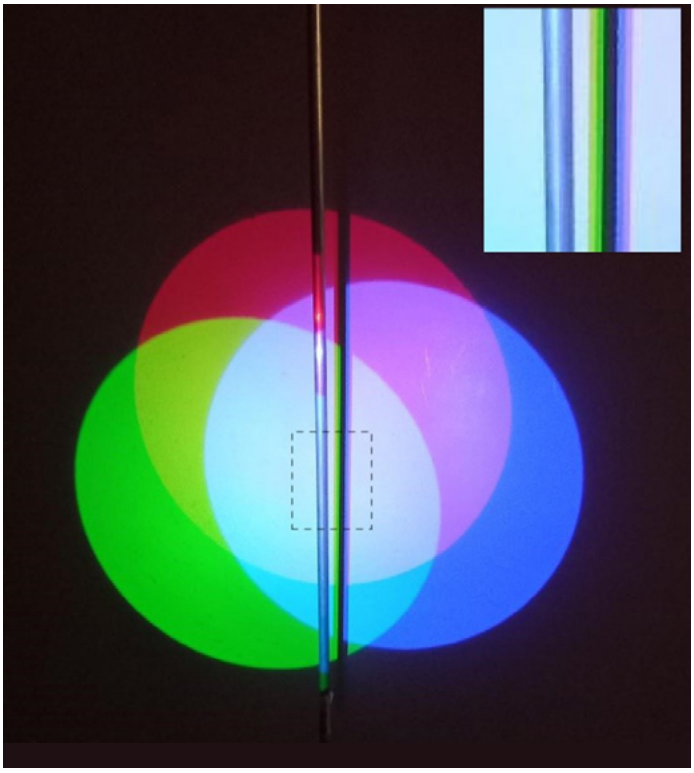


Shadows of a rod placed in front of the three LED lamps. Yellow, cyan, and magenta shadows can be clearly seen in the centre (white) region, where the red, green, and blue lights all overlap.
Image courtesy of the author

The yellow shadow forms where the rays coming from the blue light are blocked by the object. Because the light from the red and green LEDs does reach that region, the colours combine, giving the shadow a yellow colour.

In the same way, the magenta shadow forms where the green light is blocked by the object. The red and blue light in that region mixes, giving rise to a magenta shadow. Finally, in the region where the red light is blocked by the object, blue and green light mixes, giving rise to a cyan shadow.

If we bring the object closer to the screen, the shadows approach each other and eventually begin to overlap: the superposition of the yellow and cyan shadows produce green, as this corresponds to the blockage of both red and blue lights, while the superposition of the cyan and magenta shadows produces blue, as this corresponds to the blockage of both yellow and green light. The combination of all three shadows leads to the familiar black shadow.



Overlapping shadows. Inset: close up of the marked area, showing a black shadow in the centre (yellow + magenta + cyan shadows, i.e., blue, green, and red lights are all blocked) and green and blue shadows on the sides (yellow shadow + cyan shadow, i.e., blue and red lights are blocked; and cyan + magenta, i.e., green and red lights are blocked).
Image courtesy of the author

Conclusion

This set of experiments can be easily performed in the classroom and helps students become familiar with the concepts of additive colour mixing and retinal persistence, as well as understand the origin of complementary colours and coloured shadows. The content touches on other curriculum topics encountered in physics (light), biology (vision), and art (colour mixing). Regarding the last of these, students will become aware of the difference between additive and subtractive colour mixtures, typically being more familiar with the latter from childhood experience with paints or clay. «

References

[1] Gregory RL (1990) Eye and Brain: *The Psychology of Seeing* chapter 7. Princeton University Press, Princeton. ISBN: 0691048371

[2] Kuhn A, Westwell G (2012) *A Dictionary of Film Studies* 1st edition. Oxford University Press. ISBN: 9780199587261

[3] Caamaño Ros A et al. (2011) *Física y Química. Investigación, Innovación y Buenas Prácticas* pp 123–127. Grao. ISBN: 978-84-9980-081-3

[4] Presentation of the activity “Luz, color y óptica cromática”: https://www.youtube.com/watch?v=D7NpdJDP2ac

[5] Cortel A (2004) Simple experiments on perception of color using cardboard turbines. *The Physics Teacher* **42**: 377. doi: 10.1119/1.1790349

Resources

- Read about how Akiyoshi Kitaoka, a professor of psychology, combines visual science and art to produce surprising images.
- Discover more fantastic visual illusions from Akiyoshi Kitaoka.
- Explore spatial colour mixing and colour illusion.
- Discover anamorphosis and reveal hidden images with mirrors: Liang Y (2024) Exploring anamorphosis: revealing hidden images with mirrors. *Science in School* **68**.
- Build your own stroboscope and use it to create beautiful optical illusions with water: Chatzisavvas G, Giannakoudaki K (2022) ‘Defying’ gravity with a simple stroboscope. *Science in School* **60**.
- Explore how colours arise through reflection, absorption, and transmission: Félix RC, Paleček D, Correia TM (2024) Colour science with lasers, gummy bears, and rainbows. *Science in School* **66**.
- Explore the leaf pigments that play a role in photosynthesis: Tarragó-Celada J, Fernández Novell JM (2019) Colour, chlorophyll and chromatography. *Science in School* **47**: 41–45.
- Build your own spectrometer to explore the delights of colour: Westra MT (2007) A fresh look at light: build your own spectrometer. *Science in School* **4**: 30–34.
- Learn how you can turn a cheap webcam into an infrared camera: ESA Education (2022) Infrared webcam hack – using infrared light to observe the world in a new way. *Science in School* **56**.
- Read an introduction to the electromagnetic spectrum: Mignone C, Barnes R (2011) More than meets the eye: the electromagnetic spectrum. *Science in School* **20**: 51–59.
- Learn about the colour blue in nature and the chemistry behind it: Bettucci O (2022) Colour in nature: true blue. *Science in School* **60**.
- Explore the chemistry behind the colour pink: Bettucci O (2022) Colour in nature: think pink. *Science in School* **57**.
- Learn how to distinguish between real and fake astronomical images: Muñoz Mateos JC (2024) CSI Astronomy: learn how to spot fake astrophotography images. *Science in School* **69**.