The elements of colour I: colour perceptions, colour stimuli, and colour measurement

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This paper presents an extended consideration of the question of what colours are from a scientific perspective by reviewing the connections between colour perceptions, colour stimuli, and colour measurement. The colour of an isolated light can be understood to be the way in which we perceive the overall balance of its spectral composition relative to that of daylight; “overall” here meaning at the level of its long-, middle- and short-wavelength components, as detected by the human visual system. Our ability to detect variations in this overall balance, first demonstrated by Newton, is now understood to rely on comparison of the responses of three receptor types by the process of cone opponency. The colour perceived as belonging to an object when it is freely examined in daylight, which we tend to think of as the (seemingly) intrinsic colour of the object, can similarly be understood to be the way in which we perceive its overall spectral reflectance, again at the level of its long-, middle- and short-wavelength components, as detected by the human visual system. Colorimetric measures are designed to quantify for practical purposes precisely these human-perceiver-dependent ”overall” properties of spectral distributions and spectral reflectances, by ignoring physical differences that we do not perceive as colour differences. In defining two senses of word colour, “perceived colour” and “psychophysical colour”, the CIE International Lighting Vocabulary in effect expresses a pluralist ontology of colour that acknowledges that we may wish to use the word “colour” either for our perceptions of colour, or for the measurable, human-perceiver-dependent properties that dispose physically different lights or objects to appear the same colour in the same context.

Received 2 September 2022; revised 28 April 2023; accepted 8 May 2023

Introduction

It might seem reasonable to assume that most colour educators are in broad agreement about the fundamental facts concerning colour, and would disagree, if at all, only about the best ways to address those agreed facts. But my impression, based on more than twenty years of discussions with other colour educators, both in person and online, is that this perceived agreement is an illusion that would be dispelled very quickly the moment any sizeable group of such educators were to attempt to write collaboratively about colour. Widespread disagreement exists, not only stemming from traditional colour theory dogma such as “primary colours”, simplistic rules of “colour harmony”, and so on, but also in relation to our current scientific understanding of many fundamental aspects of colour.

Two particularly controversial areas even for very experienced colour educators concern (1) the questions of what colours are and what relationship if any they have with physical properties on the one hand and with what is called “colour measurement” (colorimetry) on the other, and (2) the terminology of colour attributes (hue, saturation, etc) and the concepts embodied in that terminology. This paper and its companion paper will respectively explore these two areas using insights, explanations and illustrations developed by the writer over the course of twenty years of teaching courses on colour mainly intended for adults with an art or design background, and fifteen years of creating online resources on colour. While legitimate differences of opinion exist about some details, in these papers my aim is to provide explanations that are consistent with the scientific consensus explicit or implicit in the definitions of the *International Lighting Vocabulary (ILV)* [1] of the Commission internationale de l'éclairage (CIE), except where current challenges to this consensus are explicitly noted, or where additional constructs are explicitly added, notably from the *Natural Colour System (NCS)* and the work of Ralph Evans. Founded in 1913, the CIE is the organization responsible for the international coordination of technical standards relating to colour and light. In relation to colour, the CIE established the framework of modern colorimetry from the early 20th century up to the present, and also established various colour spaces that form the basis of colour management and colour technology, various standard light sources used for colour measurement, the various standard formulae used for quantifying colour differences, and various colour appearance models that predict the perceived colour of a stimulus under different viewing conditions. The CIE *International Lighting Vocabulary*, first published in 1938 and revised periodically up to the current edition published in late 2020, gives definitions for nearly 1400 terms and is by far the most comprehensive and authoritative source available on the terminology of light and colour in science and technology.

This first paper presents an extended response to the question of what colours are from a scientific perspective by reviewing the connections between colour perceptions, colour stimuli, and colorimetric specifications. Most of the colours we perceive appear to belong either to objects or to light, whether to light perceived to be falling on objects, or to light reaching our eyes directly from a light source or reflected or transmitted to our eyes by objects. The first section of this paper considers colours of light, beginning with Newton’s crucial demonstration that the colour of an isolated light can be predicted from the overall balance or “center of gravity” of its spectral components in relation to a circuit of directions of bias relative to white light. This section then examines how our ability to perceive (within limits) variations in this overall balance of wavelengths is now understood to rely on comparison of the responses of three receptor types by the process of cone opponency. The second section examines the colours we perceive as belonging to objects and how these relate to the overall spectral reflectance of the object, again at the level of its long-, middle- and short-wavelength components, as detected by the human visual system. Because the ability of the human visual system to detect wavelength properties is limited, physically different lights/objects will match in colour if they have the same “overall” spectral balance/spectral reflectance in this sense. The third section examines how colorimetric specifications of lights and objects are designed to record for practical purposes these same human-perceiver-dependent “overall” properties of spectral distributions and spectral reflectances that dispose physically different lights and objects to appear the same colour in the same context. Based on this discussion, the paper concludes with a consideration of the pluralist ontology of colour implied by the two CIE definitions of the word “colour”, “perceived colour” and “psychophysical colour”, that acknowledges that we may wish to use the word “colour” either for our perceptions of colour, or for the measurable, human-perceiver-dependent, dispositional properties specified by colorimetric values. The present paper builds on several presentations published by the author in recent years, primarily [2-4].

The perceived colours of lights and objects can be described in terms of various sets of three attributes that can each be visualised as the three dimensions of a colour space. These perceived colour attributes are the subject of Part Two, but some of the most important terms will be briefly introduced here. The *hue* of a colour is the most similar step in the scale of red-yellow-green-blue-red and their intermediates. Colours possessing hue are called *chromatic* and those devoid of hue are called *achromatic*. One set of three attributes that is widely used to describe colours perceived as belonging to objects comprises *hue*, *lightness* (also called value, greyscale value, or tone; the most similar step on a scale between black and white) and *chroma* (chromatic intensity perceived as belonging to an object). These three CIE-defined attributes can be quantified in terms of the hue, lightness and chroma scales of the Munsell system (Figure 1) or of other colour spaces such as CIE L*a*b* in the form CIE L*C*h. Colours of objects can also be described and specified using other sets of three attributes, including the NCS-defined attributes of hue, *blackness* (resemblance to pure black) and *chromaticness* (resemblance to full colour). The colours of objects perceived to emit light lie off the scale of blackness and may be said to exhibit *brilliance*. Colours of lights can be described in terms of hue, *brightness* (perceived intensity of light) and *colourfulness* (perceived chromatic intensity of light), or hue, brightness and *saturation* (the colourfulness of a light relative to its brightness, which amounts to its perceived freedom from a white light component).

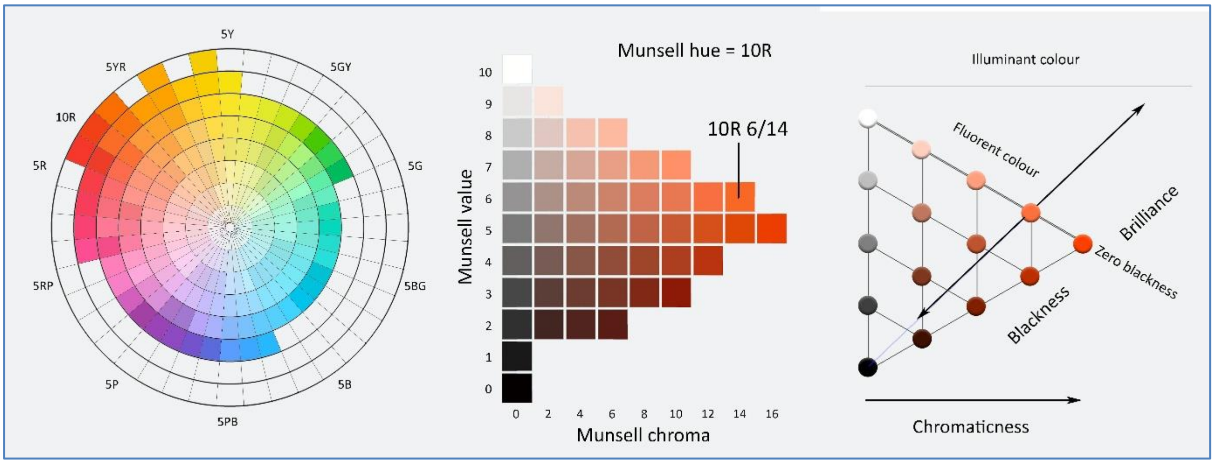

Figure 1: Left: Plan view of colours represented in the Munsell Book of Color Glossy Edition, showing colours of the lightest chips for each hue and chroma. Middle: hue page for Munsell hue 10R, showing variations in Munsell value (lightness) and Munsell chroma. The Munsell notation 10R 6/14 identifies the chip on the 10R hue page with a Munsell value of 6 and a Munsell chroma of 14. Right: Alternative classification of colours on a hue page, according to the NCS-defined attributes of blackness and chromaticness, plus the relationship to the attribute of brilliance.

Colours of lights

Newton [5] showed that the reason why light forms what he named a spectrum when it passes through a prism is because it is broken up into a series of components (we would now say different *wavelengths*) that appear different colours. Yet when we see a light compounded of different wavelengths, we don't experience multiple colour perceptions corresponding to these multiple components; we see a single colour. Crucially, Newton showed that the colour of an isolated light can be predicted from the overall balance or what he called the "center of gravity" of its spectral components in a two-dimensional circuit of directions of bias relative to light perceived to be white (Figure 2, top left). The hue of an isolated light could be predicted from the *direction* of bias relative to white light, and what he called the “fulness or intenseness of the Colour” or its “distance from whiteness”, now called its *saturation*, could be predicted from the *amount* of bias. Another way of saying this is that the colour of an isolated light is *the way in which we perceive* the overall balance of its spectral components relative to that of light perceived to be white, such as daylight. Whitish orange as the colour of an isolated light is the way in which we perceive an overall balance of spectral components biased in a certain way relative to daylight, and white as the colour of an isolated light is the way in which we perceive an overall balance of the same spectral components similar to that of daylight (Figure 2, top middle).

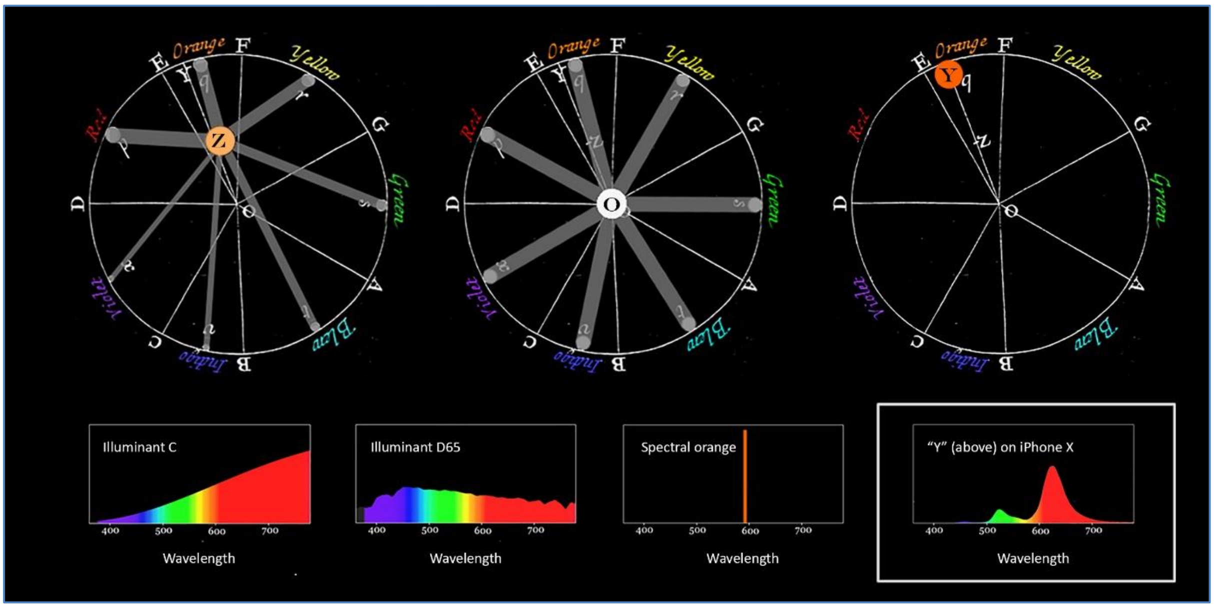

Figure 2: Above: “center of gravity” of a whitish orange, a white, and a spectral orange light, after Newton [5, Book 1, Part 2, fig. 11]. Newton’s accompanying text explaining his “center of gravity” principle reads: “Find the common center of gravity of all those Circles p, q, r, s, t, v, x. Let that center be Z; and from the center of the Circle ADF, through Z to the circumference, drawing the right Line OY, the place of the Point Y in the circumference shall shew the Colour arising from the composition of all the Colours in the given mixture, and the Line OZ shall be proportional to the fulness or intenseness of the Colour, that is, to its distance from whiteness” [5, Book 1, Part 2, p. 115]. The amounts of each spectral component, represented in Newton’s diagram by the size of the small circles, are now represented as a spectral power distribution, a plot of the wavelength-by-wavelength distribution of radiant power, measured in microwatts per cm2 per nanometre. Below left: spectral power distributions of three lights that would plot at Z, O and Y in Newton’s circle: a whitish orange illuminant, CIE Illuminant A, representative of tungsten illumination (left), a white illuminant, CIE Illuminant D65, representative of noon daylight (middle), and spectral orange (right). Lower right: spectral power distribution of the light emitted by the saturated orange dot “Y” on an iPhone X screen (right) after [6].

By this principle, *spectral orange*, the saturated orange we perceive in the spectrum, is the way in which we perceive a very strong bias in the direction of certain wavelengths, rather than a property that our visual system “detects” in those wavelengths themselves. A saturated orange light *might* consist of those orange-appearing wavelengths, but it might also contain no light of these wavelengths; the saturated orange spot Y in Figure 2, top right, emits relatively little light of such wavelengths, and depending on your screen, possibly very little! Tempting though it is to think or say so, there is no reason to suppose that the saturated orange colour that *appears* to be located in certain wavelengths of the spectrum is a property physically present in those wavelengths, or present anywhere when those wavelengths are mixed with other wavelengths to evoke a different colour perception, such as white. Spectral colours, like all colours of light, are the way in which we perceive a particular balance of spectral components, in this case, a very strong bias towards one spectral component.

Although Newton very frequently refers to the spectral components of light as *being* "Colours" (as in the quote in the caption to Figure 2), he made it clear in the *Opticks* that when he did so he was speaking "not philosophically and properly, but grossly, and according to such conceptions as vulgar People in seeing all these Experiments would be apt to frame. For the rays to speak properly are not coloured" [5, p.90]. Today Newton's insight into the composition of white light is still very often presented in the philosophically perilous form that white light is "composed of a miscellany of colors" [7], but doing so in education lays a foundation that must be thoroughly unlearned before the student can begin to develop a sound understanding of colour perception.

Daylight is defined as the visible part of *global solar radiation*, which comprises "combined direct solar radiation and diffuse sky radiation"[1,2]. Notice that the spectral power distribution typical of daylight (Figure 2) is not flat but has a broad low peak in the short to middle wavelengths of the spectrum. (CIE Illuminant E, which does have a flat spectral power distribution, appears somewhat pinkish as an isolated light). Throughout our lives our visual system continually attunes itself so that this somewhat uneven spectral power distribution of daylight is perceived as achromatic (lacking hue) by continually compensating for changes in the eye; this adjustment occurs very slowly as our lenses turn brown with age, and over a period of months when we get new ones [8]. As illustrated later (Figure 7), the more colourful the illumination of a scene appears, the more difficulty we have in distinguishing objects according to their colour, so being attuned to perceive daylight as lacking hue maximises our ability to distinguish objects by their colours under typical natural conditions.

Of course, our colour perceptions are not based on instrumental measurements but on the responses of the human visual system, and they are therefore shaped in part by the characteristics of that system. We now know that Newton's directions of perceivable spectral imbalance form a two-dimensional circuit because our colour vision depends ultimately on the responses of three receptor types, called L, M and S cone cells. Our S cone cells respond to a relatively narrow range of short wavelengths, mainly those that appear violet and blue, but our L and M cone cells respond to *all and almost all* wavelengths of light respectively (Figure 3, left). The specific wavelength of a light hitting a cone cell affects the *probability* that the cone cell will respond, and thus the strength of the overall response of that cone cell class, but the cone cell provides no information on the specific wavelength of the stimulus. The frequently expressed idea that our cone cell classes work by *individually* detecting long, middle and short wavelengths (or worse, by" detecting red, green and blue") is incorrect.

What *is* true is that the three cone cell classes divide the visible spectrum into long-, middle- and short-wavelength bands, in each of which one cone cell class responds more than the other two. *Comparison* of the responses of the cone cell classes provides information, not about the individual wavelengths present, but about the *overall balance of radiant power* between these three broad wavelength components of the light. This comparison occurs in the retina by the process of *cone opponency* (Figure 3, middle and right). Some neurons compare M cone and L cone outputs to form an *L vs M* cone-opponent signal, while other neurons compare the S cone output to the combined outputs of the L and M cones to form an *S vs LM* cone-opponent signal. By means of this *combined cone and cone-opponent system* the human visual system can detect variations in the overall balance of radiant power in relation to a circuit of directions towards long, middle, short, and long *and* short wavelengths respectively, which we ultimately experience as the circuit of hues. Light of a single wavelength can

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[1] CIE e-ILV17-29-105

[2] CIE e-ILV 17-29-101

evoke cone-opponent response combinations through only part of the circuit evoked by light of mixed wavelengths (Figure 3, lower right; Figure 4, middle).

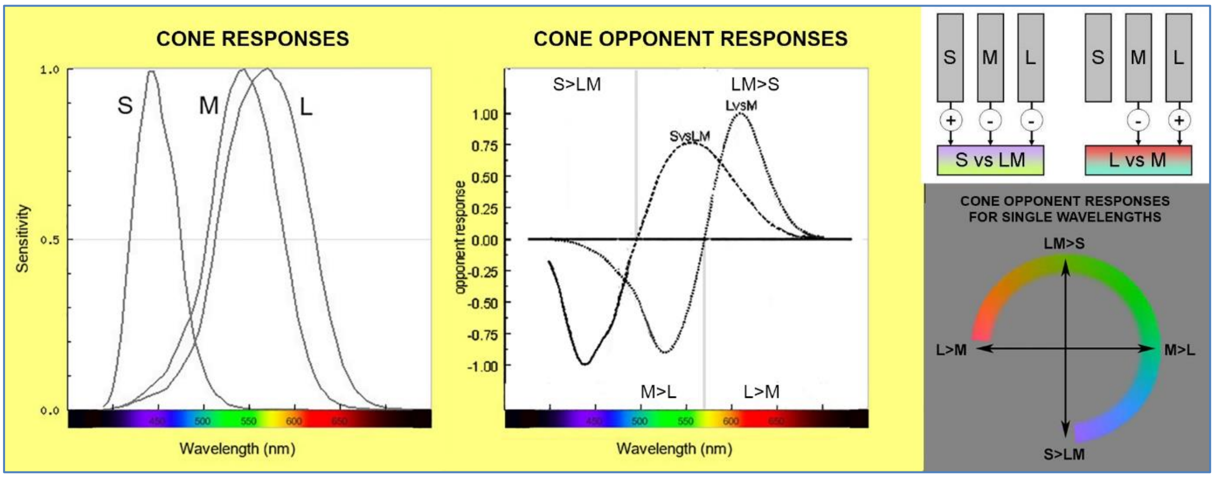

Figure 3: Left: Cone fundamentals of Stockman and Sharpe (2 degree, linear, normalised to equal height) [9]. These curves show the effective relative response of each cone cell type to different wavelengths of light reaching the eye, as opposed to the retina (that is, they take account of the filtering of short wavelengths within the eye). Middle and right: diagrams explaining L vs M *and* S vs LM *cone opponent processing and the cone opponent responses to individual wavelengths of light, all after [10].*

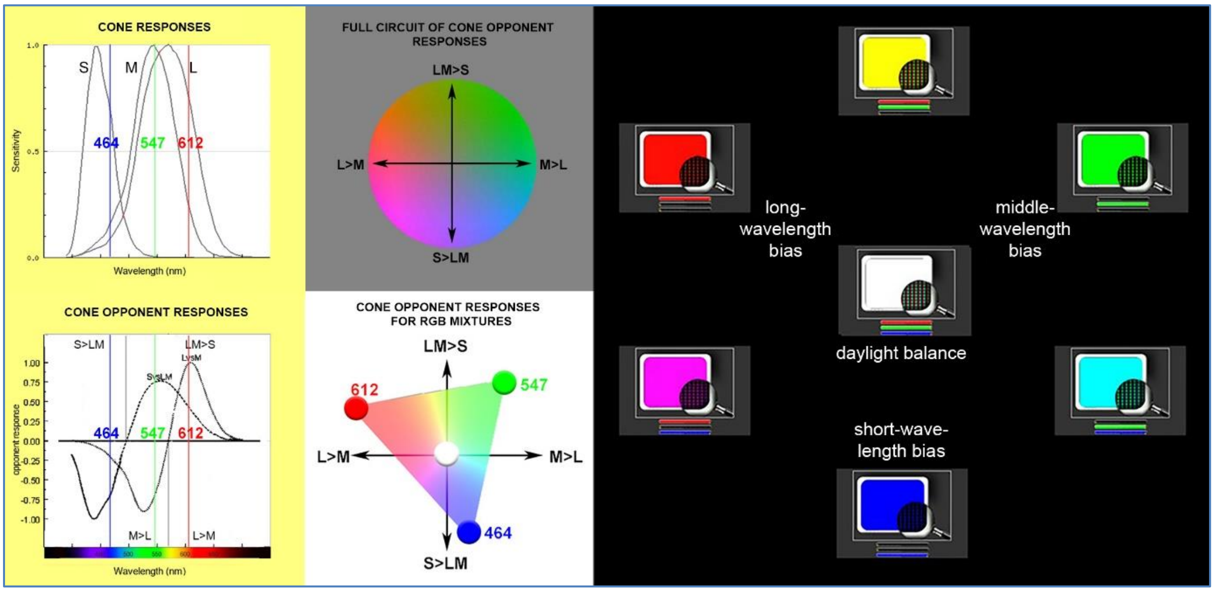

Figure 4: Left: Representative RGB digital primaries each stimulate one cone type more than the other two and thereby each evoke a strong cone opponent response. Middle: mixtures of these primaries in different proportions span the full circuit of cone opponent response combinations. Right: This two-dimensional circuit of cone-opponent response combinations, reflecting a two-dimensional circuit of directions of detectable bias towards long, middle, short, and long and short wavelengths respectively, is ultimately perceived as the two-dimensional circuit of hues perceived by colour-normal humans. See caption to Figure 3 for sources for Figure 4, left and middle.

While the role of our three cone cell types is widely covered, if somewhat misrepresented, in popular accounts of colour vision, the equally important process of *cone opponency* is much less commonly discussed, and when it is, it is often conflated with the distinct, and less securely established, concept of red/green and yellow/blue hue opponency. This omission leaves a gap that is currently filled by a collection of inventive speculations about cone signal processing that I've called "The YouTube theory of colour vision" [11]. The YouTube theory illustrates the danger of providing a wrong explanation for simplicity's sake, which is that your audience may take your wrong explanation and run with it. The well-intended simplification that says that the L, M and S cone cells detect "red", "green" and "blue" wavelengths respectively is misleading in that it encourages the assumption that the function of colour vision is to detect wavelengths individually, and it does nothing to dispel the assumption that colour is a property residing in the wavelengths themselves. The idea that our cone cells "detect red, green and blue wavelengths" is understandably taken to imply that we must "only really see" these three colours! The inference that we have no cone cells that detect orange, yellow and violet wavelengths leads in turn to the inference that our brain must "guess" that those colours are present based on the signals for red, green and blue. So we're told that when we "think we see" yellow, our cone cells are sending signals for red and green to the brain which "guesses" that yellow must be "present", sometimes "correctly" (i.e., when "yellow wavelengths" are actually present), but at other times our visual system is "fooled", as when we see a mixture of red and green primaries on a screen as being yellow. We could instead describe this situation without any of this nonsense by saying that our combined cone and cone-opponent system *correctly* determines that the mixture on the screen has the same overall direction of bias relative to daylight as wavelengths that appear yellow, and that the colour yellow is the way in which we perceive this direction of bias in both cases.

Perceived colours can be influenced by a variety of factors in addition to the spectral properties of the stimulus, as acknowledged in Note 1 appended to the CIE ILV definition of perceived colour[3]: "Perceived colour depends on the spectral distribution of the colour stimulus, on the size, shape, structure and surround of the stimulus area, on the state of adaptation of the observer's visual system, and on the observer's experience of the prevailing and similar situations of observation." Nevertheless, despite the importance of these other factors, it would be going too far to deny a connection between colour and spectral properties. It is quite reasonable to say that in many ordinary circumstances, variations in the spectral composition of light at the level of its long-, middle and short-wavelength components are detected by the human visual system and perceived as different colours. This of course is why we're all looking at machines that work by emitting different mixtures of long-, middle- and short-wavelength light (Figure 4, right).

Colours of objects

The CIE e-ILV defines an *object colour*[4] as a "colour perceived as belonging to an object" where the word "colour" links to the entry for colour "in the perceptual sense" or "perceived colour"[5]. "Perceived colour" is in turn defined as a "characteristic of visual perception" that can be described by six attributes, each of which is in turn defined as an "attribute of a visual perception", either directly (*hue*[6], *brightness*[7], and *colourfulness*[8]) or indirectly (*lightness*[9], *saturation*[10], and *chroma*[11]). So, an "object colour" as defined in the CIE ILV is a *visual perception perceived as belonging to an object*. Although they are

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[3] CIE e-ILV 17-22-040
[4] CIE e-ILV 17-22-042
[5] CIE e-ILV 17-22-040
[6] CIE e-ILV 17-22-067
[7] CIE e-ILV 17-22-059
[8] CIE e-ILV 17-22-072
[9] CIE e-ILV 17-22-063
[10] CIE e-ILV 17-22-073
[11] CIE e-ILV 17-22-074

perceptions, we perceive object colours to be located outside us in objects themselves, as in the uniform black, white and orange object colours that we perceive to be located in the tiles and cube depicted in Figure 5, left, *even though these objects are physically non-existent*. This last observation can help students to accept that the colours they perceive to be located in actual objects are similarly not located in those objects, but are perceptions that we project onto objects.

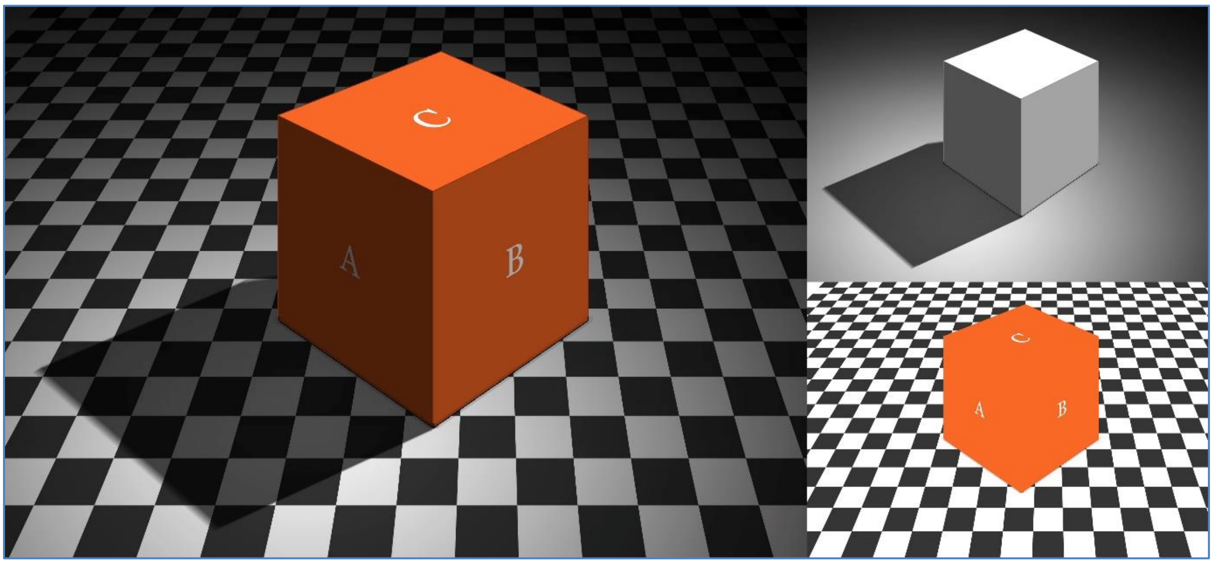

Figure 5: In the image on the left we perceive a cube having a uniform orange object colour, as if it were painted all over with the same orange paint, even though the image areas depicting planes A to C respectively appear progressively brighter and more colourful. Similarly, we perceive the lighter-coloured areas of the floor as being white things, even though the corresponding image areas appear variably bright. We do not see these variations in brightness and colourfulness as belonging to the objects themselves, but instead we instantly and automatically attribute them to variations in the illumination. Right: patterns of uniform orange, black and white object colours (below) and of illumination of varying brightness (above), that we perceive superimposed in the image on the left.

In Figure 5 (left) we perceive a cube having a uniform orange object colour belonging to it, as if it were painted all over with the same orange paint having a constant hue, lightness and chroma corresponding to a Munsell notation of about 10R 6/14 (Figure 1). At the same time, the image areas depicting planes A to C respectively send progressively greater amounts of light to the eye, evoking progressively stronger responses at the level of the retina and appearing progressively higher in brightness and colourfulness. This progressive increase in brightness and colourfulness of the light reaching our eyes is perceived in what has been called the proximal or “painters’” mode of visual perception [12], as opposed to the distal or constancy mode in which we perceive a uniform hue, lightness and chroma belonging to the cube. Similarly, we perceive the lighter-coloured areas of the floor as *being white things*, that is, as having a uniform white object colour belonging to them, even though the corresponding image areas send light of a wide range of intensities to the eye, perceived as a wide range of brightnesses.

Simultaneously within the same rectangle of Figure 5 (left) we also perceive a pattern of light *falling on* the objects, comprising areas of varying intensities of light and shadow (Figure 5, upper right). A colour perceived as belonging to the light falling on objects is called an *illumination colour*[12]. Illumination colours can vary in hue, brightness and colourfulness or saturation, but the illumination in this scene is perceived to be achromatic, varying only in brightness. Notice that our perceptions of

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[12] CIE e-ILV 17-22-051

object colour and illumination colour respectively are *superimposed* in the scene, as if the object colours are seen *through* the illumination. These superimposed perceptions of object colour and illumination colour clearly do not correspond directly to the varying responses to light at the level of the retina (which we perceive as varying brightness and colourfulness), nor do they arise by conscious analysis and interpretation of those responses. Instead, they evidently involve some form of rapid, automatic, and unconscious comparison of these responses throughout the scene. It is only because of this remarkable capacity of our visual system to *parse* the scene into perceptions of object colour and illumination colour that we perceive objects as having more or less stable colours belonging to them, and not just continually varying brightness and colourfulness.

By shining a spectrum on various artists' pigments, Newton advanced the study of object colours by finding that their physical basis, what he called "Colours in the Object", lay in the object's "Disposition to reflect this or that sort of Rays more copiously than the rest", which we would now call the object's *spectral reflectance*[13]. It is important to note that the term spectral reflectance refers to the inherent reflectance of an object for each wavelength of light, and not to the spectrum of wavelengths that an object reflects under a particular light source. Like all perceived colours, the colour perceived to belong to an object can be greatly influenced by a variety of environmental and individual factors in addition to the object's spectral properties. (Newton also made a precocious observation in relation to these factors by showing that an object that appeared grey in daylight – a mixture of powdered artists' pigments - could be made to appear white if locally illuminated in a darkened room). Nevertheless, when we can freely examine an object in daylight, the colour we perceive as belonging to the object is usually a very good indication of the object's overall spectral reflectance, meaning its spectral reflectance *at the level of its long-, middle-, and short-wavelength components* (Figure 6). (We understandably tend to think of this perceived colour of the object freely examined in daylight – the illumination in which our colour vision is most effective - as being the object's seemingly intrinsic colour).

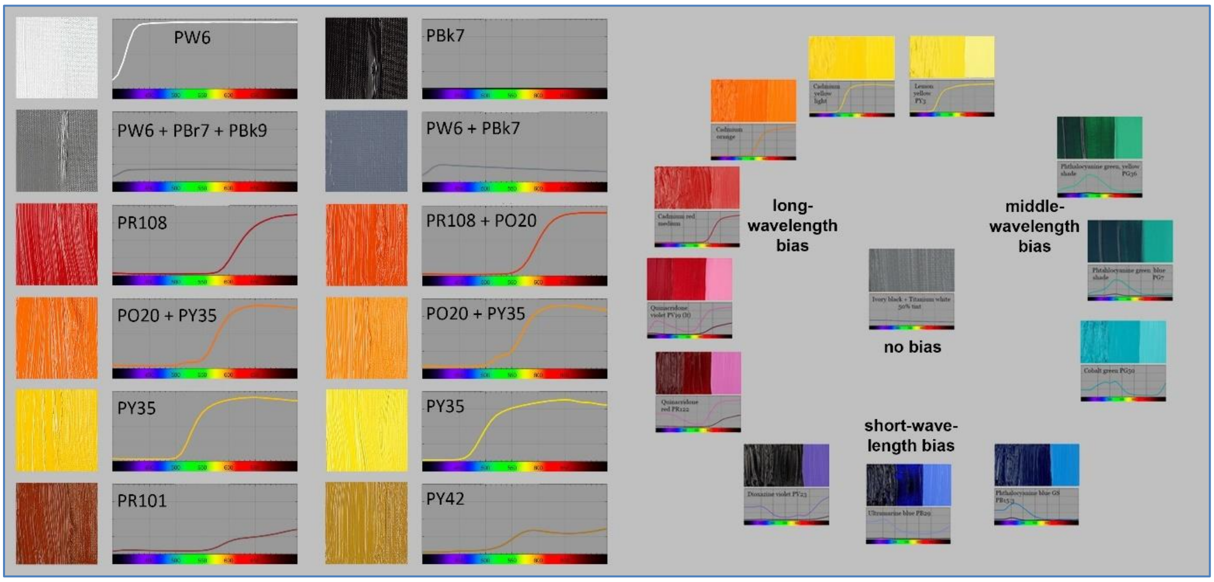

Figure 6: Left: Spectral reflectance curves for selected artists' paints [13], showing correlation of overall profile with perceived colour. For example, white, grey and black paints have a spectral reflectance that is very high, intermediate and very low respectively and about equal in their long-, middle- and short-wavelength components, while high-chroma paints have a spectral reflectance that is strongly biased towards certain wavelengths. Right: circuit of directions of overall bias of spectral reflectance towards long-, middle-, short- or long- and short-wavelengths of artists' paints and its correlation with hue.

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[13] CIE e-ILV 17-24-064, Note 1

To put this another way, the colour we see as belonging to a freely examined object in daylight is *the way in which we perceive* its overall spectral reflectance. Its lightness is our perception of the amount of light that the object reflects, and the hue and chroma are our perceptions of the direction and amount of overall bias of the object's spectral reflectance at the level of its long-, middle-, and short-wavelength components. As with colours of lights, however, our perceptions of object colour are not based on instrumental measurements but on the responses of the human visual system and are therefore shaped in part by the characteristics of that system. This of course is why we can only perceive spectral reflectance at the level of its long-, middle- and short-wavelength components. In addition, because the response of our visual system tapers towards each end of the spectrum, wavelengths near these ends have a decreasing influence on our perception of colour.

Our ability to perceive the overall spectral reflectance of an object as its colour is most effective in daylight or in lighting having a spectral distribution that is similarly balanced both on a broad scale, thus appearing "white" or achromatic, and reasonably even on a small scale, thus having a high Colour Rendering Index (CRI). Nevertheless, under illumination that is somewhat biased spectrally relative to daylight, the colours we see objects as having exhibit a *degree* of constancy. This degree of constancy arises in part because our visual system has the capacity to *adapt*, to a degree, to the spectral bias, so that the illumination appears less strongly coloured than it would otherwise, and also, quite apart from this, because our visual system has the ability to automatically and unconsciously parse the scene to some extent into colours relating to the illumination and to the objects, such that we might perceive some components of the pinkish scene in the upper right of Figure 7 to be white and grey objects under pinkish illumination. Nevertheless, our capacity to distinguish objects based on their spectral reflectance diminishes as the spectral bias of the illumination increases, and under monochromatic illumination we perceive as object colours only the objects' reflectance of the single wavelength present (Figure 7, lower right).

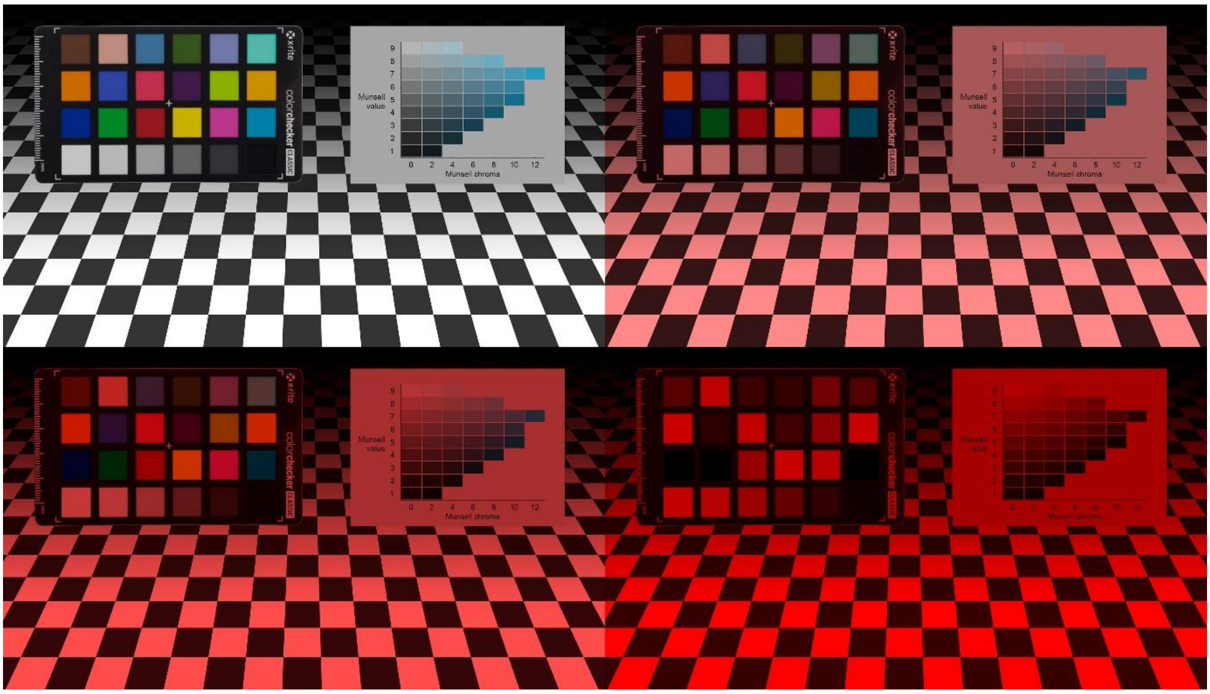

Figure 7: Simulation of a scene under white, pinkish, and monochromatic red illumination. Under pinkish illumination colour discrimination is impaired, but we may still perceive some objects as being white and grey (the colours they appear in daylight) by unconsciously attributing the pinkish colour of these areas to the illumination rather than to the objects. Under monochromatic illumination, however, we can perceive as object colours only variations in the reflectance of the single wavelength present.

I should acknowledge that under some circumstances even objects freely examined in daylight can evoke perceived colours that are very poorly correlated with their spectral properties, notably when the object is an *image area* in a depiction of illuminated objects, as in Edward Adelson's checker shadow illusion [14] and in the wonderful demonstrations of colour inconstancy by Purves and Lotto [15]. Purves and Lotto have argued that their demonstrations reveal the need for a radical new theory of visual perception, claiming for example that they show that visual perceptions, "like the perception of pain, do not stand for the actual properties of objects in the physical world, although the world is of course relevant to the way evolved visual systems determine stimuli and their frequency of occurrence" [16]. While there may be room for uncertainty over what exactly Purves and Lotto are claiming in passages like the one quoted, the idea that colours have nothing to do with physical properties has gained some traction with the general public under their influence. But this is to lose sight of the overwhelming evidence, known to anyone familiar with the spectral reflectances of paints, that when we can freely examine an object in daylight, the colour perceived as belonging to it is usually a very good indication of its overall spectral reflectance (Figure 6). So why is our perception of the spectral reflectance of this one class of objects so poor? I've argued elsewhere that in images of illuminated objects, the colours perceived as belonging to the virtual objects depicted in the images are so visually insistent that it can be very difficult to attend to and compare colour perceptions relating to the image areas themselves [17]. But if we break the representational spell of the image by providing a target seen as being outside the depicted illumination, as in Figure 8 (right), the difficulty in comparing the image areas veridically is removed immediately.

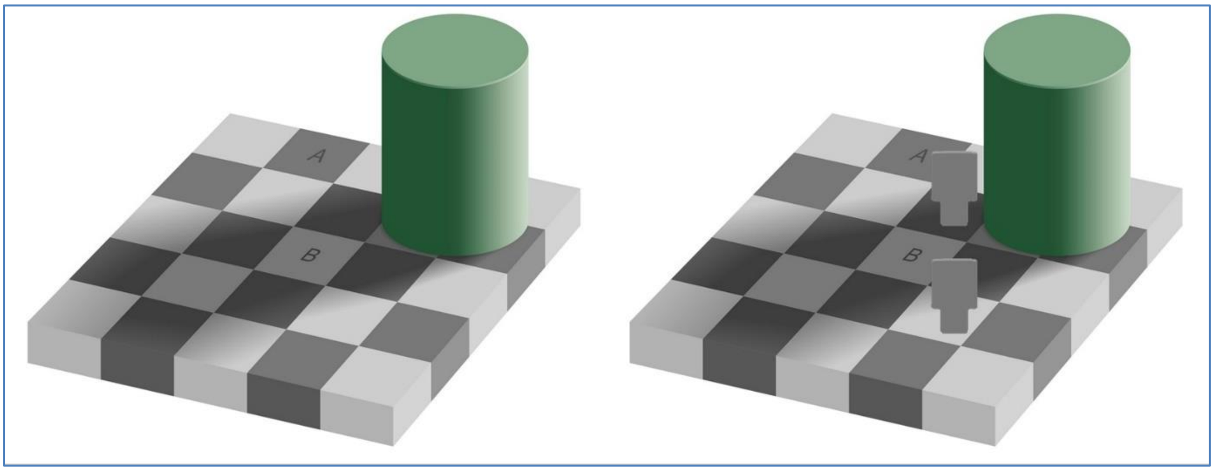

Figure 8: In Edward Adelson's checker shadow illusion (left, ©1995, Edward H. Adelson), the image areas labelled A and B physically match and thus have equal luminance, but it is difficult to perceive the light from these areas as equal in brightness. We could of course compare the luminance of these areas veridically by masking out the rest of the scene, but interestingly we can achieve the same result if we break the representational spell of the image merely by introducing targets seen as being outside the depicted illumination. This suggests that our difficulty in comparing the image areas stems from our attention being held by the perceived colours of the virtual objects depicted in the scene at the expense of colours relating to the actual image areas [17].

Colorimetry

Colorimetric specification of lights and objects can be an area of confusion in the broader colour community, and I've sometimes encountered the view that colorimetry is all very well for technology but has nothing to do with human perception. In fact, colorimetric specifications of lights and objects are purpose-built to represent for practical purposes just those differences that we perceive as colour differences by ignoring physical differences that are not perceivable to human colour vision.

Figure 9 shows an intuitive, nonmathematical way of explaining the rationale for the colorimetry of lights. I begin by explaining that if my computer screen could emit a sufficient range of light intensities, I could visually match the light reaching my eye from most points in my environment with a light on my screen, and so could represent those lights in a cubic *RGB* colour space according to the R, G and B components of the matching lights, much as a digital camera is designed to do in a different way. However, while we need three dimensions to describe the colour of an object, for many purposes we can consider the colour of a light to be separate from its brightness, and correspondingly we can specify the colour of a light for many purposes using only two dimensions. If I were to leave out the total amount of light (as did Newton in his circle), I could represent these RGB quantities as a two-dimensional triangle, showing only the ratio of the matching long-, middle- and short-wavelength primaries, *R*, *G* and *B*. A two-dimensional diagram of this kind, showing the ratio of three primaries but not their absolute intensity, is called a *chromaticity diagram*[14]. But whatever *R*, *G* and *B* primaries my screen uses, some highly saturated lights would be outside the range that I could match directly, and so would lie outside the cube and outside the triangle.

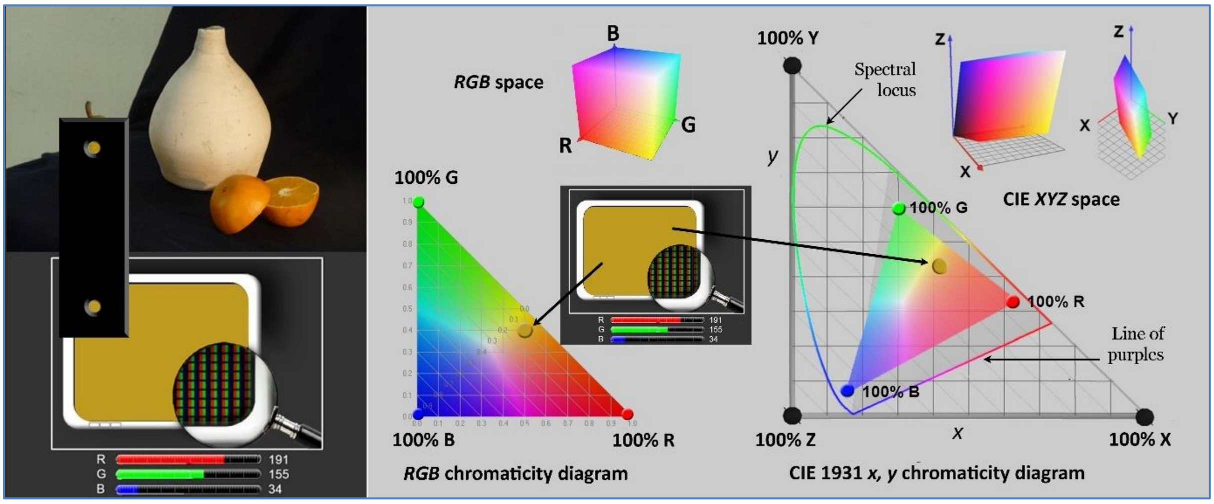

Figure 9: Nonmathematical explanation of the CIE 1931 x,y chromaticity diagram by analogy with an RGB chromaticity diagram (see text). Graphics exported from ColorSpace by Philippe Colantoni and Maxwell Triangle by efg2.com (both now unavailable).

The CIE 1931 x,y chromaticity diagram is based on the idea that all lights can be specified using a framework formed by three purely *theoretical* primaries, CIE X, Y and Z, that are impossible to produce as actual lights, but lie just far enough outside the range of actual lights to be able to specify all such lights mathematically with positive values. We can think of these theoretical and arbitrary but mathematically useful primaries as being lights that contain negative amounts of some wavelengths. Just as the *ratios* of the R, G and B primaries in the matching lights can be plotted in a two-dimensional RGB triangle, the ratios of these theoretical *X*, *Y* and *Z* primaries can be plotted in the triangle shown in Figure 9 (right). All actual lights fall within the area enclosed by the horseshoe shaped *spectral locus*, representing the wavelengths of the spectrum, and the straight *line of purples*, representing mixtures of the two extremes of the spectrum.

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[14] CIE e-ILV 17-23-054

The CIE *x,y* diagram is not the latest but is still the most familiar descendent of Newton's colour circle. Location in the *x,y* chromaticity diagram represents the overall balance of wavelengths in a light at the level of its long-, middle- and short-wavelength components, as detected by the visual system of a mathematically defined "standard" human observer. As was already implicit in Newton's circle, physically different mixtures of spectral components can evoke the same perceived colour if they have the same "center of gravity", or overall balance of spectral components. Figure 10 (left) illustrates three spectral distributions that appear white as isolated lights: CIE illuminant D65, representative of noon daylight, CIE illuminant F7, representative of a fluorescent illumination that matches D65 in colour, and a specific white LED screen adjusted to match these illuminants. Despite their considerable physical differences, these three spectral distributions match as isolated lights because they have the same overall balance at the level of their long-, middle- and short-wavelength components, as detected by our combined cone and cone-opponent system. Physically different lights that match in colour like these and plot at the same point in a chromaticity diagram are said to be metameric[15].

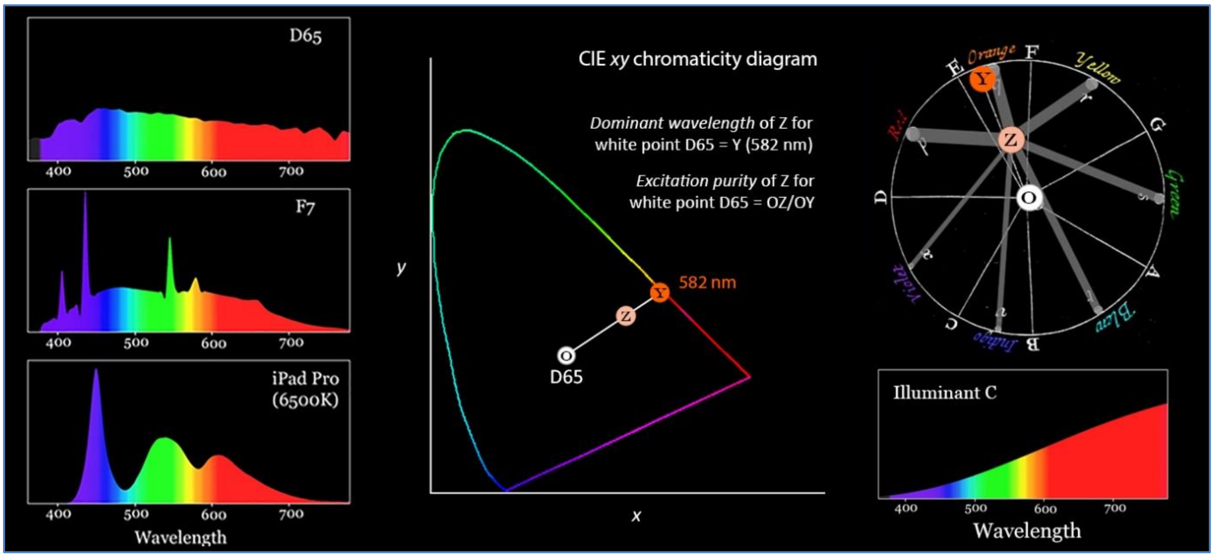

Figure 10: Three spectral power distributions, after [6], having the same overall balance at the level of their long-, middle-, and short-wavelength components from the point of view of the human visual system, and thus matching in colour (appearing white as an isolated light), and plotting at the same point (O) in the CIE 1931 x,y *chromaticity diagram. Compare concepts of dominant wavelength and purity to Newton's predictors of hue and saturation.*

These three lights that match daylight all plot at the point D65 near the middle of the triangle, while positions displaced from this point signify an overall bias relative to daylight in a circuit of directions towards long, middle, short or long and short wavelengths. The direction of displacement from a given white is specified as the *dominant wavelength*[16] if it is towards the spectral locus and as the complementary wavelength if it is towards the line of purples. The amount of displacement can be specified by the excitation *purity*[17], the ratio of the distances from the given white to the chromaticity and to the spectral locus or line of purples. These colorimetric correlatives of hue and saturation respectively very closely recall those Newton described in his colour circle (Figure 2; Figure 10, right).

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[15] CIE e-ILV 17-23-008

[16] CIE e-ILV17-23-062

[17] CIE e-ILV 17-23-066

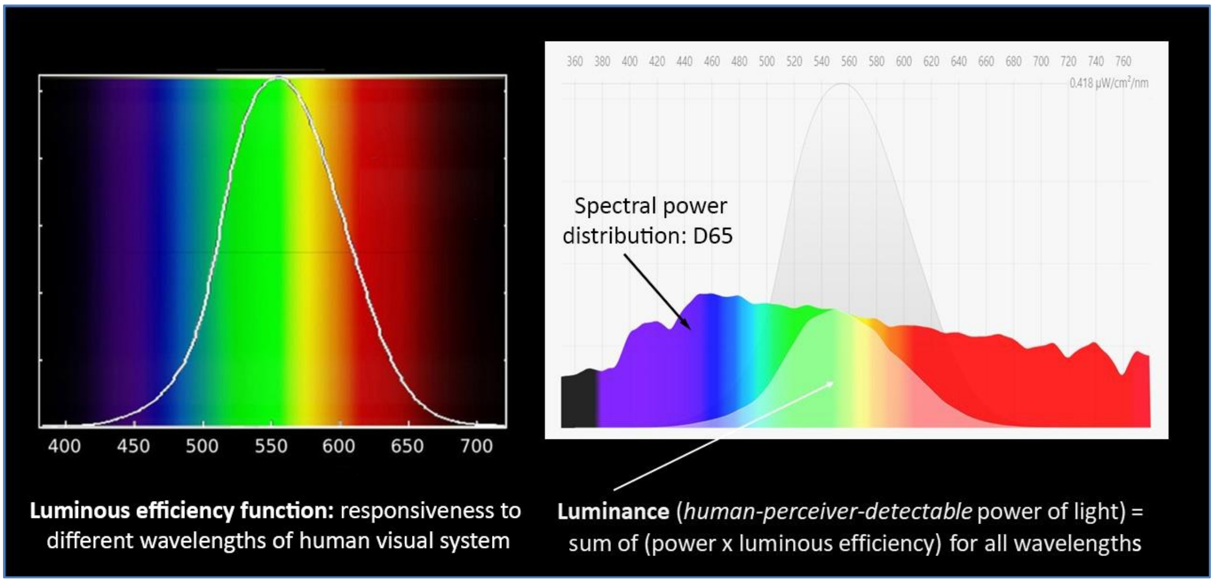


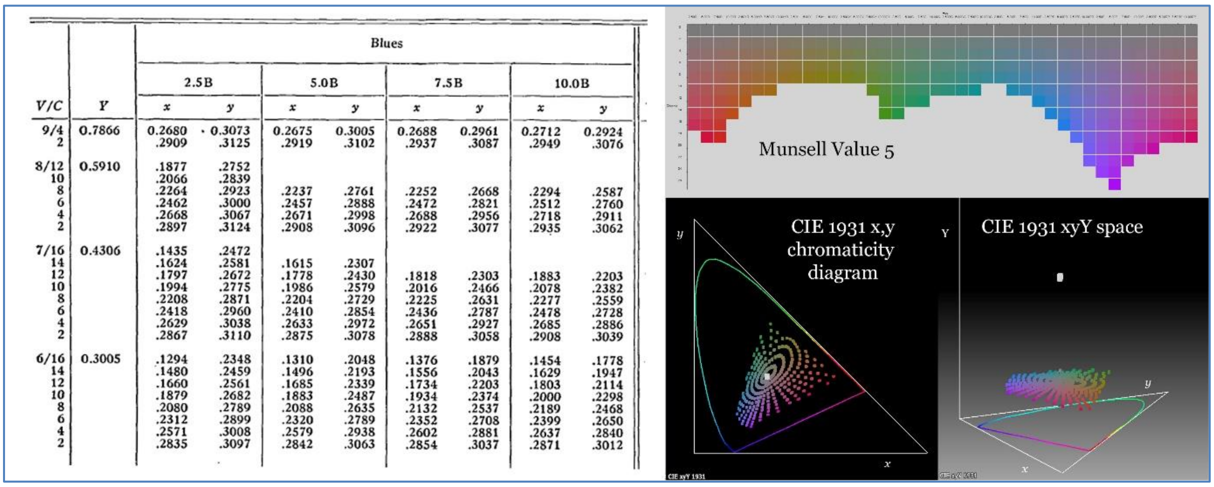
Figure 11: Left: luminous efficiency function after [9].Right: calculation of luminance from the luminous efficiency function and the spectral power distribution for illuminant D65 [6].

We say that light, or visible radiation, ranges from about 380 to 780 nanometres in wavelength, but in fact wavelengths towards the limits of this range are barely visible, and the response of the human visual system increases from these limits up to the middle of the range, peaking in the wavelengths perceived as yellow-green. This curve showing the responsiveness of the visual system of a standard human observer to different wavelengths is called the *luminous efficiency* function (Figure 11, left). The amount of of light that an area emits, transmits or reflects is quantified colorimetrically as *luminance*, the physical power of the light weighted wavelength-by-wavelength by the responsiveness of the human visual system (Figure 11, right). Two lights adjusted to match in brightness when compared in certain ways, notably by showing no flicker when alternated very rapidly (a method called flicker photometry) or by finding the point at which they exhibit a minimally distinct border, would be expected to have the same luminance. (Note: if these lights differ in colour they might be perceived to differ in brightness when compared by other methods, as will be discussed in Part Two).

A colorimetric specification of a light represents a class of physically varied lights having a *common disposition* to evoke a perceived colour, in the sense that physically different lights having the same colorimetric specification *would be expected to match in perceived colour when viewed under the same conditions*. Thus, a colorimetric specification of a light may be said to quantify what Newton called colours "in the Rays", meaning the light's "*Power and Disposition to stir up a Sensation of this or that Colour*". A colorimetric specification does not however correspond to a single perceived colour; our three lights in Figure 10 should match in perceived colour in various different viewing environments, but this matching perceived colour could be different in each of these environments. Colorimetric specifications are not intended to describe perceived colour, and their failure to do so is not a fault of colorimetry.

Colorimetry of objects involves colorimetric specification of the light reflected by the object under a specified light source, normally a standard daylight illuminant. For a spectrally neutral object (one that reflects all wavelengths equally), the chromaticity of the light it reflects is the same as that of the illuminant, and other chromaticities result from various directions and degrees of perceivable bias of the spectral reflectance at the level of its long-, middle- and short-wavelength components. Specifications of this reflected light can be plotted in the three-dimensional colour space CIE xyY, formed by adding to the x,y chromaticity diagram the third dimension Y, representing the relative luminance of the light reflected compared to a reference white, (Figure 11, lower right). As with colorimetric specifications of lights, this *xyY* specification of object colours was designed to ignore physical differences that we do not perceive as colour differences. Granted the necessary assumptions of a standard observer and a specific daylight illuminant, CIE *xyY* values quantify for practical purposes the human-perceiver-dependent property of an object that we perceive as the colour of that object in daylight - which is the colour that we tend to think of as the (seemingly) intrinsic colour of the object. Each chip in the Munsell system, representing a specific combination of hue, lightness (value) and chroma, is manufactured to embody a CIE *xyY* specification of the light that the chip would reflect under Illuminant C, a standard daylight illuminant used at the time the current Munsell notations were defined in 1943 (Figure 12, left). Each of these *xyY* values represents a class of physically different spectral reflectances of objects that would match in colour to the standard observer under Illuminant C, and for practical purposes would be expected to appear essentially the same hue, lightness and chroma to a colour-normal observer when freely examined in daylight.

Figure 12 (right) shows the varying chromaticity and fixed relative luminance of a set of digital Munsell swatches of Munsell value 5 in *xyY* space. Even from this diagram it can be seen that *xyY* space does not arrange the swatches in the regular concentric circles of equal chroma and radiating lines of equal hue that they occupy in the Munsell system. In 1976 the CIE developed two colour spaces intended to be more perceptually uniform, CIE L*a*b* and CIE L*u*v*. These transform *xyY* specifications into arrangements resembling (though not identical to) their arrangement in the Munsell colour solid, which in turn permits these specifications to be converted to correlatives of hue, lightness and chroma. CIE L*a*b* is familiar to photographers and digital painters as the "Lab" space in Adobe Photoshop, and is a more convenient framework in the digital environment than the Munsell system because L*a*b* values can be obtained from RGB coordinates by direct calculation rather than by the much more computationally intensive process of interpolating values in a table.



		Blues							
		2.5B		5.0B		7.5B		10.0B	
V/C	*Y*	*x*	*y*	*x*	*y*	*x*	*y*	*x*	*y*
9/4	0.7866	0.2680	· 0.3073	0.2675	0.3005	0.2688	0.2961	0.2712	0.2924
2		.2909	.3125	.2919	.3102	.2937	.3087	.2949	.3076
8/12	0.5910	.1877	.2752						
10		.2066	.2839						
8		.2264	.2923	.2237	.2761	.2252	.2668	.2294	.2587
6		.2462	.3000	.2457	.2888	.2472	.2821	.2512	.2760
4		.2668	.3067	.2671	.2998	.2688	.2956	.2718	.2911
2		.2897	.3124	.2908	.3096	.2922	.3077	.2935	.3062
7/16	0.4306	.1435	.2472						
14		.1624	.2581	.1615	.2307				
12		.1797	.2672	.1778	.2430	.1818	.2303	.1883	.2203
10		.1994	.2775	.1986	.2579	.2016	.2466	.2078	.2382
8		.2208	.2871	.2204	.2729	.2225	.2631	.2277	.2559
6		.2418	.2960	.2410	.2854	.2436	.2787	.2478	.2728
4		.2629	.3038	.2633	.2972	.2651	.2927	.2685	.2886
2		.2867	.3110	.2875	.3078	.2888	.3058	.2908	.3039
6/16	0.3005	.1294	.2348	.1310	.2048	.1376	.1879	.1454	.1778
14		.1480	.2459	.1496	.2193	.1556	.2043	.1629	.1947
12		.1660	.2561	.1685	.2339	.1734	.2203	.1803	.2114
10		.1879	.2682	.1883	.2487	.1934	.2374	.2000	.2298
8		.2080	.2789	.2088	.2635	.2132	.2537	.2189	.2468
6		.2312	.2899	.2320	.2789	.2352	.2708	.2399	.2650
4		.2571	.3008	.2579	.2938	.2602	.2881	.2637	.2840
2		.2835	.3097	.2842	.3063	.2854	.3037	.2871	.3012

Figure 12: Left: Extract from the tables of Munsell notations expressed as CIE xyY values, from the 1943 Munsell renotation [18]. Right: Digital colours of Munsell value 5 (above, exported from the Virtual Colour Atlas [19]), below, plotted on a CIE x,y chromaticity diagram and in xyY colour space, using the program Artists' Helper [20].

Colour ontology

In philosophy of colour there are many different theories of *colour ontology*, the subdiscipline concerned with questions about the fundamental nature of colour. Many (though not all) of these theories accept the scientific view that colour perceptions arise within the visual system but differ among themselves in part over what the word “colour” is taken to apply to. In *eliminativism* the word “colour” is taken to apply *exclusively* to colour perceptions (red, blue etc), leading to such statements as “colours do not exist”, meaning that they do not exist outside the mind. *Adverbial* formulations such as [21] better acknowledge the connection between colour perceptions and the stimuli that usually evoke them, for example leading to such statements as that we perceive a certain stimulus “bluely” or, I think more naturally, that the colour blue is *the way in which we perceive* the stimulus. In other widely held theories, the word “colour” is taken to apply to the power or disposition of lights and objects to cause perceptions of red, blue etc. (*dispositionalism*), or to cause such perceptions in a given perceiver and environment (*relationalism*). Colour *physicalism* on the other hand applies the word “colour” to the spectral reflectance of an object, relegating red, blue etc to being merely the *appearance* of this actual, physical colour. For a clear and concise account of these and other positions on the ontology of colour see [22].

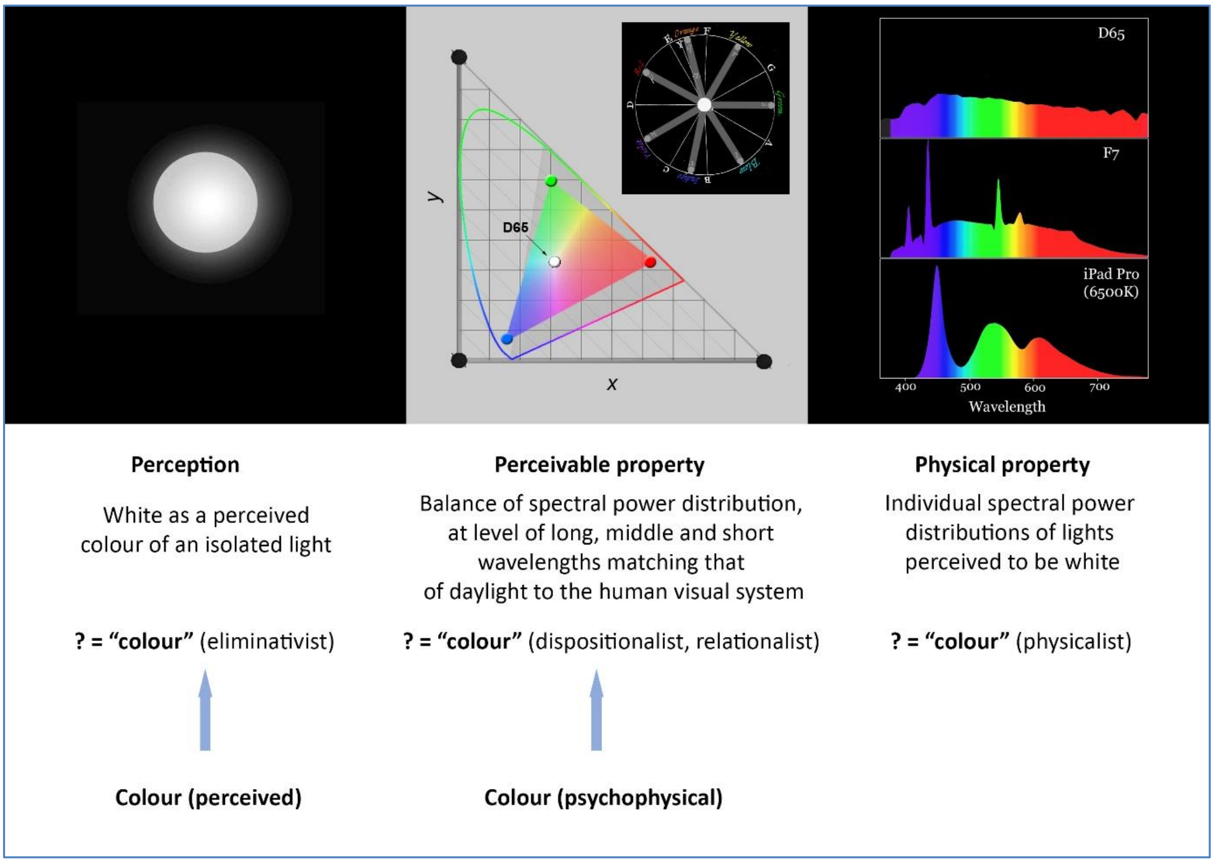


Figure 13: “White” as a colour of an isolated light (a perceived colour designation) is the way in which we perceive a spectral power distribution’s overall balance, a human-perceiver-dependent property represented by its colorimetric specification (a psychophysical colour designation). This perceivable property may be shared by many physically different spectral power distributions. In the ontological position known as physicalism these individual spectral power distributions are called “colours”; this usage is not supported by the scientific consensus embodied in the CIE ILV and does not correspond to any sense of the word ”colour” defined therein.

The CIE ILV defines the word “colour” in two distinct senses. Along with “colour” in the perceptual sense or “perceived colour”[18], discussed previously, the ILV also defines “colour” in the psychophysical sense, as a “specification of a colour stimulus in terms of operationally defined values, such as three

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[18] CIE e-ILV 17-22-040

tristimulus values”[19]. “Tristimulus values”[20] are in turn defined as the “amounts of the reference colour stimuli, in a given trichromatic system, required to match the colour of the stimulus considered”, giving as examples the tristimulus values represented by the symbols R, G, and B, and X, Y, and Z in CIE colorimetry. Thus, one might say that in a demonstration of simultaneous contrast or assimilation on a computer screen, matching physical stimuli having the same psychophysical colour (the same RGB value) appear two different perceived colours. When we speak of “colour measurement”, “colour difference formulae”, many “colour spaces” and the 16.7 million RGB “colours” on our screens, we are using the word “colour” in this second sense.

Many in the broader colour community find the concept of psychophysical (or colorimetric) “colour” to be philosophically suspect or even nonsensical. How can a numerical specification be a colour? But as I’ve argued above, colorimetric measures are designed to specify for practical purposes the human-perceiver-dependent property of a light, or of an object viewed in daylight, that philosophers have long called its *disposition* to be perceived a particular colour. Traditional colorimetry specifies this disposition for a mathematically defined “standard observer”, but more recent developments make possible adjustments for observer variation [23]. In defining two senses of the word “colour” the CIE ILV in effect expresses a pluralist ontology that acknowledges that we may wish to use the word “colour” either for our perceptions of colour or for the measurable property shared by physically varied lights or objects that disposes them to appear as having the same colour. In terms of philosopher C. L. Hardin’s well-known quote – “colored objects are illusions, but not unfounded illusions” [24] - “psychophysical colour” specifications identify for practical purposes the *perceivable* properties of objects (and lights) that our “illusions” of perceived colour are founded on.

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