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How might educational research into children’s ideas about light be of use to teachers?

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Introduction

Light is a surprisingly difficult topic to teach in schools. Considerable evidence shows that children and professional scientists do not always understand this phenomenon in the same way (Driver et al., 1994; Duit, 2009). In this article we explore what children think about light, and how teachers can help.

What difficulties might children encounter when studying light?

In exploring the challenges professional scientists meet in their work, Allchin (2002 p. 42) identified four types of problem which could be applied equally well to child scientists. Material problems refer to difficulties with the resources or the procedure, discursive problems entail communication issues, observational problems involve methods of perception and data gathering and conceptual problems involve difficulty with ideas. The latter will be discussed in the next section of this article. To illustrate these four types of problem we will discuss the use of a piece of science equipment, common in UK secondary schools, called a ‘ray box’. This consists of a small bulb in an opaque box where one face may be replaced with a single slit or multiple slit plate. The plate can be positioned to produce a single projection, or parallel beams, of light. This equipment is shown below in Figure 1.

Figure 1: A ray box (image used with permission)
A material problem might occur if a child places the prism in Figure 1 on a rectangular rather than a semi-circular face.

The way we discuss light may also cause difficulties for children (a discursive problem). For example the phrase, ‘the light goes from the bulb to my eye’ could indicate that light is something which travels from the bulb to my eye, but may also be interpreted as meaning that light is something which stretches from the bulb to an eye in the same way as a rope goes from a ship to a dock (La Rosa et al., 1984; Watts, 1984). A car or road metaphor might be particularly confusing for children when thinking about light as the Champs-Elysées ‘goes from’ Place de la Concorde to the Arc de Triomphe, but so do cars. Expressions like ‘the light is bad’, ‘poor lighting’ or ‘most people see us in a good light’ could impute moral implications to some learners.

An example of an observational problem with this equipment might be a child seeing the way the light rays appear to fade with distance in Figure 1 and concluding that the light does not travel far. Scientists think that light which has been made by a source would continue to move (in a vacuum) for ever. Research has shown that many pupils do not think that light travels very far, particularly in day-time (Stead and Osborne, 1980).

Finally a conceptual problem might occur when a pupil describes light as an entity. Light sometimes behaves like particles (called photons) and sometimes resembles a wave. The science idea that light waves do not travel in any medium is very challenging. Children sometimes think that light is a ‘thing’, such that a ‘block of light’ might squeeze through a gap (Meyer and Woodruff, 1997). Some children describe light flowing around an object like the sea encircles a sand castle (ibid.).

Science language like ‘light ray’ can lead to children separating their everyday experiences from those that happen in the science classroom (Ramadas and Driver, 1989), and as ‘ray’ is a term used frequently in science fiction, children may not consider it to be
This article will now focus on some of the conceptual problems children may encounter when learning about light.

**Naïve scientific concepts**

Considerable evidence suggests children hold a wide variety of ideas about the natural world, and light in particular, which are at odds with established scientific thinking (Driver *et al.*, 1994; Duit, 2009; Allen, 2010, pp. 167-173). ‘Naïve concept’ (a term used by, for example, Inagaki and Hatano, 2002) is one of many words used in the literature to refer to children’s ideas which differ from accepted scientific conceptions. Teachers and researchers find that some children appear to resist changing their ideas, or relapse into previous ways of understanding, in different ways and for a variety of reasons (Illeris, 2007, p. 157). ‘Conceptual change’ replaced to a large extent ‘misconception’ in the literature in the early 1990s for many reasons (diSessa, 2006, p. 266), including a desire by researchers to be more positive about children’s thinking and the recognition that helping children to become aware of their own naïve thinking can help learning. Another reason is that studies have shown evidence of several different types of conceptual change (Clement, 2008, p. 433) including ‘synthetic concepts’ where a naïve concept may be combined with scientific thinking. Only part of the idea is a ‘misconception’, so it seems unfair and unwise to label the whole thing as erroneous.

In addition to naïve concepts, developmental psychologists have observed children using naïve learning methods (Zimmerman, 2005). For example the hypothesis ‘tap water is good for plants’ (one children are familiar with) is not investigated by children in the same way as ‘coffee grounds are good for plants’ (an unfamiliar idea) according to Zimmerman (2005). Children may use a combination of learning methods which are sometimes similar to those which researchers have identified by investigating the methods used by professional
scientists (Darden, 1991), and at other times resemble naïve learning methods according to Riordan (2013, p. 118).

This article takes an enormously helpful (and brief) review of research into children’s naïve thinking about light (Driver et al., 1994, pp. 41-45 and 128-132) as a starting point and explains what we think are some significant contributions to our understanding of children’s ideas about light since then. Clearly much of this will be very familiar to experienced colleagues. The aim here is to identify and describe the discoveries about children’s thinking about light of most use to teachers and to see how research may support the pedagogical decisions teachers make.

What is light?

Light is a highly abstract concept and it is not obvious to pupils in school what light is (Watts, 1984). It is important to give a clear definition each time this topic is taught, but what can be said depends on the particular learner one is working with. So definitions may range from, “Light is something that moves very quickly from an object that makes light, like a light bulb, to your eye.” to the following:

**light** The agency by means of which a viewed object influences the observer’s eye. It consists of electromagnetic radiation within the wavelength range 4 x 10⁻⁷ metre to 7.7 x 10⁻⁷ metre approximately; variations in the wavelength produce different sensations in the eye, corresponding to different colours. (The Penguin Dictionary of Science, 1979)

and even:

\[ \nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0} \quad \text{etc.} \]
However, pointing at a light bulb in the room whilst emphasising that I’m not talking about the light bulb, and tracing the path of the light with my finger to a teddy bear and thence to my own eye, might be a more effective definition for school children than all the above.

Given that a ray of light can only be seen if it shines directly into the eye, pupils are being asked to consider something which they cannot always see whilst being told that light explains vision, which may be very confusing (Ramadas and Driver, 1989). A low power laser pen (used with care to avoid eyes) shone through dust or smoke (used with care to avoid causing respiratory problems) may help understanding. But this could encourage children to think that light can be perceived from the side, which is a naïve concept (Viennot, 2006). Light from the laser pen scatters off the dust and some of the light goes into our eyes. The fact that light appears to travel in straight lines is important for understanding (Andersson and Bach, 2003, call this the ‘key idea of optics’), but challenging as light does bend as it goes round the edge of an object or through a gap (diffraction) and when it goes from travelling in one medium to another (refraction). Some children may even be aware that gravity can bend light.

**Where does light come from?**

A primary source of light is one which makes light. We have ordered the following list of primary sources of light from what we consider the most typical to the least typical: fluorescent tube, filament light bulb, torch, candle, fire, lightning, Sun/star (many children and adults do not think the Sun is a star according to Lightman et al., 1987), LED (light emitting diode), gas hob, red hot metal bar heater, mobile phone screen, computer monitor, bioluminescent animals (for example fish, jellyfish, insects, plankton, bacteria), bioluminescent plants (for example foxfire mushrooms), genetically modified fluorescent pig. Research shows that if people are asked to order exemplars of a category from typical to
atypical, the order in the lists they produce is not always identical (Rosch, 1975). For example, we might agree that an apple is a more typical fruit than a tomato, but disagree as regards whether an orange is more or less typical than a banana. Furthermore the threshold beyond which an object is no longer considered an exemplar of a concept differs between people. This is important for science teachers to know in that what I might consider a typical example of a source of light (say an Angler Fish) may not be considered to be an example of this category at all by some pupils in my class. Teachers may be wise to pick exemplars from the ‘extremely typical’ end of the spectrum, and even then to check that everyone in the group agrees that what we’re talking about is actually a source of light.

By the age of 7 children know a number of sources of light, but research has found that these are mostly primary sources rather than secondary ones (Osborne et al., 1990). A secondary source of light does not make light itself, but redirects light from a primary source (for example by reflection, scattering or transmission) and may be neglected by some children because they think that light is only associated with large luminous objects (Watts and Gilbert, 1985). The ‘typicality’ argument made above should also be considered when using exemplars of secondary light sources. One list, in order of typicality, might be: banana moon, Earth, mirror, rainbow, Interactive Whiteboard screen (except the back-lit type), red-eye. Many children think that the moon makes light according to Philips (1991). Hence the moon might be considered to be a primary source of light by one pupil (a naive concept), while another in the same class may think of it as a secondary source (which is what scientists think).

It is common for children to confuse a source of light (like a candle) with light itself (Guesne, 1985). A phrase like ‘turn on the light’ may suggest to a pupil that light is a source (or even a switch). When using this expression we mean ‘turn on the light bulb’, which is where the light comes from, not the light itself. Some children do not think of light as
something that moves at all (ibid.) or, as mentioned earlier, that it doesn’t travel far (Stead and Osborne, 1980). Children experience effects like a patch of light on the floor and sometimes think that the patch itself is light, rather than an effect produced when light hits a surface and scatters off (ibid.). Expressions like, “The room is light” lead to confusing a state like ‘bright’ with light itself (ibid.). Questions involving ambient daylight may not be answered in the same way as ones about a source like a desk lamp (Driver et al., 1994, p.44) showing that the context within which an idea is explored can have a significant effect on a child’s thinking (Wellman and Gelman, 1992). We turn next to children’s naïve thinking about sight.

**How do we see?**

Many children consider that seeing is obvious and does not require an explanation (Osborne et al., 1990; Shapiro, 1994). Expressions like ‘I see the banana’, which focus on the subjective experience of seeing, make it hard for children to accept the scientific explanation of vision which involves light going into our eyes. Children may use different explanations for how they see luminous and non-luminous objects (Guesne, 1985). Thinking that the pupil of the eye is a black spot (Gonzalez-Espada, 2003) may act as a barrier to understanding that light enters the eyeball through this hole (which is covered with the transparent cornea).

Some children think that we see by something coming out of our eyes (a naïve concept), others think that something enters our eyes (a scientific concept), and some think that we see by something entering and something leaving (a synthetic concept). This thinking is illustrated in this section of transcript where a teacher (TU) talks with several pupils (JK, CS, JB, LN, EM and BN):

1a:366   **TU (teacher): [...]** Let’s vote. If you think that you see that way [out from eyes] put your hands up. [CS and JB straight away. JK next.}
LN next. EM slowly. BN hand held next to her cheek - unclear if she is voting or not

JK: [To CS] That is only when you go to sleep.

1a:367

TU: If you think that you see that way [towards eyes] put your hands up. [JK says err and stretches] [BN puts her hand up]

1a:368

BN: You sort of see both ways.

Riordan (2013, p. 216)

Conceptual change researchers call line 1a:368 a ‘synthetic concept’, where someone has adopted a new idea without relinquishing the old one, and this is one of several types of conceptual change which have been identified (Clement, 2008, p. 433). Some pupils have been found to use a ‘light into the eye’ model for luminous objects and a ‘light out of the eye’ one for non-luminous objects (Guesne, 1985).

It is difficult to interpret correctly drawings which show naïve explanations of how we see and it is frequently necessary to listen to the way a pupil understands what they have drawn. Figure 2 below shows some of the ways people use words and drawings to explain how they see things (adapted from Heywood, 2005). Many other combinations of explanations and drawing are possible. Figure 2g represents how a scientist might draw and explain how a duck is seen.
Figure 2: Diagrams of 'how we see a duck' (adapted from Heywood, 2005, p.1454 - with permission)
Figure 2a may indicate that a pupil thinks that ‘I see the duck’ is a sufficient explanation for vision, and Figure 2b could suggest the naïve concept that an image is a corporeal entity which the eye can pick up (Heywood, 2005, p. 1456). Some people combine the ideas expressed in Figure 2b and c to argue that light is ‘reflected’ back and forth between the duck and eye as illustrated in Figure 2h (ibid.). The first three diagrams (2a, 2b and 2c) may indicate that a pupil does not consider a light source to be necessary for someone to see, but even where a light source is shown, this may be understood as ‘bathing an object in light’ or ‘helping us see’, and not indicate an understanding of the mechanism of sight. The idea that seeing involves something that comes out of our eyes is called the ‘active eye’ idea by researchers (Driver, 1994, p. 43), and this can be combined with other ideas by children as shown in 2d and 2h. One participant in Heywood (2005, p. 1463) thought that light moves like a gas to fill up a space. Naïve thinking about gases may be influencing naive ideas about light (Driver, 1994, p. 80, 104-111). The interpretation of the drawings of pupils is a complicated matter, and listening to the interpretation of ‘correct’ and ‘incorrect’ drawings may help teachers and pupils identify naïve concepts and promote conceptual change. For a review of research into children’s ideas about ‘vision’ see Driver (1994, p. 43-45).

Even when a child gives a ‘correct’ explanation of vision, this can sometimes mask naïve thinking. In the following example (from Riordan, 2013, p. 87) teacher and pupils were discussing why we see a teddy bear. One student (UA) expressed very clearly the science explanation of how we can see an object:

3a:335 UA: But when you turn on the torch, because it generates a light source, if you point it at a specific area the the thing or object or area that has been hit with the light you'll be able to see that because the light bounces back into your eye. So you're able to see - so you're able to see where it is.
The teacher later asked what happened inside the eye. It became clear from a later interview (3b:90-93) that this was asked in order to extend the answer, and there was no indication that what came next was expected by the teacher. The same pupil (UA) went on to explain that after the light has gone into the eye, it then bounces out so that we can see objects (a naïve concept – see for example Fetherstonhaugh and Treagust, 1992, p. 653).

UA: I think - I think there’s. I'm not sure what it is called but I think there is something in your eye that allows the light to sort of - yes. As I say - bounce back. But when it bounces back to the original space so you’re able to see where it was.

Some light does bounce off the surface of our eyes (one can sometimes see objects reflected in the eyes of another person) and the retina can reflect light (causing ‘red-eye’ in photography), but I do not think this pupil is referring to either of these ideas. Synthetic concepts like this show how teachers need to be aware that even the correct answer to a question does not always indicate scientific understanding.

Asking pupils to imagine walking into an entirely dark room, with no windows or other sources of light inside, can be fascinating as the following transcript of a discussion between a teacher (TU) and six 11 year-old pupils illustrates:

TU (teacher): So we've gone into a dark room.
JK: Yes
TU: Can you see the teddy bear?
JK: No, not without a torch.
EM: Not technically without a torch because some people, some people like my Dad are really good at seeing in the dark because they stay up all the time, they never go to bed. Um, so basically
TU: So do we mean a dark room in our houses where there is a little bit of light coming in through the curtains or are we talking about a
really [with emphasis and hand gesture] pitch black, like if you go into one of these rides at the fairs where it is totally black. Let’s just make sure we know what type of room we're going in.

JB: Thorpe Park [an amusement park]

1a:291 EM: I think we're talking about, if we turn all these lights off. Get loads of [indicating with her hand the windows] - put some blinds there. Make sure they're properly shut and we can't get

1a:292 TU: OK, so a really really dark room. And we walk in through the door and teddy is in the middle of the room.

EM: Got to make sure the TV is off.

TU: OK no TV on. Are we going to shut the door behind us in this dark room?

1a:293 EM: Yes.

BN: No.

TU: Oh, we'd better agree.

BN: No.

TU: I think we're going to shut the door the door.

JB: Why?

TU: I think we're going to go in the room we're going to shut the door. Can we see teddy?

1a:294 EM: Yes. [Still working on her drawing]

LN: Yes. [Still working on her drawing]

CS: No.

BN: No.

(Riordan, 2013, p.139)

Line 1a:289 may suggest that the pupil (EM) thinks that light is unnecessary for us to see and that all, or some, people can see in total darkness (cf. Ramadas and Driver, 1989). Children
who live in the countryside are less likely than those who live in towns to think this, and many children think cats can see in pitch darkness (Fetherstonhaugh and Treagust, 1992). The teacher guided the group in line 1a:290 to consider a pitch black room with no sources of light. In 1a:293 one pupil (BN) appears to resist the idea of such a room and another pupil (JB) questions the need to close the door. This reluctance might reflect the fact that the experience of pitch black is very rare now (photographic ‘dark rooms’ are a thing of the past and not everyone will have experienced so called amusement rides in absolute darkness). This teacher guides the pupils to a point where the pupils themselves are able to understand that they don’t agree about this idea (line 1a:294). We turn next to children’s ideas about colour.

**What is colour?**

White light is a mixture of light of different colours and in primary schools these are traditionally categorised as red, orange, yellow, green, blue, indigo and violet, but some children do not believe this, or don’t know which colours are involved (Anderson and Smith, 1983). It may be worth playing or singing in the classroom the song ‘I can sing a rainbow’ before pointing out that they obviously can’t. Other pupils explain colour without referring to light at all, as a property of an object which our eyes allow us to see (ibid.). As each of the colours are bent, meaning refracted, by different amounts when they pass through a plastic prism, this can be used to separate out these constituents of white light (something children really need to be given the opportunity to do themselves). In the previous sentence teachers need to be wary of how they relate terms such as ‘bent’ to refracted, as pupils may think that these are two different things, or consider bent to imply curves. Research shows that some pupils think light carries colour (Watts and Gilbert, 1985). A red object absorbs orange, yellow, green, blue, indigo and violet light whilst scattering the red, some of which goes into
our eyes allowing us to see it. Coloured filters are hard for children to understand. A blue filter allows only blue light to go through and it absorbs red, orange, yellow, green, indigo and violet colours within white light. Although dyes are used in the manufacture of filters, some children think a filter ‘dyes’ white light or that the white light knocks out the colour of the filter (Zylbersztajn and Watts, 1982). Developing the understanding that white light consists of light of a range of different frequencies (some of which we can see and others which we cannot) is a hugely challenging task for children in school. Next we develop the ideas of coloured objects and coloured filters by discussing more generally the interactions between light and the medium within which it moves.

The interactions of light with matter

A variety of phenomena occur when light encounters matter. Scientists describe objects as transparent, translucent or opaque. Light may be absorbed, reflected or scattered by a surface, with different effects occurring for different frequencies. Transmission may involve the light changing direction (refraction) and light moving through a gap or past an edge may be diffracted. In addition two waves may superimpose to form a resultant wave where the height of the wave (called the ‘amplitude’) may be bigger or smaller than that of the original waves, a phenomenon called interference. Pupils may think that light does not travel at all, does not travel far from a source, does not travel during the day, travels further in the night than during the day or even that it does not travel during the night but does during the day (Driver et al., 1994, p. 130). Firstly we will discuss the interaction of light with opaque matter, secondly children’s ideas about reflection and scattering, and finally some thoughts about refraction.

A shadow is an area where direct light from a source cannot reach because of the presence of an object. Some children think a shadow is a thing which light allows us to see or
which light pushes out of objects, a naïve concept beautifully illustrated in ‘Peter Pan’ by J. M. Barrie (Stead and Osborne, 1980; Feher and Rice, 1988). This is an example of what Chi (1992) called an incorrect ontological classification. Children may think that shadows only occur in bright light (Watts and Gilbert, 1985). Though most children over the age of about 13 can correctly predict where their own shadow will fall if they stood in the Sun, it is worth asking them to predict where the shadow of another object (say a tree) will be, as research has shown that they sometimes find this harder (Tiberghien et al., 1980 quoted in Driver, 1994, p. 130). Physicists consider darkness to be the absence of light, whereas many children think of it as an entity in itself (Ramadas and Driver, 1989), which is worth considering when interpreting the shading in children’s drawings about why they see things. The influence of drawings and diagrams on naïve thinking about light will be discussed later.

Next we discuss a demonstration and diagram commonly used by UK science teachers when exploring light in order to illustrate how naïve thinking may be fostered by pedagogy. The learning objective is to understand the shadows (umbra and penumbra) caused when the light from an extended spherical source encounters an opaque spherical object like a ball. This is illustrated in Figure 3 and Figure 4. Light ray 1 in Figure 3 illustrates how light from this source can reach some parts of the white screen without hindrance. Ray 2 shows the closest light can get to the very centre of the screen. Hence no light reaches the part of the screen in the middle, and this area is called the umbra. Some light (see ray 3), but not all light (ray 4), can reach the area surrounding the umbra, so a partial shadow is formed which scientists call the penumbra. We can see the blue ball because blue light is scattered (ray 5). It is quite hard to describe this demonstration without using language which could be misinterpreted to mean that a shadow is a thing (for example, ‘the shadow in the centre is called the umbra’). Demonstrations in well-lit rooms give an umbra which itself may be a partial shadow. If the screen in the diagram is white, then it will scatter the yellow light and
so should be drawn yellow (as in Figure 3). If the umbra is circular, then the object must have a circular cross section. So it may help pupils if the blue ball is drawn in such a way as to indicate that it is a sphere rather than a flat cylinder (compare Figure 3 with Figure 4).

Figure 3: Diagram showing a light source, a blue ball and a white screen.
Many pupils think light bounces off mirrors but not off other objects, whereas others do not think it scatters off anything (Anderson and Smith, 1983). Even if they do understand that light bounces off objects, this concept may not be linked in their mind with seeing (Driver et al., 1994, p. 131). The phrase “bounce off” may not be synonymous with ‘reflect’ for some children. For physicists reflection is a special case of ‘scattering’, where the latter term describes how light changes direction as a result of non-uniformities in the medium in which it moves. Children may understand ‘scatter’ to mean spread out in the same way as children might scatter in a playground. Some children argue that light stays on a mirror when it is reflected (Fetherstonhaugh and Treagust, 1992), and/or that the image is on the mirror (Goldberg and McDermott, 1986).

When discussing the refraction of the light which scattered off a pencil in a glass of water, Shapiro (1989) found:

“The most common response, from about 25 per cent of the children, was that the water made it look broken. Other popular answers were that water bends the light rays, that the shape of the beaker makes it look broken or that the combination of water and the beaker made it look bigger. Some children thought the water acted as a magnifier and some related their answers to light rays.” (Driver et al., 1994, p. 131)

The purpose of showing children this ‘broken pencil trick’ may be to illustrate the refraction of light, but a cylindrical container of water will magnify light which passes through it. Hence teachers help children distinguish between different phenomena which are evident in the same demonstration, and need to be cautious about what a pupil actually means when they use the word ‘magnify’, as this could be synonymous with ‘reflection’ for some children. In one study primary school teachers, with the support of researchers, constructed explanatory models which they could then use with pupils to explain observations such as a
straw being ‘bent’ when in a glass of water (van Zee et al., 2005). These ideas included light travelling in straight lines unless something happens to make it do otherwise, and the way light ‘sprays out’ from a point in all directions. The paper shows how these concepts become modified and more confidently adopted as they are applied to new situations. We turn next to the way light is represented in drawings such as Figure 3 and Figure 4.

**Drawing light**

Dark pencil lines are often used in classrooms on white paper to represent light rays when black paper and white pens or Interactive Whiteboards make it possible to have a black background and yellow line representing the light. Compare Figure 4 where yellow lines from a yellow light source are used, with Figure 5 which shows grey rays emerging from a yellow object. When asking pupils to put arrows on lines to indicate the direction that light is travelling in, teachers need to be aware that arrows themselves can be a challenging concept. Ray direction is not indicated in Figure 4. One of us taught a pupil recently who could draw an arrow shape, but who did not understand that it indicates a particular direction. His arrows were drawn in random directions, even when asked to draw an arrow pointing to the door. Light rays in diagrams in physics textbooks often stop when they reach an object. This may be appropriate for black objects, but it does not convey the reflection or absorption of colours by coloured objects (so in Figure 3 light can be seen scattering off the blue ball). Drawings of objects in books often show single rays, or a small number, coming from the boundaries of an object. This may be a barrier to children understanding that an accurate representation of light in such diagrams would require an infinite number of rays.

**Theoretical Models for light**

Classical electromagnetism can explain most optical phenomena, but in school pupils encounter a variety of simplified theoretical models for light such as geometric rays, wave
fronts, transverse waves, or photons. Research shows that even university physics students have significant difficulty in synthesising the geometrical and wave front models (Colin and Viennot, 2001). Multiple representations are necessary as no one model adequately depicts the extraordinary phenomenon we experience as light. For example waves are more useful than geometric rays in explaining ‘brightness’ (Galilli & Lavrik, 1998). Discussing the advantages and limitations of theoretical models is important for the development of an understanding about how science works.

Teachers sometimes unconsciously, or consciously, use a theoretical model which pupils are not yet familiar with. Practitioners can ‘make the familiar strange’ for themselves so that pupils are made aware of, and understand, the assumptions on which an explanation rests. This is sometimes called ‘defamiliarization’, and involves a teacher trying to see well-known demonstrations and experiments in the way a child might when encountering this for the first time. Perhaps we must, “stop seeing only the things that are conventionally ‘there’ to be seen” (Becker, 1971, p. 10).

We would argue that teachers must, to some extent, interpret during the lesson the naïve and scientific knowledge pupils bring with them, so as to adapt practice appropriately. We also acknowledge that in some areas of physics children may not yet have thought at all before about the issues discussed (for example the photoelectric effect). Although exam specifications in the UK rarely prescribe which theoretical models should be used, our experience suggests that schools tend to opt for ray diagrams for teaching about how we see, reflection and refraction. Key Stage 3 pupils in the UK (aged 11 to 14) focus on how we see different objects and colours, whereas Key Stage 4 science (for pupils aged 15 to 16) explores electromagnetic radiation. Colour is often discussed in relation to the dispersion of white light as a result of refraction by a prism. Eventually pupils are shown that colours correspond to our perception of electromagnetic waves of different frequencies. The wave front model is
commonly used with Key Stage 5 students (aged 17 or 18) to explain interference. As far as we are aware there has been no research comparing the effectiveness of teaching using different models for children at different stages in their education.

To illustrate some practical difficulties children may have with the way science teachers use models for light we will discuss two ways in which refraction is described diagrammatically. The wave front model follows Huygens’ principle, describing every point as the source of a spherical wave of light. This model illustrates the way the energy associated with waves spreads out during propagation. It can also help understand why light ‘bends’ (refracts) as it passes into different materials as shown in Figure 5a below:

![Wavefront model](image)

![Ray model](image)

**Figure 5: An illustration comparing the wave front model for light with a geometrical ray model**

Figure 5b shows how the same phenomenon may be described using geometrical optics (although on its own it does not explain why light refracts). The word ‘medium’ may conjure images of a séance in the minds of children, so needs to be explained if used. Diagrams cut and pasted from the internet may confuse children when alternative models for light are being explored. For example Figure 6 below shows two diagrams taken from the internet which may be compared to the diagrams in Figure 5.
a) Wave front model                  b) Ray model

Figure 6: An illustration comparing the wave front and geometrical ray models using diagrams from the internet (GNU free licences)

The orientation of the two mediums in Figure 6a and Figure 6b is not the same, which could be very confusing for children were these diagrams used together in a lesson. Figure 6a includes both wavefronts and rays, which are perpendicular to each other by definition, but this may confuse pupils if not carefully explained. It is unclear why the wavefronts change colour in the new medium. Colour is related to frequency which remains constant here as speed varies. In Figure 6 no source is shown, which might suggest to a learner that light may just appear out of nowhere. The ‘normal’ line in diagrams like Figure 6b is an imaginary line running perpendicular to the surface which is used by scientists as a reference against which the angle of an incoming or outgoing ray may be measured. This may need quite a lot of explaining in a classroom, and may not appear very normal to children. We would argue that using Greek letters in school physics is often unnecessary.

Advanced physics brings further challenges which we will not explore in depth in this present article. Suffice it to say that pupils and teachers may perhaps be forgiven for confusing on occasion radiant energy (in Joules), radiant flux (or the energy radiated per second - measured in Watts), intensity (power per unit area), radiant intensity (the power per
unit solid angle), radiance (power passing through or emitted from a surface, measured in Watts per steradian per square metre - also called ‘intensity’ in some branches of physics), irradiance (the power per unit area incident on a surface - measured in Watts per metre squared), luminous intensity (in candela), luminance (in candela per square metre - otherwise known by the non-SI name of the ‘nit’), etc. etc.

**Teaching Models**

In addition to different theoretical models used in the teaching of light, physical models are often used to illustrate certain properties of light. For example ripples on water, spinning coloured disks, a car driving into a patch of mud, or cocktail sticks taped parallel to each other in a long row such that a wave travels along when one stick is displaced.

We argue that it is important for teachers to distinguish teaching models from scientific understandings. For example, Viennot (2006) draws attention to the use of ray-boxes to illustrate that light travels in straight lines. Teachers might describe the patches of light which come from the slits in front of ray box as ‘rays’. However, these patches are actually the projection of the slits and, as Viennot illustrates in Figure 9 below, they can be made to show wavy lines which seemingly contradicts scientific understanding.

![Figure 9: Light box with wavy slits from Viennot (2006, p. 401) - used with permission](image)

The issue is that the physical model being used to illustrate phenomena such as reflection has limitations, as any model does. After using a ray box pupils may be forgiven for concluding
that ‘rays’ of light are usually a few millimetres thick and are separated by areas of darkness. More subtly, they may notice that they become wider and fade with distance from the source but not realise that this is because the ‘rays’ are actually formed by the length of the slits and the relative position of the bulb inside. The inverse square law which relates light intensity to distance from source is here obfuscated by the experimental setup which restricts how far the patches of light extend.

The use of ray boxes allows pupils to visualise light travelling in a straight line and can be used in the demonstration of reflection and refraction. Teachers must be cautious however that ‘teaching models’ be they physical representations, diagrams, animations or analogies are carefully explained and related to scientific understanding. Research suggests that evaluating a range of models is important in developing a fuller understanding of a phenomenon (e.g. Trigidgo & Ratcliffe, 2000) and as such we advocate the use of a variety of models in teaching about light, each introduced and evaluated carefully with pupils.

An approach which appears repeatedly within the research literature is the use of an extended light source, such as a square or cross made of light bulbs, and an object or hole in front of a screen (Meyer & Woodruff, 1997; Anderson & Bach, 2005; Heywood & Parker, 2010). Typically pupils manipulate the source, object and relative distances to see the change in image produced. As well as experimental enquiry the literature also contains studies in which computer programmes are specifically designed to provide scenarios through which pupils can consider light phenomena. For example Valanides & Angeli (2008) describe children using a computer simulation to explore colour. Whilst studies into specific approaches often show pupils gaining a more scientific understanding of light there are no systematic comparisons of their merit. Researchers often conduct studies in order to develop theoretical perspectives on conceptual change and we advise that teachers use such studies
for inspiration but recognise that what is best for their class will remain a matter of judgement.

As well as theoretical models and what we have called teaching models, there is a broad literature on how historic context might be used within the classroom. For example some researchers use classroom activities based on historic problems such as Kepler’s consideration of the shape of shadows at different distances from sources (Galili & Hazon, 2000; Dedes & Ravinas, 2009). The historic reasons for the inclusion of indigo in the rainbow and cultural differences in descriptions of colour are also fascinating. As with teaching models, historic context can be engaging and allow conceptual development but teachers should not assume that it will have a predictable impact upon pupil understanding.

This variety of theoretical models, teaching models and historic context used in the classroom might be overwhelming for some learners. Comparing different models for a phenomenon like light has the advantage that one representation may be more accessible to a particular learner than another, but the cognitive challenge of retaining and using multiple models simultaneously should not be underestimated. More sophisticated models for light need to be introduced sensitively, taking care not to provide new ways of thinking too quickly or too slowly. The construction and subsequent demolishing of a theory is a familiar cycle to physics teachers (a ‘rug removal’ tactic), yet the emotional impact on learners of these small bereavements should not be underestimated.

**The conceptual ecologies of pupils**

So far we have considered what research has to say about the way pupils think about light and how teachers might influence this, both intentionally and otherwise. Each pupil in a class may have a different collection of ideas about light, and the notion of a ‘conceptual ecology’ (Posner et al, 1982, p. 213) may be useful in appreciating this.
A learner’s conceptual ecology includes not just concepts but also ontological categories and epistemological beliefs (Toulmin, 1972). Ontological commitments, which involve what we believe exists, can constrain a learner’s ability to restructure their thinking (Vosniadou, 1994, p.55). When thinking about light, pupils may struggle to assign light to an ontological category, for example some pupils may consider light as a process by which energy is transferred, some may consider it as an entity in itself and some may not consider such categories at all. Differences like these will influence how concepts change (Chi, 2008).

Considerable evidence suggests epistemological beliefs also influence conceptual change (Deniz, 2011). An epistemological belief is one about the nature of knowledge. For example, people differ in whether they believe we can know things for certain or not and this will influence how they might respond to new information.

Motivation will also play a significant part in how pupils’ ideas change (Pintrich, Marx and Boyle, 1993). We propose that classrooms could be considered as complex systems in which learning is dynamic and sensitive to the specific conditions and history of the system (Hardman, 2011). However we understand the interactions of concepts, beliefs and motivation, it is clear that the learning in each classroom is unique. We think that any attempt to prescribe a fixed approach to teaching light would be inappropriate. We consider instead what research has to say about strategy in promoting conceptual change.

**Strategy and changing naïve concepts**

Much of the literature about teaching light comes from the era in which studies focused on pupil ‘misconceptions’. This field became part of the kaleidoscope of common sense and theoretical ideas now known as conceptual change research (DiSessa, 2006). Three ‘traditional’ areas of research into conceptual change were identified by Sinatra (2005, p. 108): the exploration of cognitive factors (for example Vosniadou and Brewer, 1992) which
included the attempt to list children’s ‘misconceptions’ in science (for example Driver et al., 1994), a developmental perspective which examined the origins of children’s naïve thinking (for example Carey, 1985), and the exploration of conceptual change pedagogy (for example Posner et al., 1982). We will now discuss some of the different ways in which instructional strategy for conceptual change can be understood.

Teachers sometimes describe classroom discussion about naïve concepts using war metaphors (Riordan, 2013, p. 94). Other metaphors for communication are possible according to Krippendorff (1993), but he argues that a war metaphor works best when there is something to gain or lose in an exchange (see also Lakoff and Johnson, 1980, p. 4). As one aim in teaching might be to promote conceptual change, pupils sometimes do lose naïve concepts and gain scientific ones (and vice versa), so this military language may occasionally be appropriate. We find this understanding of strategy useful in considering how to teach about light where concepts, beliefs and motivations of learners and teacher interact dynamically. Some would suggest that conceptual change is largely a matter of reaching consensus (Meyer and Woodruff, 1997), but we feel that this does not recognise the ‘conceptual conflicts’ which occur when pupils and a teacher talk about naïve concepts (Riordan, 2013). Others use the word ‘strategy’ to mean a plan (for example Scott, Asoko and Driver, 1991 p.1). Whilst acknowledging that planning is an important aspect of strategy, we would argue that this understanding overemphasises the intended curriculum. The enacted curriculum rarely corresponds to that intended (Gehrke, Knapp and Sirotnik, 1992, p. 55), so tactics and strategy must be dynamic; responding to circumstance. Research suggests that experienced science teachers already have a wide repertoire of instructional techniques for managing the learning of pupils in their care (Riordan, 2013, p. 99). These techniques include redirecting the conversation in the classroom, reminding pupils about what has been said (i.e. summarizing) or requesting clarification, using activities like experiments, grouping pupils in
different ways etc. etc. These techniques may be used in both simple and sophisticated ways. We define tactics as the theory of the use of teaching and learning techniques in a single ‘conceptual combat’. Strategy can be defined as the theory of the use of such conceptual combats to try and meet an objective. So, for example, a teacher aiming at a scientific understanding of light might make a strategic decision to not introduce reflection until pupils can explain shadows (Andersson & Bach, 2005).

One striking feature of the literature we reviewed is the long timescales over which pupils (and teachers) develop their concepts in relation to light. Many of the studies devoted far more time to developing a ‘basic’ understanding of light propagation and shadow formation than is spent sometimes on the whole topic of light in secondary schools. Creating the time and a supportive atmosphere in which pupils are able to explore, discuss and consider phenomenon is essential.

Light is a topic in which the subject matter presents significant challenges for the learner and in which there is likely to be a variety of understandings within a single classroom. This necessitates teachers being responsive and making tactical and strategic decisions continually. As such we would urge caution in adopting simple ‘research-based tips’ or ‘toolkits’ for how to deal with ‘misconceptions’ (for example DiSpezio, 2010). We also note that quantitative analyses, such as that by Hattie (2008, 2011), of the relative ‘effect size’ of different teaching techniques are useful but they do not tell the whole story. Teachers may use techniques for a range of strategic and tactical reasons despite their impact upon attainment being minimal.

The pace and unpredictability of interactions within the classroom mean that hard and fast rules about teaching light are of little use to teachers. We argue that teachers are often already skilled tacticians and strategists, and research which tries to describe these behaviours may be of more use to practitioners than that which attempts to prescribe what should be
done. The role of conceptual change research may be likened to the statistics displayed on the TV during a rugby match. It is sometimes helpful to know relative possession of the ball or territorial advantage, but such numbers do not determine the outcome of the game. Pupils and teachers are the players, referees and coaches enjoying the game.

**Bibliography**


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