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

Part of the IOP 'Promoting and Interpreting Physics Education Research' project

by Mark Hardman and John-Paul Riordan

mark.hardman@canterbury.ac.uk john-paul.riordan@canterbury.ac.uk

Canterbury Christ Church University

Abstract

This paper offers a synthesis of research evidence around teaching light to primary and secondary school pupils, as part of the Institute of Physics (IOP) Promoting and Interpreting Physics Education Research (PIPER) project. Conceptual change literature describes many difficulties young people have with understanding the phenomenon of light, and this knowledge can be useful in the classroom. Pupil teacher dialogue is used to illustrate some of the pedagogical challenges teachers face in this topic. This paper highlights a range of influences on pupils from everyday life and from the classroom, with a view to promoting teacher awareness of conceptual change research evidence.

Acknowledgements

We would like to thank the Institute of Physics (IOP) for their support for this work which was part of the 'Promoting and Interpreting Physics Education Research' (PIPER) project.

Introduction

Light is a surprisingly difficult topic to teach in schools. Considerable evidence shows that child and adult scientists do not always understand this phenomenon in the same way (Driver *et al.*, 1994; Duit, 2009). This paper is a brief overview of what some children think about light.

What difficulties might children encounter when studying light?

In exploring the challenges adult scientists meet in their work, Allchin (2001 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. 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.

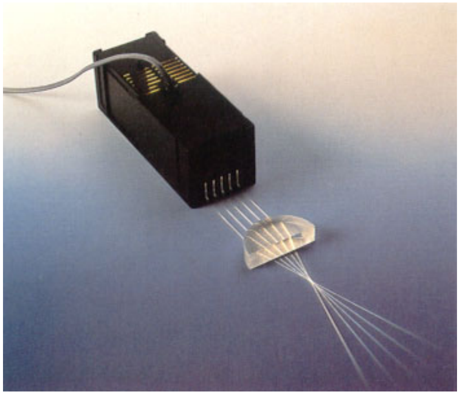


Figure 1: A ray box (image used with permission from National Junior College, 2014)

A material problem might occur if a child places the transparent block in Figure 1 so that light is incident on a rectangular rather than a semi-circular face, giving different results.

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. According to physics light which has been made by a source would continue to move (in a vacuum) for ever. Research has shown that many 13-16 year old 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 idea that light waves can travel without a 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 12-13 year old children describe light flowing around an object like the sea encircles a sand castle (*ibid.*).

In a study by Ramadas and Driver (1989) of the thinking of 13-15 year old pupils, science language like ‘light ray’ can lead to children separating their everyday experiences from those that happen in the science classroom (), and as ‘ray’ is a term used frequently in science fiction, children may not consider it to be real (*ibid.*). 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 11-12 year old children in the same way as 'coffee grounds are good for plants' (an unfamiliar idea) according to Zimmerman (2005). 11 to 12 year old children may use a combination of learning methods which are sometimes similar to those of adult scientists (Darden, 1991), and at other times resemble naïve learning methods, according to Riordan (2014).

A review by Driver *et al.* (1994, pp. 41-45 and 128-132) of research into children's naïve thinking about light was used as a starting point for this present paper. We also explore some more recent contributions to our understanding of children's ideas about light, which we consider significant. 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 which are of most use to teachers.

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:

$$\nabla \cdot E = \frac{\rho}{\epsilon_0} \qquad \text{etc.}$$

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. This 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, 2004, 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, as predicted by Einstein.

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: 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), whereas a third pupil might not consider it to be a primary or a secondary source.

It is common for children (aged 10-11 and 13-14) 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. Some children do not think of light as something that moves at all (*ibid.*) or, as mentioned earlier, that it does not 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 7 to 11 year old children consider that seeing is obvious and does not require an explanation (Osborne *et al.*, 1990). 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). This naïve thinking was found among university physics students (*ibid.*).

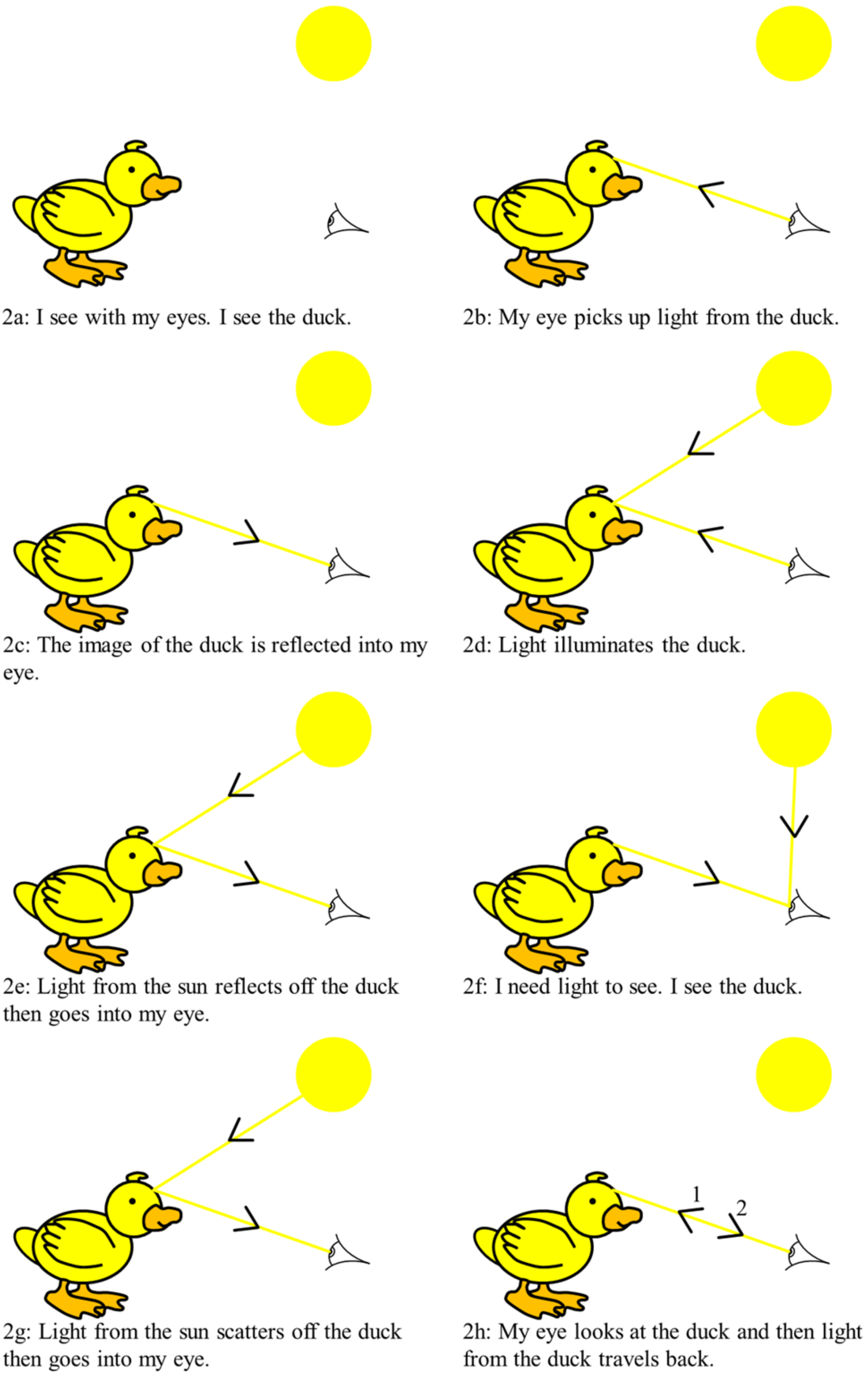
Some children think that we see by something coming out of our eyes (a naïve concept), others think that something enters our eyes (a scientific concept), and some think that we see by something entering <u>and</u> something leaving (a synthetic concept). This thinking is illustrated in this section 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 (2014, 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 non-specialist undergraduate trainee primary teachers 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.



2a: I see with my eyes. I see the duck.

2b: My eye picks up light from the duck.

2c: The image of the duck is reflected into my eye.

2d: Light illuminates the duck.

2e: Light from the sun reflects off the duck then goes into my eye.

2f: I need light to see. I see the duck.

2g: Light from the sun scatters off the duck then goes into my eye.

2h: My eye looks at the duck and then light from the duck travels back.

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 (see for example di Leo, 1999; and Edens and Potter 2003), 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, 2014, p. 87) teacher and pupils were discussing why we see a teddy bear. One student (UA) expressed very clearly the scientific 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).

3a:357 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 we 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:

1a:287 **TU (teacher): So we've gone into a dark room.**
JK: Yes
TU: Can you see the teddy bear?
1a:288 JK: No, not without a torch.
1a:289 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
1a:290 **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, 2014, 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). In a study with 13 to 18 year old children, those who live in the countryside are less likely than those who live in towns to think this, and many children think animals like cats and foxes 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) and perhaps even frightening for some children. 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 10-13 year old 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 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 13 year old 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 (2013) 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 10-12 year old pupils sometimes give different answers for different objects (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.

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). The latter finding was with first year university physics students.

When 11 year old pupils discussed the refraction of the light which scattered off a pencil in a glass of water, Shapiro (1994) 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. The word 'medium' may conjure images of a séance in the minds of children, so needs to be explained if used. We turn next to the way light is represented in drawings.

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 or white line representing the light. 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. One of us taught a pupil recently who could draw an arrow shape, but who did not understand that this shape 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 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.

Conclusion

We have here given an overview of some of the specific conceptual difficulties that children have when learning about light. This begs the question as to what teacher should do about these difficulties (see for example Scott, Asoko and Driver, 1991). We recognise that this will vary depending upon the specific context and learners and that teachers already have a wealth of knowledge about conceptual change pedagogy (Riordan, 2014). The conceptual change literature is now so vast and complicated that one way to make use of this fascinating work is to build close partnerships between science teachers and educational researchers who specialise in conceptual change. For example, a team of 23 experienced science teachers, two educational researchers and six Imperial College physics professors are currently exploring physics conceptual change research (including some of the literature on light described in this present paper), in a 'London Schools Excellence Fund' research project. The plan is to write together a 'research inspired' Key Stage 3 (so for pupils aged 11 to 15) physics Scheme of Work. We will then run a Randomized Control Trial of the scheme in twenty more London schools next year as the National Curriculum changes in UK schools.

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 express how they understand phenomena is essential, and both researchers and teachers have a role to play in this.

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Words: 6,178 (5,265 excluding bibliography)

Mark Hardman
Senior Lecturer in Secondary Science Education at Canterbury Christ Church University. Directs the INSPIRE Programme which equips post-doctoral researchers in the physical sciences to teach. Part of the Teach First tutor team for London. Undertaking a PhD study evaluating the development of complexity theory within education. https://canterbury.academia.edu/MarkHardman

John-Paul Riordan
Part-time secondary science teacher (special education). Part-time senior lecturer in Primary Education at Canterbury Christ Church University. PhD in conceptual change pedagogy (2014). https://canterbury.academia.edu/JohnPaulRiordan