Contemporary axioms for colour reproduction

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Colour is a complex subject that is inherently multi-disciplinary or trans-disciplinary. This can lead to misunderstandings in the way that the subject is taught. This paper is concerned with common misunderstandings of colour science, in the context of colour reproduction, that are widespread in social media but which can even be found in university-level textbooks. The misunderstandings are represented by four axioms that would need to be true to support the misunderstandings; these are critically evaluated using data (such as colour measurements) where possible or by reference to contemporary theory. None of the four axioms can be supported. Four new axioms are articulated that are supported by empirical evidence. It is suggested that these four axioms could form the basis of teaching material for colour reproduction in a 21st century curriculum.

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Introduction

Colour is a complex topic. Studies of colour can span the academic disciplines from philosophy and art, through social science, to chemistry and physics to name but a few. Indeed, it has been suggested that the subject of colour is a perfect topic to introduce students to STEAM (Science, Technology, Engineering, Art and Mathematics) education [1]. However, the complex and inherently multi-disciplinary nature of colour can lead to misunderstandings in the way that it is taught [2-5]. One such misunderstanding is where it is widely taught that three colour primaries can be mixed in various proportions to generate all colours. An example of such an assertion is where it is explicitly stated that all other colours can be mixed from red, yellow and blue on an educational revision website published by the British Broadcasting Corporation in the UK [6]. Although it is possible to make all hues by mixing red, yellow and blue colourants it is not possible to make all colours using red, yellow and blue colourants or, indeed, by any three primaries [3, 7-10]. Sometimes it is suggested that the reason why we cannot mix three colourants to create all colours is because the colourants themselves are imperfect [3]. However, it is not possible to conceive of a set of three colourants that could be mixed to generate all colours (as long as we accept the reasonable and necessary constraint that the spectral reflectance factors cannot be less than zero at any wavelength).

This paper addresses the way in which colour reproduction is widely misunderstood and sometimes taught. The paper does not claim to advance new understanding about colour but rather critically evaluates specific misunderstandings that can be widely found in contemporary educational material. The misconceptions that are addressed in this paper are related to what has previously been called the 'YouTube theory of colour vision' when Briggs [11] brought attention to several notable YouTube videos that incorrectly describe the process of colour vision including a video entitled 'This is not yellow' [12] which currently has over 21M views. In 'This is not yellow' Stevens puts forward the idea that if you look at a yellow lemon in real life, for example, then you are seeing real yellow but if you look at an image of a yellow lemon on an emissive display then you are seeing fake yellow. To support his argument, Stevens notes that displays do not emit any yellow light whereas when you see a real lemon you are seeing the wavelengths of yellow light that are reflected from the lemon (with the other wavelengths being absorbed). The suggestion is that the yellow that you see on a display is the result of the eye/brain being 'fooled' because the display emits only red and green light whereas the yellow of a real lemon results from seeing actual yellow light. Explicit within these ideas is the notion that light is coloured. The idea can also be seen in an educational video on YouTube entitled 'Tetrachromats don't have superpowers' in which it is stated that 'purple is not a real colour' because 'there is no wavelength that corresponds to purple' and that purple 'exists as a conjuring of your mind' [13]. Again, we can see the implication that some colours are real and others are not. The misconception is that since purple only occurs when we see combinations of wavelengths at the same time it is an 'imagined colour' whereas the colours that we see when we look at individual wavelengths in the visible spectrum are real, because light is deemed to be coloured. The value of this paper is to provide a critical analysis of some of the most important misconceptions and this is valuable because of the widespread proliferation of books and websites that include these misconceptions.

This paper puts forward four axioms that need to be true to support the 'youtube video of colour vision' and these are presented in Table 1. Each of these axioms will be critically evaluated against empirical evidence. Where the evidence does not support the axiom, the axiom will be rejected and replaced by an alternative related axiom that can be accepted. The implications of this analysis in terms of colour education will be discussed.

Axiom 1:	Light is coloured.
Axiom 2:	Coloured objects absorb all the wavelength of light apart from those of a particular colour which they reflect.
Axiom 3:	Emissive devices only emit red, green and blue light.
Axiom 4:	Some colours (e.g. yellow) generated by emissive devices are not real.

Table 1: The four axioms that are evaluated in this paper.

Axiom 1: Light is coloured

Newton famously wrote that 'the rays are not coloured' and before him Democritus distinguished between perceived properties such as colours and tastes, which exist only 'by convention,' in contrast to the reality of atoms and the void [14]. Despite these early insights, it is easy to find modern sources that state that light is coloured rather than just appearing to be coloured to us [15]. However, the idea that light looks coloured rather than is coloured is established in the scientific community [3]. Briggs (2018) noted that it is a fallacy that 'hues are properties residing in wavelengths of light' [11]. However, in philosophical terms there is some room for argument [16-17]. The problem with the idea that light merely looks coloured rather than is coloured is that in everyday life it certainly seems that light is coloured; just as, in our everyday experience, it seems as if objects, for example, really are coloured. There are good evolutionary arguments about why our colour vision experience has evolved in this way. Nevertheless, this is an example where our scientific understanding of the world is difficult to reconcile with some of our experiences and alternative views have therefore been put forward. A form of colour physicalism, for example, identifies colour with the spectral reflectance properties of objects [18]. However, Chirimuuta notes that many philosophers reject colour physicalism (even if they support physicalism in many other areas) because of the mismatch between colour physicalism and many other aspects of visual experience [19]. It is hard, for example, to reconcile the idea that colour is either the property of an object or the property of light with phenomena such as colour contrast whereby the colour of a physical stimulus can be shown to depend on factors such as the surround against which the stimulus is observed.

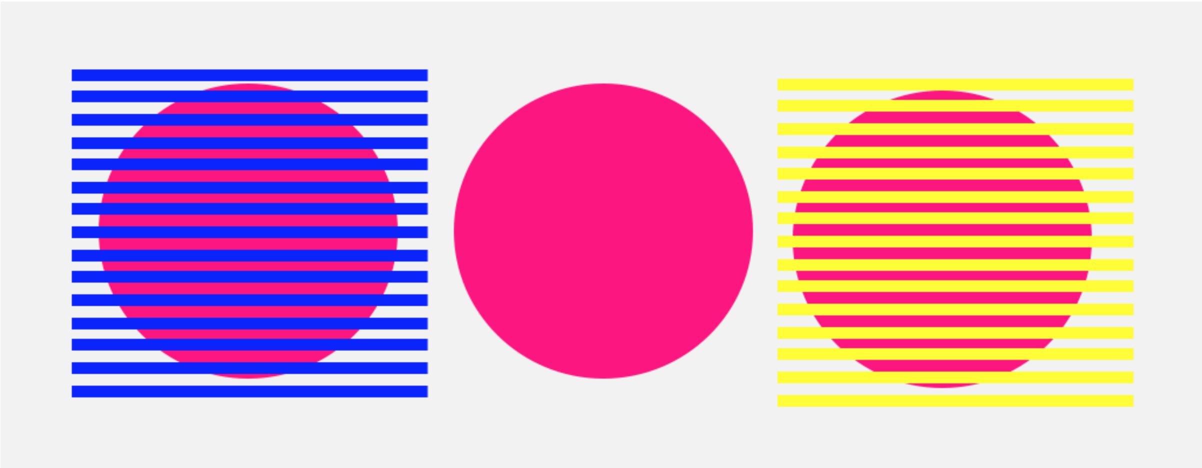


Figure 1: The three circles are all physically identical. However, their colour appearance varies depending upon the presence of the horizontal lines. This is an example of assimilation.

Figure 1 shows an effect where three physically identical stimuli (the three circles) look different in colour because of the presence or absence of coloured horizontal lines. Colour contrast is a well-known phenomenon that was extensively discussed by Helmholtz and Hering, whereby the colour appearance of a patch tends to take on the opposite colour appearance of the surround against which it is seen [20]. However, Figure 1 shows an example of a lesser known effect referred to as assimilation where the colours of the circles become more similar to the colours of their surround (in this case the surround field is the set of horizontal lines). Colour assimilation was first demonstrated by von Bezold (1876) who showed that a black field could be lightened when it was overlaid by white lines [21]. Explanations of contrast and assimilation effects can be found in spatial processing mechanisms of neural activity in the visual system.

Axiom 1 is difficult to completely refute because there is a wide range of visual phenomena which could support the axiom being accepted or rejected and we might also define the word colour in different ways. However, in this paper we will accept the view from science that colour is a perception [22-23]. We therefore reject Axiom 1 and replace it with an alternative form, Axiom 1A: Light looks coloured. Later, we will present a further argument why Axiom 1 should be rejected.

Axiom 2: Coloured objects absorb all the wavelengths of light apart from those of a particular colour which they reflect

The colours that we normally associate with each wavelength of light are given in Table 2. Newton originally proposed five colours in the spectrum but after discussions with some of his contemporaries he settled on seven: red, orange, yellow, green, blue, indigo, and violet [4]. Note that the colours given in Table 2 are somewhat different from those that have been taught since Newton. It has been suggested that this is because those colours that Newton originally called blue and indigo would, in contemporary terms, be called cyan and blue respectively [24].

Red	~ 700-635 nm
Orange	~ 635-590 nm
Yellow	~ 590-560 nm
Green	~ 560-520 nm
Cyan	~ 520-490 nm
Blue	~ 490-450 nm
Violet	~ 450-400 nm

Table 2: The colours that we normally associate with the wavelengths of light [25].

If we were to accept Axiom 1 and assume that light is coloured, then since light at 580nm is yellow (Table 2), it might be concluded that if we see light that looks yellow then this must be light at 580nm. This implies a one-to-one relationship between colour and wavelength. This has led to the idea that a yellow reflective object, for example, looks yellow because it only reflects the wavelengths of light that are yellow and absorbs all of the other wavelengths (see Figure 2a); diagrams consistent with this can be found in several textbooks about colour that are targeted at a university-level education [26-27].

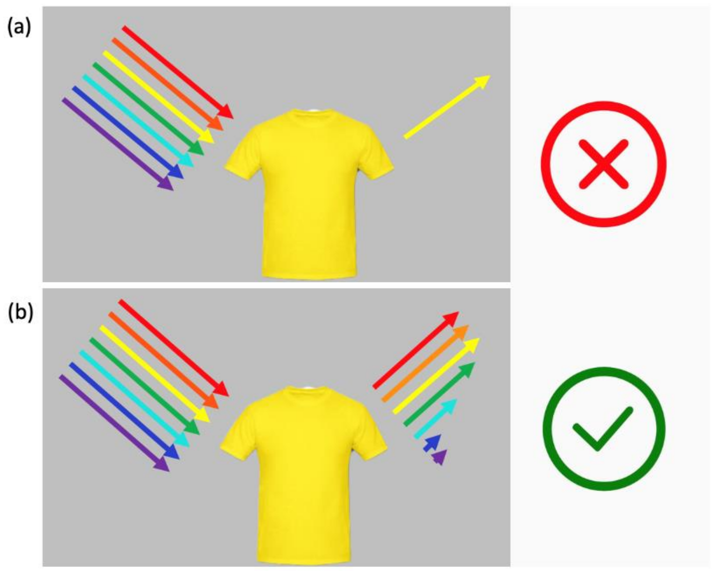


Figure 2: (a) The upper diagram illustrates the concept that a yellow object is yellow because it reflects the yellow wavelengths and absorbs the other wavelengths. It is consistent with both Axiom 1 and Axiom 2. (b) On the other hand, the lower diagram is a more realistic representation of how material reflect light.

If this simplistic view is accepted then we would conclude that the yellowness of a yellow object derives from the fact that light of a certain wavelength (about 580nm) is yellow and that only this light is reflected by the object. Acceptance of Axiom 1 and Axiom 2 together leads to the notion that colour is a physical property of light and that reflective objects in the world are coloured because they reflect certain wavelengths. However, it has already been noted elsewhere that the idea that reflective objects are coloured because they reflect narrow bands of light of a particular colour is not correct [28]. Figure 3 shows the measured reflectance factors for three yellow samples from the Munsell Book of Color. It can be seen that all three of these yellow chips reflect strongly at wavelengths of light between 540nm and 700nm (corresponding to wavelengths that look red, orange, yellow and green) and even reflect between 10-30% of the light at some of the wavelengths that on their own would be seen as cyan (refer to Table 2). In other words, it simply isn't the case that any of these three yellow objects reflect only those wavelengths that, if seen in isolation, would look yellow. However, the additive combination of the wavelengths that are reflected does look yellow in each case. The spectral data in Figure 3 also pose a challenge for people who would like to accept Axiom 1. Since these objects do not only reflect the wavelengths of light that we normally associate with yellow, how is it that we perceive them as looking yellow? In other words, Figure 3 is also a refutation of Axiom 1.

That reflective yellow objects tend to have quite broad spectral reflectance curves that cover the medium- and long-wavelength ranges has been previously noted [28].

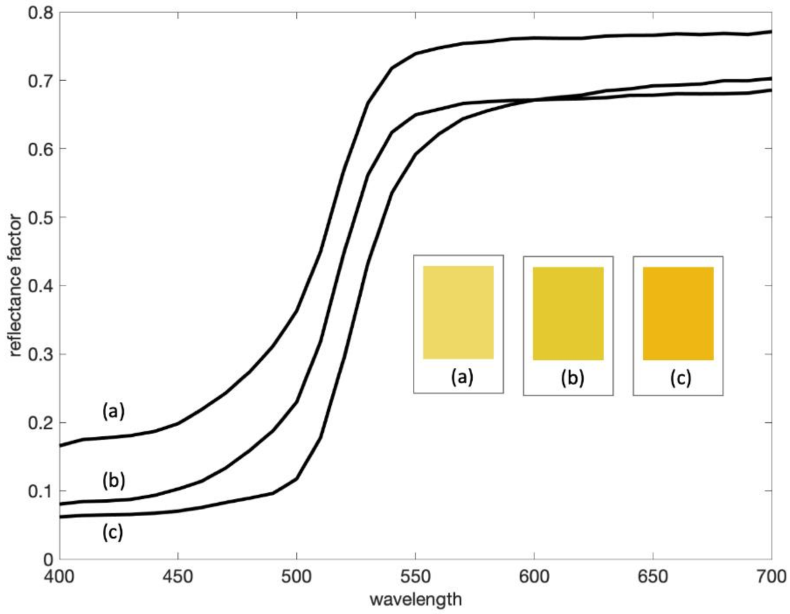
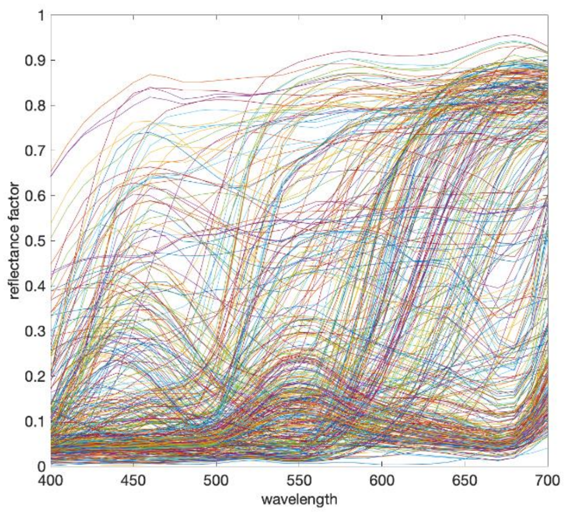


Figure 3: Spectral reflectance factors for three yellow samples from the Munsell Book of Color. The sRGB colour representations are also shown for reference.

The observation that objects do not reflect in narrow bands of wavelength is true for reflective objects generally. Figure 4 illustrates the spectral reflectance factors of a set of 404 objects that were measured in the natural world [29]. It is evident that all of these objects tend to reflect at every wavelength of light to some extent but reflect more strongly at some wavelengths than at others.

A consequence of these natural constraints is that the reflectance spectra of reflective objects always vary smoothly with wavelength and, as a result, materials that reflect only in a very narrow band of the spectrum (such as those wavelengths that we associate with yellow) do not occur either in nature or in the man-made world. Figure 5 shows a hypothetical reflectance spectrum for a sample that only reflects at the wavelengths that (according to Table 1) we see as yellow and does not reflect at all at any of the other wavelengths. It is important to remember that the physics of how matter interacts with light does not make such an object realisable. However, if such an object could be realised what would it look like? The answer is shown (see the inset of Figure 5) as a dark mustard colour.



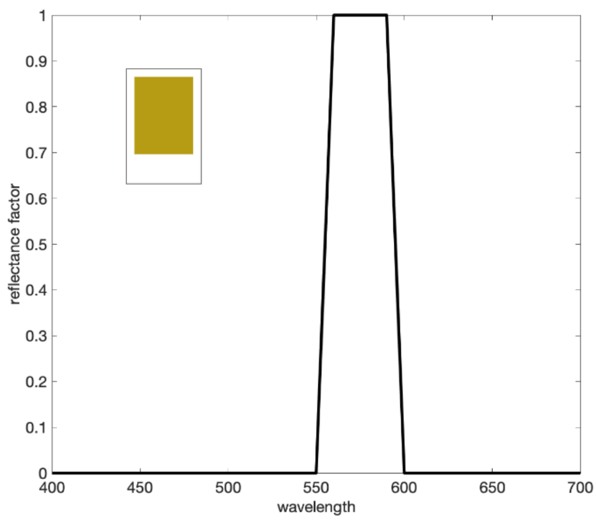


Figure 4 (left): Spectral reflectance factors for 404 different coloured samples measured from the natural world [29].

Figure 5 (right): It is not physically possible to manufacture a material that only reflects at the wavelengths (560-590nm) that are associated with yellow. Although such a material cannot be manufactured in practice it is possible to calculate its CIELAB colour coordinates from the hypothetical spectral data and show its sRGB representation. The sRGB colour representation is shown (inset); the colour is dark mustard because not enough light is reflected for yellow.

The empirical evidence from spectral reflectance measurements allows us to strongly refute Axiom 2 and replace it with an alternative form, Axiom 2A: Coloured objects tend to selectively absorb some wavelengths of light more than others. Energy that is not absorbed is reflected or transmitted and may be observed.

Figure 2a should be replaced by a diagram similar to that shown in Figure 2b in which it is evident that the material reflects light broadly across much of the spectrum. Not only is this more correct than Figure 2a but it should also encourage the student to think critically about why the material still appears yellow. This will lead to a critical appraisal of Axiom 1 and subsequent enquiry into the process of colour vision.

Axiom 3: Emissive devices only emit red, green and blue light

By emissive devices here we imply those trichromatic devices based on red, green and blue primaries or RGB. Stevens' argument [12] that the yellow of an actual yellow object is real whereas the yellow seen for a digital image of a yellow object is not real is based on two mistaken concepts: the first is that a yellow object in the real world only reflects light of those wavelengths that we typically see as yellow (for which we would need to accept Axiom 1 and Axiom 2) and second, that digital RGB displays do not emit yellow light (for which we would need to accept Axiom 3).

Figure 6 shows measurements [33] of spectral power output for four different emissive displays when white (R=255, G=255, B=255) was displayed. The measurements were made at wavelengths between

380nm and 780nm at intervals of 1nm. There is some similarity between the measurements for some of the devices; all are based on LCD technology. However, it is evident that all of the displays emit some light at all of the wavelengths between about 430nm and 680nm and the same conclusion is reached when considering a wider set of 20 displays that were measured [33] but not included in this paper. The RGB primaries of these displays may emit light that looks red, green and blue respectively but this is not light that is restricted to the wavelengths in the spectrum that we would normally associate with these colours.

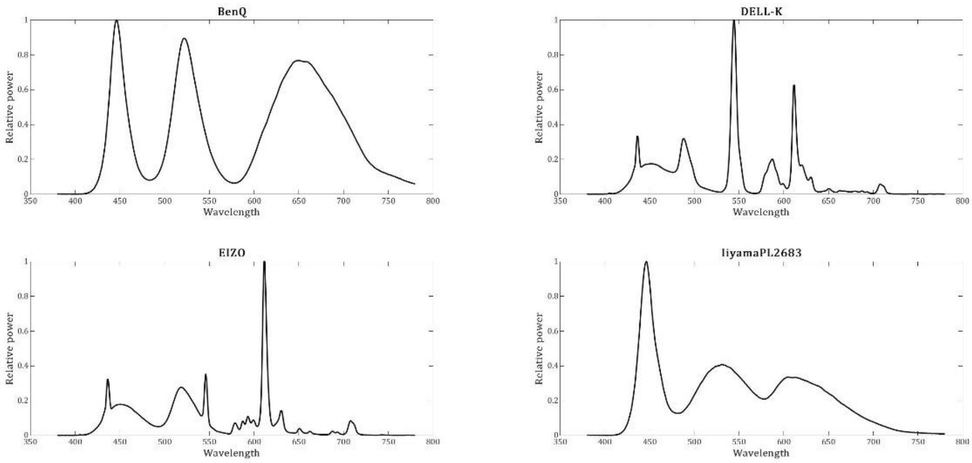


Figure 6: Measurements of the spectral power output at each wavelength when white is displayed for four different emissive displays [33]. Note that BenQ and EIZO are professional displays where the other two are consumer displays.

Figure 7 shows the relative spectral power emitted by two of the displays from Figure 6 when they are displaying yellow (R=255, G=225, B=0) and it can be seen that both emit light in the range 560-590nm. It is evident from Figure 6 that all of the displays emit light at the wavelengths that we associate with yellow (Table 2) and therefore we can refute Axiom 3 and propose the replacement Axiom 3A: Emissive displays based on RGB technology emit light that looks red, green and blue to create a range of colours.

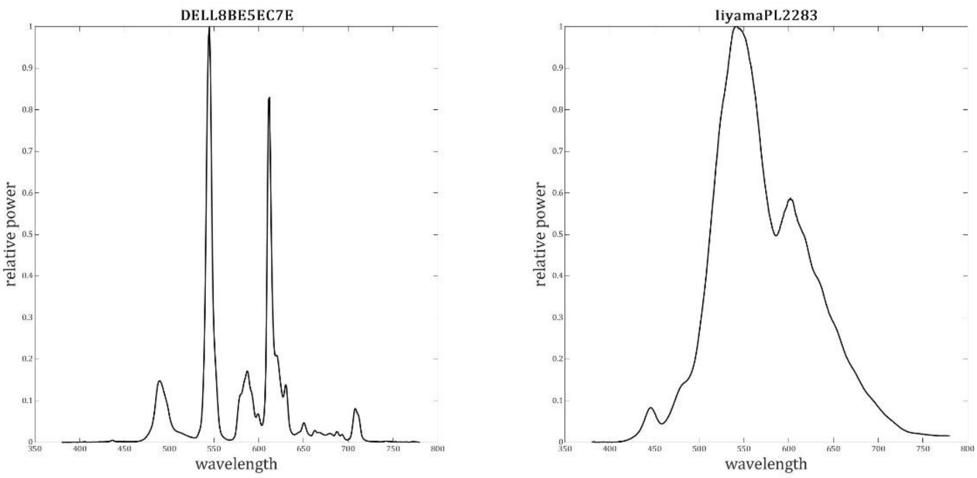


Figure 7: Spectral power measurements for two of the displays from Figure 6 when they are displaying yellow (R=255, G=225, B=0) [33].

Axiom 4: Some colours (e.g. yellow) generated on emissive devices are not real

In order to critically evaluate Axiom 4 we need to explore how colour vision works and discuss what we mean by 'real' and 'fake' colour. Briggs pointed out that one of the common misunderstandings of colour science is that in humans the three classes of cones respectively respond to red, green and blue light [11]. A more extreme representation of this misunderstanding is that we (humans) see the world in red, green and blue and that our visual systems generate the full range of colours from these three primary colours. Figure 8 shows the spectral sensitivities of the long-, medium- and short-wavelength sensitive cones, known as LMS cones. Notice that all three classes have quite broad spectral sensitivity. Recall that absorption spectra of colourants are constrained to be approximately Gaussian-shaped [32]. The cone pigments are no different in this regard and they also have broadband, approximately symmetrical, sensitivities. Note particularly that the L cones, sometimes colloquially known as red cones, have a peak sensitivity in the yellow region of the spectrum rather than the red region. It is certainly far from the case that the human LMS cones are only sensitive to red, green and blue light respectively.

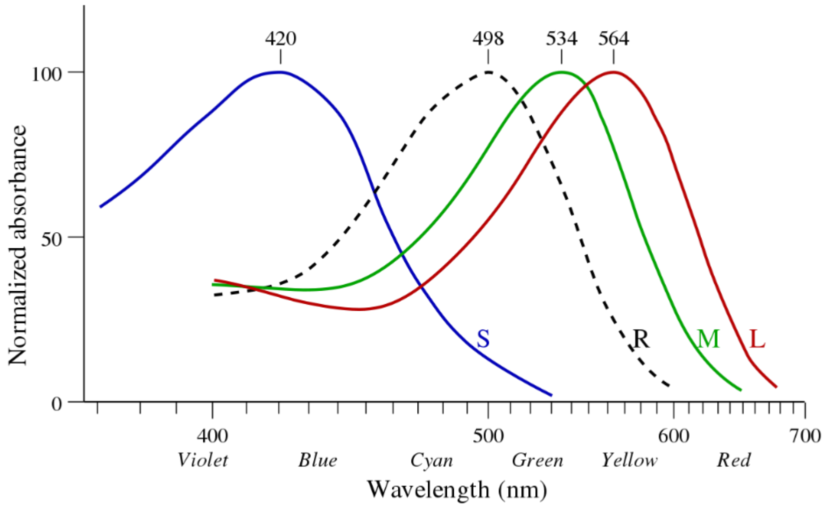


Figure 8: Spectral sensitivities of the human cones (red, green and blue lines) and rods (dashed line). The wavelengths of peak sensitivity are shown above each curve.

Colour vision is mediated by the responses of the LMS cones. However, it is critical to understand the univariant nature of the responses of these cones [34]. The principle of univariance was first introduced by Rushton (1972) who postulated that "The output of a receptor depends upon its quantum catch, but not upon what quanta are caught" [35]. The meaning of this is that a cone cell can produce the same response when excited by varying combinations of wavelength and intensity. This leads to the phenomenon of metamerism whereby two physically different stimuli can produce identical cone responses and therefore be indistinguishable to the visual system. The cones neither respond specifically to red, green and blue light nor capture red, green and blue signals.

The cone responses are combined and compared in the retina through the way that they activate retinal ganglion cells, for example. Some of the comparisons are spatial – that is, cone responses in one location of the retina are compared with those in a different location of the retina – and this provides plausible neural mechanisms that can explain some visual phenomena such as contrast and assimilation. Spectrally and spatially opponent signals are developed that leave the eye through the optic nerve and make their way to the occipital lobe (visual cortex) of the brain where we might consider colour vision to occur. The actual mechanism by which activations of cells in the visual cortex give rise to the experience of colour is not known. Indeed, this has been referred to as the hard problem of consciousness by the philosopher David Chalmers [36]. We might be able to correlate our conscious experience and our experience of sensations such as qualia with neural activity in various parts of the brain; but we do not know how the neural activity causes these experiences. However, the way in which brain activity gives rise to qualia such as colours is not particularly relevant to this paper. All that is sufficient is to note that whatever the mechanism is, it is the same mechanism that gives rise to the colour yellow that we see when we look at a lemon in real life or look at a digital image of a lemon or, indeed, look at the yellow produced by light in the wavelength range 560-590nm.

The implication of the univariant response of cones is illustrated in Figure 9 in which three physically dissimilar stimuli may generate identical cone responses in the observer and hence identical colour sensations. Figure 9 is, in fact, in itself a simple refutation of the 'YouTube theory of colour vision'. It is also a refutation of Axiom 4.

Figure 9: A physical lemon (left), a digital reproduction of a lemon (middle), and light at wavelengths between 560 and 590nm (right) can all produce exactly the same sensation of yellow. In this case the cone responses, LMS, are identical for the three stimuli even though the wavelength distribution of the light that reaches the eye from the three stimuli may be quite different.

Shifted spectrum argument

One of the consequences of rejecting the axioms (particularly Axiom 1) in Table 1 is apparent if we consider the inverted spectrum Gedanken or thought experiment. If there is nothing intrinsic about light at 700nm, for example, that accounts for its redness then isn't it possible that the colour someone experiences when they see light at 700nm is the same colour that other people experience when they see light at 400mn. In other words, someone who sees an inverted spectrum would experience the opposite colours for the spectrum compared to other people. This is known as the inverted spectrum argument and it was proposed by the English philosopher John Locke who in 1679 wrote that:

> ...by the different Structure of our Organs, it were so ordered, that the same Object should produce in several Men's Minds different Ideas at the same time; v.g., if the Idea, that a Violet produced in another Man's Mind by his Eyes, were the same that a Marigold produced in another Man's, and vice versa [37].

The feasibility and consequences of the inverted spectrum argument have been widely debated elsewhere [37]. Here we will simply note that a person with an inverted spectrum might never know they have this condition; since our experience of colour is private, whatever we experience when we see light at, for example, 700nm we are taught to attach the language label of red to this. In other words, there may be no behavioural difference between someone who sees a normal spectrum and someone who sees an inverted spectrum.

Here we extend the idea of the inverted spectrum to present a similar argument to illustrate the consequences of refuting Axiom 1 and accepting Axiom 1a which we call the shifted spectrum argument. Humans are sensitive to the approximate wavelength range of 400-700nm. However, we might ask what colours would we see if our cone spectral sensitivity was shifted to say 700-1000nm? As is illustrated by Figure 10, it is totally plausible that we would see the same colours, that is, blue to red, but mapped instead to the wavelength range 700-1000nm rather than 400-700nm. Someone with this shifted-spectrum condition would not be able to see light at wavelengths below 700nm at all, and light at 700nm would appear a blue-violet colour. We suggest that the shifted spectrum argument is a good way to frame a critical discussion about whether colour is the property of light (Axiom 1) or whether light merely appears coloured to us (Axiom 1a).

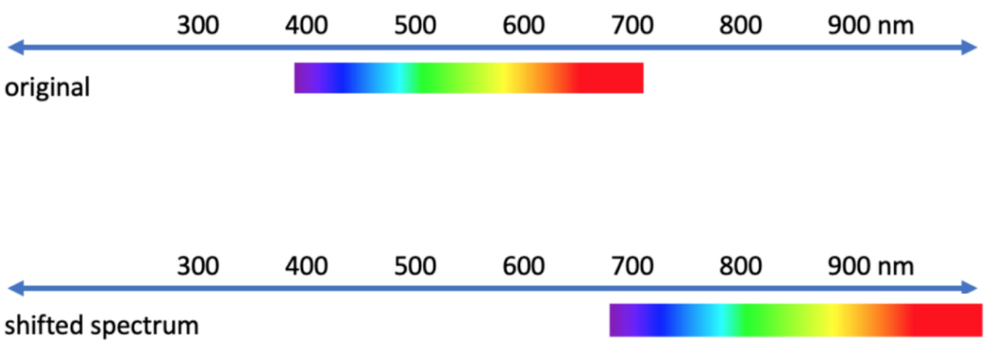


Figure 10: The human visual system is sensitive to the approximate range 400-700nm and maps the colours blue-red to this range (upper diagram). Someone with shifted spectral sensitivity may see the same colours blue-red but mapped now to the wavelength range 700-1000nm whereas the wavelengths below 700nm would be invisible.

Discussion

This paper has explored some common misconceptions of colour which were expressed by four axioms (Table 1). These axioms were critically evaluated and it was found that none could be supported. An alternative set of axioms has been developed (Table 3) that are supported by empirical observations and modern understanding of colour.

Axiom 1a:	Light looks coloured.
Axiom 2a:	Coloured objects tends to selectively absorb some wavelengths of light more than others. Energy that is not absorbed is reflected or transmitted and may be observed.
Axiom 3:a	Emissive displays based on RGB technology emit light that looks red, green and blue to create a range of colours.
Axiom 4a:	Colours, whether seen with reflective objects or emissive displays, are perceptions.

Table 3: The four alternative axioms that are proposed in this paper.

What is the significance of this analysis? For example, it could be argued that the axioms listed in Table 1 are in effect a 'straw man', a simplification of misunderstandings that are sometimes found that can easily be refuted. Indeed, this paper does not purport to present any new knowledge about colour that is different to that which is already established. However, there is undoubtedly a problem with the quality of colour education in today's world and that is the justification for the analysis in this paper. The Stevens' video [12] has been widely viewed and can therefore have been expected to have influence. However, it is more serious when misunderstandings are presented in university level textbooks and in educational curricula. The misconception on the BBC website [6] that all colours can be made from red, yellow and blue is actually part of revision notes for the National 5 Art and Design Curriculum in the UK (National 5 is a qualification taken by students in Scotland, generally during their secondary senior phase of education).

It has already been noted that diagrams that express the idea that is shown in Figure 2a (that objects reflect only a narrow band of wavelengths that correspond to the colour that is seen when the object is observed) can be found in university-level textbooks despite ample evidence to the contrary. In fact, such misconceptions can be found at every level of education. For example, in one study that involved > 2500 participants (ranging from primary students to university teachers) nearly 10% responded that colour is the property of an object and more than 50% believed that the colour of an object was the result of the combination of the colour of the light source and the colour of the object [38]. An earlier study found that the common understanding of the word colour is that of coloured matter rather than colour as a perception. The level of education for colour in the design field has been noted to be particularly problematic [39-40]. Csillag et al. noted that 'There is no lack of books on colour theory and practice published for designers, but these are often of very questionable level' [41]. Csillag et al. also remarked that the lack of quality colour education leaves students and future designers with little alternative but to choose colours based on their intuition or personal preference [42]. The need for education that leads to a deeper understanding of colour has been highlighted so that students are not only able to understand how to use colour but can also answer questions about why [28, 42]. The axioms listed in Table 3 – and, specifically, the difference between the axioms in Table 1 and those in Table 3 – can be used as a basis for the design of learning and teaching content for colour reproduction that could address many of the limitations that currently exist. The contribution of this paper is to highlight these misconceptions and to provide arguments and data that could contribute to progressive colour education. However, we note that the ideas that have been considered in this paper are far from the complete set of ideas that should be considered in a rounded colour curriculum. Nevertheless, they address some of the most important misconceptions that can currently be found in the field of colour reproduction. The topic of colour vision itself is in fact a more complex topic and misconceptions can be readily found in that field too. This analysis is, however, outside the scope of this paper that has addressed issues of colour reproduction.

The broader and more complete limitations of the way that colour is sometimes taught, especially in early years but also at university level, is currently being addressed by a Colour Literacy Project [43] that is endorsed by the International Colour Association (AIC) and the Inter-Society Colour Council (ISCC). The importance of a systematic and modern approach to colour education especially for designers is also evident in a current research project funded by Tsinghua University in China, ' The theory of design work based on art and science of colour'. This project advocates that designers need to learn not only the aesthetic side of colour but also the scientific side of it. However, it can also be argued that colour scientists could benefit from understanding and appreciating the ways in which other disciplines approach colour. Colour education should lead the way in terms of STEAM education.

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