What is the 'opposite' of 'blue'? the language of colour wheels

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Abstract—Colour wheels are a tool for ordering and understanding hue. Different colour wheels differ in the spacing of the colours around the wheel. The opponent colour theory, Munsell's colour system, the standard printer's primaries, the artist's primaries, and Newton's rainbow all present different variations of the colour wheel. I show that some of this variation is owing to imprecise use of language, based on Berlin and Kay's theory of basic colour names. I also show that the artist's colour wheel is an outlier that does not match well to the technical colour wheels because its principal colours are so strongly connected to the basic colour names.

1 Introduction

COLOUR wheels provide a way to describe the ordering of hue and, in some cases, to aid understanding colour mixing. The artist's colour wheel (Figure 1), epitomised by Itten [Itt70], is used extremely widely in teaching. Its primary colours are red, yellow and blue.This is the colour wheel that students meet in primary school. In this wheel, the opposite of blue is orange. When students meet more advanced material in colour theory, they find apparent contradictions. The printer's colour wheel has primaries cyan, magenta, and yellow, which the student might be taught to understand as a refinement of blue, red, and yellow. But curiously for the student the colour labelled "blue" in the printer's colour wheel is opposite to yellow, not to orange. In my own early introduction to colour, I found the art books' insistence that orange was the opposite of blue conflicted with my observation that, in many works of art and design, yellow appeared to me to be the more apposite opposite. Further confusion comes to the student when they meet the opponent colour theory, in which there are four principal colours, with blue opposite yellow (Figure 3); and Munsell's colour system in which there are five principal hues, with blue opposite yellow-red (Figure 4). The challenge for the educator is in explaining these differences.

These differences can be downplayed in educational material. For example, one text for art students states that "Colour wheels must always have an even number of hues and that number must be divisible by three. *Any other combination would not be a true and accurate colour wheel*" [Ble12, p.66, emphasis mine]. This is a simplification by the author for the benefit of the students, as the author is well aware of the NCS and Munsell colour systems which have four and five principal colours [Ble12, p.31] and which have a well-defined notation for describing colours around the hue wheel.

One of the reasons to question the received wisdom is that almost all art texts, inspired ultimately by Itten's seminal work [Itt70], use angles on the colour wheel to determine "harmonious" colour combinations (Figure 2). If

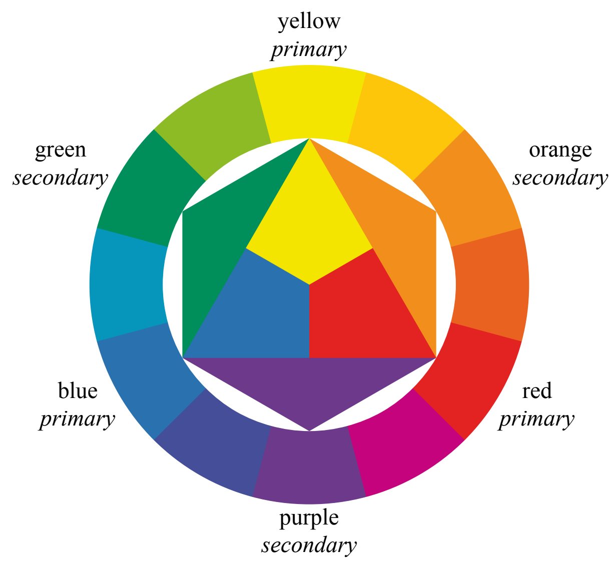

Fig. 1. An Itten colour wheel with twelve hues. The three primaries, red, yellow, and blue, combine to make three secondaries, green, orange, and purple. Each primary combines with its neighbouring secondaries to make six tertiary colours.

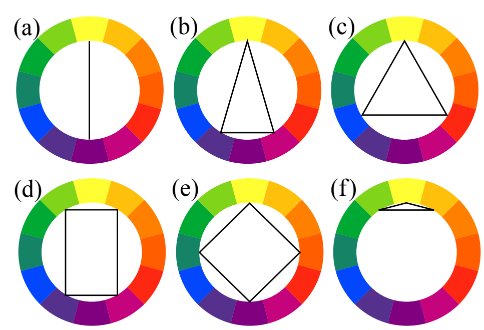

Fig. 2. The artist's harmonious colour combinations: (a) complementary, (b) split complementary, (c) triadic, (d) tetradic rectangle, (e) tetradic square, (f) analagous. (b)–(e) are from Itten [Itt70, Figs. 54, 55].

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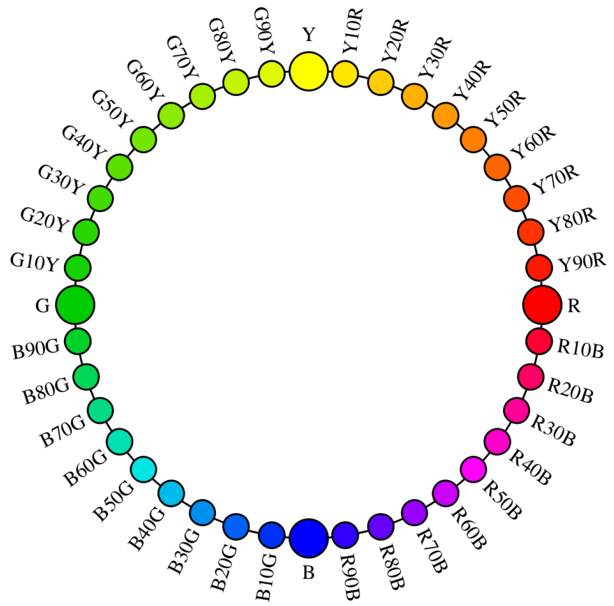

Fig. 3. An NCS colour wheel with four principal hues [HST96] [NCS18] [Swe89]. The four principals are red, yellow, green, and blue. The circle is divided into 400 units, 100 between each pair of principals. Hues between the principals are indicated by numeral between the two principals' initial letters. In this chart we see units every ten steps for each of the four quadrants.

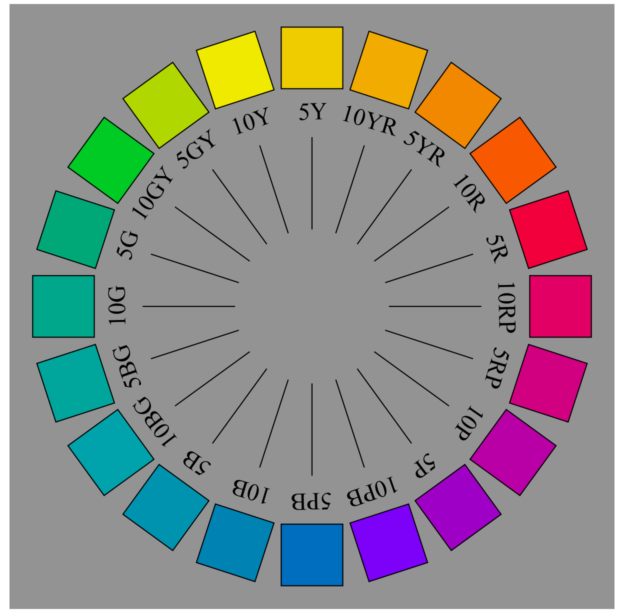

Fig. 4. A Munsell colour wheel with five principal hues and five intermediate hues [Mun76] [Mun18]. The five principal hues are red, yellow, green, blue and purple. The intermediates are indicated by combinations of the colour letters (e.g., YR=yellow-red). The wheel is further subdivided into ten sections for each principal and intermediate, indicated by numerals. In this chart we see the 5 and 10 units for each of the ten sections. The "5" unit is the prototypical version of each hue. The "10" unit is a half-and-half mix of the hues either side. Image used under a Creative Commons 3.0 license from WikiMedia author Thenoizz.

the colour wheel is not immutable, as the different colour wheels suggest, then these harmonies rest on insecure foundations. This is by no means a new problem [Ber81, Ch.6B] [Bri07]. Some of the difference between the different colour wheels can be explained from the principles underlying their constructions and the uses for which they are designed. There is difference in how you construct your colour space depending on whether you are mixing coloured lights, mixing coloured pigments, or dealing with human visual perception [Der91]. For example, Itten's artist's colour wheel is based in subtractive colour mixing of pigments; opponent colour theory is based in visual perception; and Munsell was aiming to bring clarity to colour communication by establishing an orderly system for accurately identifying all colours. All the colour spaces discussed in this paper are ways of specifying or mixing colours so all can be considered ways of dealing with pigment.

The contribution of this paper is to argue that our understanding of colour wheels is mediated by the terms we use to describe colours, in particular in the use of basic colour terms [BK69]. This leads to some of the apparent differences between colour wheels in two ways. First, generally across all colour wheels, we use the same basic colour name, such as *blue*, to represent subtly different colours in different wheels (Section 5), which confuses the student. Second, and specific to the artist's colour wheel (Figure 1), while the artist's (RYB) and printer's (CMY) colour wheels should both be identical, because they are both subtractive colour mixing models, I argue that the differences between them are largely owing to the artist's colour wheel being actively driven by basic colour terms in a way that puts it at odds with the optimal physical colour mixing embodied in the printer's colour wheel (Section 6).

I first give a summary of the history of colour spaces and colour wheels (Section 2), then a history of colour naming and an outline of Berlin and Kay's theory of basic colour terms (Section 3). I describe five of the most commonly used colour wheels (Section 4). I demonstrate that imprecise use of colour names explains a substantial amount of the apparent inconsistencies between the different wheels (Section 5), allowing us to reconcile these differences. This leads to the observation that the technical colour wheels are broadly consistent with one another, provided we are precise about our specification of the principal colours in those spaces, but that the standard artist's colour wheel is substantially different from the technical colour wheels (Section 6), because its primary and secondary colours are so strongly related to use of basic colour terms in English.

2 History

Colour has fascinated philosophers and artists since antiquity but it is only in the last century that we have come to understand the psychophysical and biological mechanisms of colour vision, so early writers could be said to be working in the dark. Aristotle described seven principal colours (white, yellow, red, violet, green, dark blue, black) which he considered all to be mixes of white and black [Sha94], a misconception that started to be challenged in the fifteenth century [Alb66] but still held some sway until the eighteenth century. The discovery that red, yellow and blue are the artist's primaries was made in the early seventeenth century. Shapiro cites Parkhurst and Gage as reporting that four scholars independently discovered the artist's tri-chromatic primaries. All four scholars were conversant with both art and the natural sciences, giving them access to the understandings needed to make this discovery. Shapiro asserts that it "...was the most important discovery in colour before Newton's own theory" [Sha94, p.624].

In the late seventeenth century, Newton conducted extensive investigations into the nature of colour, discovering that white light split into an infinite range of colours: the visual spectrum. This discovery was at odds with the widely-held belief that white was "pure" and could not be split and also at odds with the three primary colours discovered earlier that century, discrepancies that caused him much trouble to attempt to reconcile and which led to substantial challenges in his work being accepted. Neverthless, in his writings before *Opticks*, whenever he listed his principal colours of the spectrum, he always added some phrase such as "with their innumerable intermediate gradations" to indicate that there were countless discernible colours, but in *Opticks* he omits to say this in all but one place, possibly in an attempt to placate his critics [Sha94, p.619]. Newton's early work described five principal colours: red, yellow, green, blue and purple, but he later added orange and indigo, leading to English's current seven-colour rainbow (see longer discussion in the Appendix).

At the start of the nineteenth century, Goethe launched a challenge on Newton's purely physical approach, tackling colour instead as a perceptual phenomenon. To a technically trained modern, some of Goethe's arguments can seem misguided when compared with Newton's empiricism. But Newton was, in his own way, blinkered: fitting the data to suit his hypothesis rather than the other way round [Pla06] [Rib85]. The challenge Newton faced was that his evidence was inconsistent, because he was assuming that mixing lights (additive colour mixing) and mixing pigments (subtractive colour mixing) should produce consistent results. It was only in 1852 that Helmholtz deduced that different rules apply to the mixing of pigments and of lights [Sha94]. In additive colour mixing, different coloured lights are used, each with its own spectrum. The mix of the lights is a spectrum that is the weighted sum of the spectra of the individual lights, weighted by the intensity of the lights. Additive colour is used in display devices and the usual primary colours used are a red, a green, and a blue. This is in contrast to subtractive colour mixing, in which coloured pigments, inks, paints or dyes are mixed together. Each pigment absorbs some part of the spectrum of light. The mix of pigments absorbs a weighted sum of the absorptions of the individual pigments. Subtractive colour mixing is used in painting, printing and dyeing [Ber81].

The chemist, Chevreul, dyemaster at the Gobelin work in Paris, published *De la Loi du Contraste Simultané des Couleurs et de l'Assortiment des Objets Coloris* in 1839 [Itt70]. This, and other emerging colour theories, had substantial influence on artists in the nineteenth and early twentieth centuries. Itten says that "Delacroix...is the founder of the tendency, among modern artists, to construct works upon logical, objective colour principles, so achieving a heightened degree of order and truth." [Fry06, p.418]. The Impressionists and Post-Impressionists, in particular, used theories of colour contrast and optical colour mixing.

Several early commentators on colour, including da Vinci, noted that there appear to be four fundamental colours: red, yellow, green and blue, in addition to black and white [Har06]. Hering formalised this into the opponent theory of colour vision [Der91] [HJ57]. Hering's theory was further developed by Hård, Sivik and Tonnquist in their creation of the Natural Colour System (NCS) [HST96]. There is evidence that the four opponent principal colours are physiologically determined [Gou91] [Har05]. Hering's theory was not widely embraced at the time because there was no understanding of how responses to two different colours of light could interact to create a colour-opponent signal. We know today that the neurons in the retina process the outputs of the light-sensitive cones to produce three channels of data to the brain: a high resolution luminance channel, a lower-resolution red-green channel and an even lower-resolution blue-yellow channel [Ber81, p.16] [HJ57]. The opponent colour channels explain well several features of human vision, including the way in which colour blindness manifests and the complementary afterimages caused after fixating on a coloured field. Consistent with this theory is that you cannot perceive a colour as having simultaneously components from either end of an axis, so a yellowish-green and a bluish-green both make sense, but a human can never perceive a colour that is "reddish-green", such a mixture being a nonsense.

Over far more than a century, philosophers, scientists and artists have grappled with ways to represent and understand colour, leading to many systems of colour representation. Basic introductions can be found in computer graphics and design texts [FvDFH90, Ch.13] [JMF94] [SAM09, Ch.20–22] [Sto03], with more detailed explanations in specialist texts [Ber81] [Ble12] [Bri07] [KB96], and a full history of colour spaces in Kuehni and Schwartz's 2008 book [KS08].

A colour space is a three-dimensional representation of colour. We can restrict ourselves to three dimensions because the human visual system has three types of receptor for colour vision. All of the colour spaces are mathematical transformations of one another. Hunter gives a detailed history of nineteen colour spaces developed in the attempt to create a perceptually uniform space, starting with the CIE 1931 colour space and Munsell's original system, through to the CIELUV and CIELAB systems of 1976 [Hun75, Ch.8]. Derefeldt gives the background of the most important colour appearance systems, including Munsell, NCS, CIELAB and CIELUV. She gives their basic attributes, and the principles for scaling and notation of the variables. In particular, she makes a comparison of the hue spacing of the different spaces [Der91]. Note that there is considerable evidence that colour vision is non-Euclidean, so any colour space is not going to be a metric space, perceptually [Ber81, p.64]. For example, the CIELAB system has a cube-root relationship with the signals that are received by the cones in the human eye. This is to better match the perceptual response of the human visual system but means that linear mixes in the CIELAB system do not necessarily match mixes of pigments.

A colour wheel is a representation of one dimension of a colour space: hue. Colour wheels have been used for centuries. The earliest known drawing of a colour wheel dates from 1611 [PF82], a century before Newton's *Opticks* [New04].

A colour wheel or, more accurately, a hue wheel, is a circle that passes through all of the spectral colours and then through the purples to join the two ends of the spectrum (Figure 1). Hue is explicitly one of the three dimensions in some colour systems, including NCS (Figure 3) and Munsell (Figure 4), and is implicit in others, where hue is a function of two or three of the principal dimensions of the space. For example, in the case of CIELAB, $h^\circ = \tan^{-1}(b^*/a^*)$. When considering a colour wheel, the hues always appear in the same order around the wheel but they differ in which hues appear opposite each other and in the relative angular separation of pairs of hues.

A student may make an assumption that a "true" colour wheel exists and that the different colour wheels essentially stretch or contract sections of the "true" wheel to fit their predilections, as if the colours were painted on a rubber bicycle wheel and we nailed certain hues to certain points on the rim. The stretching and contracting is epitomised in the differences in the angles red–yellow and green–blue, shown in Table 1. When a colour wheel is used as a mechanism to *describe* hue, then such stretching or contracting is fair: the wheel is not purporting to show precise physical relationships. However, when a colour wheel is used to describe relationships or mixes between distant hues, such as in defining the "opposite" of a hue or "harmonious colour combinations" (Figure 2), then this stretching and contracting becomes questionable.

3 Basic colour terms

Berlin and Kay proposed the theory that there are basic colour terms in all languages [BK69]. These are the terms that you teach small children and which produce categories of colour that are irreducible, that is, all other colour terms are considered, by most speakers of the language, to be variations on these basic colour terms.

In antiquity, classical scholars certainly privileged certain colours above others. In the distant past, the fundamental colours appear to have been severely limited. Berlin and Kay quote Geiger as suggesting that "Democritus and the Pythagoreans [fifth century BC] assumed four fundamental colours, black, white, red and yellow" [BK69, p.136]. Elsewhere, Geiger comments that Aristotle [fourth century BC] "in his 'Meteorology' calls [the rainbow] tri-coloured, viz., red, yellow, and green" [Gei80, p.57]. By the fifteenth century, things had developed a little further. Alberti cites three fundamental colours: red, green, blue, combined with grey [Alb66, Book I, paragraph 9] while da Vinci lists what we now call the colour opponent set of principal colours: red, yellow, green, blue [Har06]. In the seventeenth century, Boyle listed the standard artist's primaries: red, yellow and blue [Har06], but added green and purple when actually conducting his experiments on colour [Boy64, p.187]. In the early eighteenth century, Newton started with these five principal colours: red, yellow, green, blue and purple, then added orange and indigo (see longer discussion in the Appendix).

There is a question of nature versus nurture: how much the colour categories are inherent in our psychophysiology and how much they are cultural constructs. There is good evidence that black, white, yellow, red, blue, and green are strongly tied to the perceptual mechanisms in the human brain [Har05]. Hardin notes that the four principal colours (yellow, red, blue, green) ". . . prove to be both necessary and sufficient for an English speaker to describe any spectral stimulus" [Har98]. The other basic colour categories may be more culturally determined. Children are able to match and discriminate colours long before they have consistently codified the boundaries in colour space of the basic colour terms, so providing evidence that the boundaries are a social construct [ATF86]. In any case, in order to communicate clearly between members of a language group, the learnt categories must be at least partly a social construct, reinforced by parents, kindergartens and primary schools because all members of the language group broadly agree on them.

Berlin and Kay identified that the number of basic colour terms range between two (representing light and dark colours) and twelve, depending on the language. In English there are eleven basic colour terms: red, orange, yellow, green, blue, purple, pink, brown, black, grey and white. As an example of the irreducibility of these basic terms, consider how difficult it is to convince a child that brown is really "dark orange" or that pink is "light red" [Har98, p.210]. You may teach a particular child or student to make finer distinctions, as between "cyan", "azure", "indigo" and "turquoise", but there is a cultural push towards teaching and agreeing on the eleven basic colour terms [KB96, Ch.11], and there is demonstrated effect of these basic categories on the ability to perform colour discrimination [WWF+07]. The maximum number of basic colour terms in any langague appears to be twelve. Russian, and a few other languages, distinguish light blue (Russian *goluboy*) from dark blue (Russian *siniy*) [Par05]. This paper considers the case of English though most other European languages use the same eleven categories, which is important to our discussion because Itten, in particular, was working in German.

Rather than conducting new perceptual experiments, we are able to make use of results from three previous studies [BK69] [RDD00] [RH72], which used colour chips evenly chosen from Munsell's colour space.

Ignoring the monochrome black, grey and white, there are eight basic colour terms in English. Roberson et al. [RDD00] experimented with an array of 160 coloured chips, evenly spaced within the Munsell colour system, asking English speaking subjects to categorise each chip into one of the eight colour categories.

Figure 5 shows the mean colour chosen by subjects for each colour chip. In addition, each colour region contains a small cross that marks the "best-example choice" for each of the eight colours, as described by Rosch [RH72]. Notice the difference in sizes of the different colour terms: orange (5.5 cells), yellow (6.5 cells) and brown (9 cells) each take up only a small part of the colour space compared with green (52.5 cells) and blue (36 cells). While I acknowledge that Munsell's colour space is non-uniform and is somewhat compressed in the yellow-red area and expanded in the blue-green area, that cannot explain the full magnitude of this difference. Over 50% of the chart is categorised as one of two terms blue and green; by contrast, red, orange and yellow between them take up just 14% of the chart (see also Hardin's comments on the relatively small sizes of the "warm" colours' regions compared with the relatively large

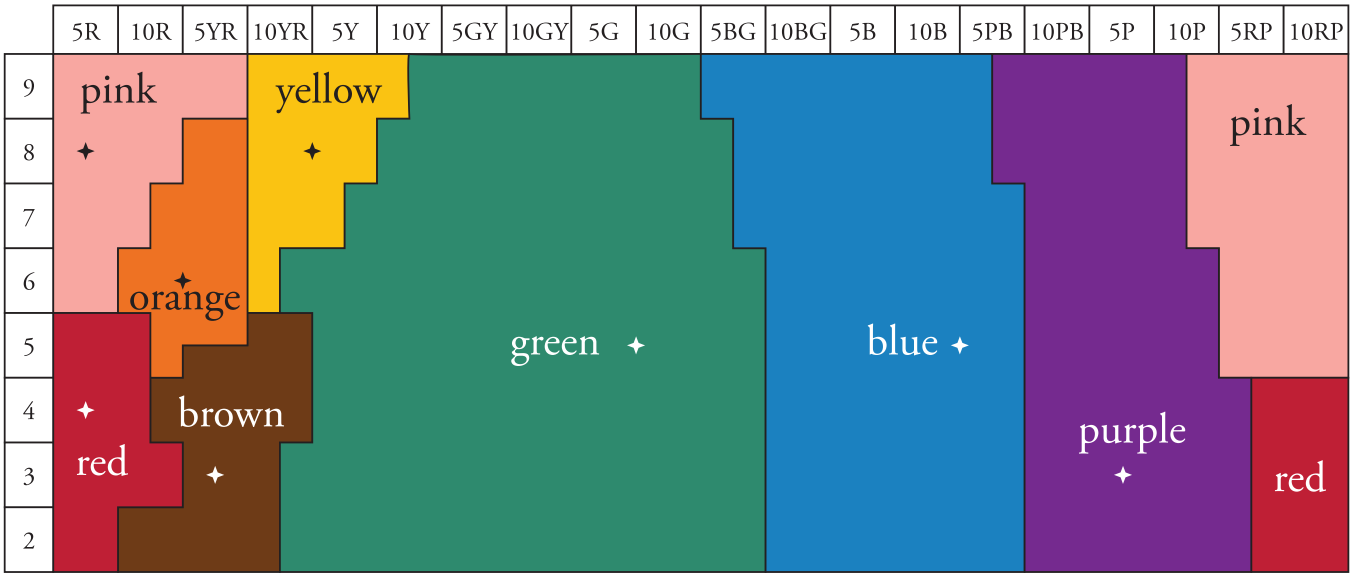

Fig. 5. Roberson, Davies and Davidoff's diagram of the eight basic colours in English (redrawn from [RDD00, Fig.1a]). The colour space is that of the Munsell colour system, which has five principal colours, red (R), yellow (Y), green (G), blue (B), purple (P), and their various combinations along the horizontal axis, with brightness on the vertical axis (2=dark, 9=light). See Figure 4 for an explanation of the notation. The experiments used a 160 chip Munsell array and the array shows, for each of the 160 cells, the mean colour chosen by English speakers for each colour chip. Some cells lie on the boundary, in which case the boundary passes through the centre of the cell. The small crosses mark the "best-example choices" for each of the eight colours, as described by Rosch [RH72]. The colour of each area matches that best-example choice, within the limits of the available gamut. The "best-example choices" are taken directly from Rosch's 1972 paper [RH72]; the locations of several of these "best examples" are placed incorrectly in Roberson et al's 2000 paper [RDD00, Fig.1a].

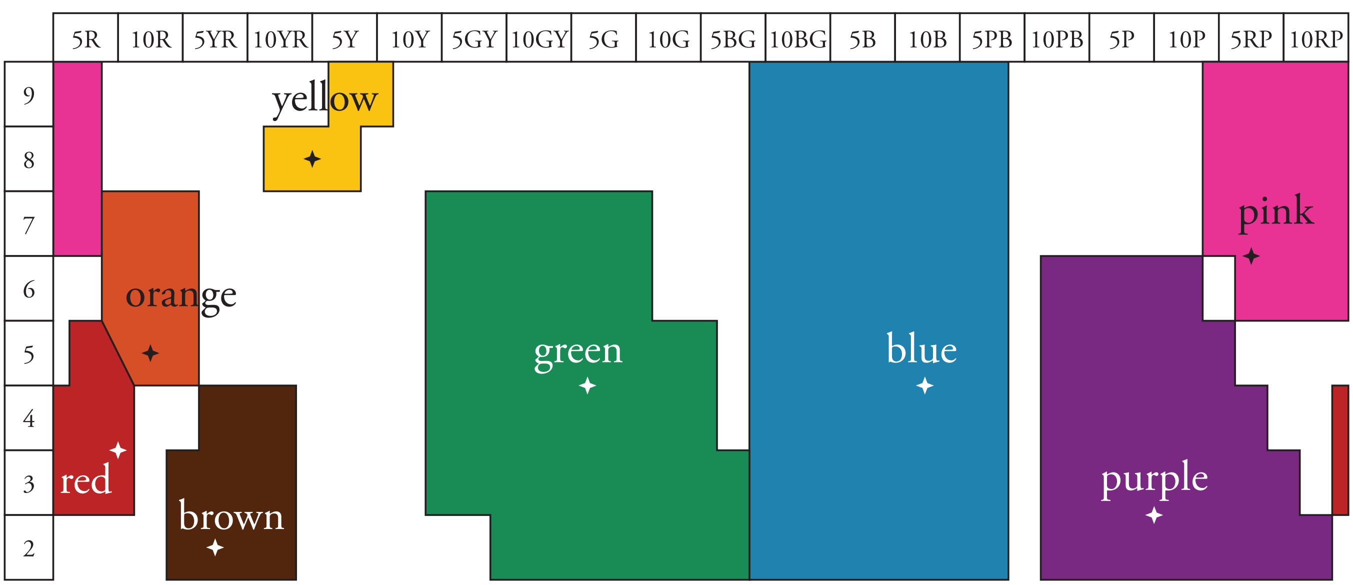

Fig. 6. Berlin and Kay's diagram of the eight basic colours in English (redrawn from [BK69, Appendix I, p.119]). As in Figure 5, the colour space is that of the Munsell colour system. See Figure 4 for an explanation of the notation. Berlin and Kay used a 320 chip Munsell array. They asked participants to determine, for each basic colour term, ***x***, (1) all those colour chips which they would, under any conditions, call ***x***, and (2) the best, most-typical examples of ***x***. The small crosses mark the locations of the "best, most-typical example" for each colour. The colour of each area matches that best most-typical example, within the limits of the available gamut. The white areas represent colour chips that were not given an unequivocal colour name.

sizes of the "cool" colours' regions [Har05]). Describing a colour as "red", "orange" or "yellow" will always give a colour close to the "best-example choice", that is, the colour will be close to what an average person would imagine it to be. By contrast, describing a colour as "green" or "blue" can give a colour that is a significant distance from the "best-example choice". Hardin discuses the consistency of such studies, noting that, across the many studies,"No matter how many basic color terms languages might have, their foci ["best-example choices"] tend to cluster reliably in relatively narrow regions of the [Munsell] array, whereas boundaries are drawn unreliably, with low consistency and consensus for any language." [Har98, p.208]. As evidence that there is consistency between observers, consider that the NCS colour system is predicated on there being good agreement between observers on what Berlin and Kay call the "best, most-typical example" of the four principal colours red, yellow, green and blue [HST96].

Berlin and Kay undertook a different experiment [BK69], using a 320 Munsell chip array, in which, for each basic colour term, they asked English speaking subjects to select all those chips that they would, under any conditions, categorise as being of that colour. Figure 6 shows the regions in which they got an unequivocal response from their subjects. One important result, for our investigation, from Berlin and Kay's work is that both cyan and indigo were *unequivocally* described as "blue" by their subjects.

Note that pink and brown do not appear on the standard colour wheel. Pink is a light variant of red. Brown is a dark variant of orange. The basic English colour terms along the visual spectrum are thus red, orange, yellow, green, blue and purple. Of these, orange is a relatively recent addition to the basic colour terms in English. Red (Old English *réod*), yellow (*geolu*), green (*grene*) and blue (*blaw*) are all ancient colour terms. Purple was brought into English, from the Latin, in the ninth century. Orange, by contrast, was adopted only in the early sixteenth century. Its first attested use as a colour name was in 1512. Prior to this it had been known as yellow-red (Old English *geoluréod*). It is unclear when orange became a basic colour term in English, but it is a possibility that Newton's description of the spectrum was an influence. Similarly, in German, *gelb*, *rot*, *blau*, and *grün* are ancient terms with words for orange and purple being more recent [Jon13].

4 The Colour Wheels

Figure 7 illustrates the principal colours of five colour wheels in common use. It is immediately obvious that they do not map linearly to one another. The colour that is diametrically opposite to blue ranges from yellow (Fig. 7(a),(c)) through orange (Fig. 7(b),(d)) to a red-orange (Fig. 7(e), but see also the Appendix). I briefly describe each of the five colour spaces, including the purposes for which it was designed and the principal colours it uses.

4.1 Opponent colour spaces, RYGB, Figure 7(a)

The opponent colour spaces are based on the perceptual opponent colours of Hering. The opponent principal colours, RYGB, are used in the CIELAB colour space [Ber81, p.67], which is designed to be a reasonably uniform space, perceptually (see Section 2), and in the Natural Colour System (NCS) [HST96] [Ber81, p.39] [Fai05, p.99] [NCS18] [Swe89] (Figure 3), which is designed for specifying colour in a similar manner to Munsell's colour system but, in the case of NCS, using the observer's in-built understanding of what is meant by a "pure" red, yellow, green, blue, black and white [NCS18]. Derefeldt notes that "The development of the NCS began by psychometric testing of Hering's conceptual framework having observers estimate qualitative colour attributes by assuming that observers could imagine six elementary colours by means of verbal definitions only. These imaginary colours, which constitute cognitive, natural reference points, were used as references in absolute judgments without any physical representation of the references. . . . The definitions of the six elementary colours. . . follow Hering's definitions of primary colours closely." [Der91, p.234].

Both CIELAB and NCS are used for specifying colour rather than purporting to represent colour mixing. Because CIELAB is non-linear, a linear mix in CIELAB space will not necessarily create the same colour as mixing matching pigments. Because NCS is entirely perceptual, there is, again, no guarantee that a linear mix of two NCS colours will match the mix of two pigments. The principal colours, RYGB, are four of Berlin and Kay basic colour terms.

4.2 Munsell colour system, RYGBP, Figure 7(b)

The five principal colours in this space are those used by Boyle in his seventeenth century colour experiments [Boy64, p.187] and are the original five colours of the rainbow specified by Newton. Munsell formalised this in the early twentieth century, using the ". . . guiding principal of equality of visual spacing" [Ber81, p.36]. The colour space was designed to aid in colour specification, originally for schoolchildren. The specific colours of the five principal hues were determined visually. Munsell's colour order system was extensively reworked ("renotated") in the 1940s by the Optical Society of America. This was a painstaking process of measuring the discriminability of the colors and adjusting the spacing of the colours to optimize them for use in science and industry [Mun76] [Mun18]. It should be made clear that Munsell's space is not a uniform colour space: small steps should be roughly equal visually but large steps cannot be compared. Berns implies that having five principal hues leads to greater visual equality between neighbouring hues than a system based on the four principal unique hues of red, green, yellow, and blue [Ber81], though Kaiser and Boynton suggest that there is evidence that the Munsell principal hues are not necessarily spaced evenly perceptually, in particular that P and PB are too far apart [KB96, p.494]. All five principal hues are Berlin and Kay basic colour terms.

4.3 Printer's colour wheel, RYGCBM, Figure 7(c)

This is the most pragmatic of the colour wheels, relating directly to how printing works. The colour space is explicitly designed for colour mixing. The three principal colours, cyan, magenta and yellow, are the *primaries* of subtractive colour mixing, as used in printing. Each primary

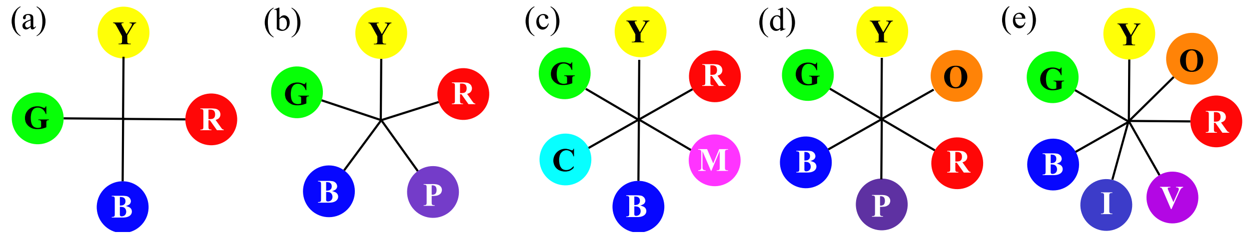

Fig. 7. Representations of the principal colours of five colour wheels, as they might be constructed by a student. All colours are represented by their initial letter: **R**ed, **O**range, **Y**ellow, **G**reen, **C**yan, **B**lue, **I**ndigo, **P**urple, **V**iolet, **M**agenta. All colour names are taken at face value. Left to right: (a) colour opponent theory, with four principal colours, **RYGB**; (b) Munsell's colour system with five principal colours, **RYGBP**; (c) the printer's colour wheel with the three subtractive primaries for colour printing CMY and their three secondaries RGB, **RYGCBM**; (d) the artist's colour wheel with the three painting primaries RYB and the three secondaries OGP, **ROYGBP**; (e) Newton's colour wheel, with the seven colours of the rainbow, **ROYGBIV**, notice that Newton's colours are not evenly spaced round the wheel (see Appendix).

is physically realised as a pigment that absorbs certain wavelengths of light. When two primaries are mixed or superimposed, the mixture absorbs the wavelengths that are absorbed by each pigment in proportion to the amounts of each primary mixed. The specific primaries chosen are pigments that, when mixed, allow production of a large gamut of colours. Good choices for primaries, that produce close to the largest gamut achievable with three pigments, are broadband yellow, broadband cyan, and broadband magenta (see Section 6). Mixing each pair of primaries produces the three secondaries, which are called red, green and blue, although these turn out to be rather imprecise descriptions (see Section 5.6). While four of these six colours are Berlin and Kay basic colour terms, it is important to our discussion that cyan and magenta are not. As a consequence, cyan and magenta are relatively precise terms, and each is well-localised in colour space compared to say, blue or green.

4.4 Artist's colour wheel, ROYGBP, Figure 7(d)

This is the wheel that Itten exemplified (Figure 1) [Itt70]. This colour wheel has been known for over two centuries, but Itten's work in the 1950s and '60s pushed it to preeminence. Prior to Itten, other colour wheels had been used in art teaching. For example, an opponent-colour system designed by Wilhelm Ostwald was used in British art education between the two world wars, in which the colour wheel had four principal colours, though Ostwald used a bluish-green opposite red [Bri07, Sec.7.3] rather than the pure green used by NCS and Hering. Itten, by contrast, designed his colour wheel on the foundations that there must be three primaries and that diametrically-opposite colours must mix to grey [Itt70, p.21]. Briggs comments on how pervasive Itten's influence has become: "Itten's book [*The Art of Colour* (1961)] has been so influential that it defines the limits of artistic colour theory for the majority of sources on the internet today. . . As a result of its half century of ascendancy, many artists today assume that traditional colour theory has dominated art education continuously since its origins, and assume modern colour theory is a very recent intrusion" [Bri07, Sec.11.3]. Itten himself developed the concepts of harmonious combinations of colour (Figure 2), which are specified by precise angular relationships around the colour wheel. The artist's colour wheel is used to help artists understand colour relationships and colour mixing. Red, yellow and blue are the primary colours (in which primary is used in the same sense as in the printer's colour wheel, Section 4.3), mixing to make the three secondaries: orange, green and purple. All six of the primary and secondary colours are Berlin and Kay basic colour terms (see Section 6 for a discussion of the implications of this).

4.5 Newton's rainbow, ROYGBIV, Figure 7(e)

This is the prototypical early colour wheel, from when evidence was beginning to be gathered about how coloured light and colour mixing worked. It is misguided in several respects (see the Appendix). Newton originally described the rainbow as having five colours, the same five that Munsell used two centuries later, but Newton quickly adopted two extra colours (orange and indigo) to make the seven colour rainbow that is taught in all English-language primary schools. His colour wheel is not evenly spaced and his use of the terms "blue" and "indigo" do not match their modern uses but this colour wheel has gained almost unstoppable traction in English education about colour, to the confusion of many students. Newton's rainbow has the same colours as the artist's colour wheel plus indigo.

5 Reconciling the Different Colour Wheels

Consider the structure of the various colour wheels as a student would view them. Figure 7(a)–(d) shows the result if you place the principal colours evenly spaced around the wheel, as they are in all diagrams in the student's text books (e.g., Figures 1, 3, 4). Table 1 tabulates the angle a student would measure between red and yellow and that between green and blue. The red-yellow angle varies from 60° (Figure 7(c)) to 120° (Figure 7(d)), while the green-blue angle varies from 120° (Figure 7(c)) to 60° (Figure 7(d)). In a non-metric space, these angles are, at best, approximate, but a student will still worry about why the angular distances around the wheels differ so markedly, especially if they have been trained to build the harmonious colour combinations of Figure 2, which explicitly require consideration of angle. They will also be concerned to understand why diametrically-opposite colour pairs differ between colour spaces.

5.1 What is meant by "opposite"?

Let us return to the question "what is the opposite of blue?". The discussion above has implicitly assumed that

TABLE 1
The first four colour wheels from Figure 7, showing the differences in angle between the pairs red-yellow and blue-green, and giving the opposite colours to red and blue.

Colour wheel	red-yellow	blue-green	opposite of red	opposite of blue
Opponent (RYGB)	90°	90°	green	yellow
Munsell (RYGBP)	72°	72°	blue-green	yellow-red
Printer's (RYGCBM)	60°	120°	cyan	yellow
Artist's (ROYGBP)	120°	60°	green	orange

the "opposite" of a given hue is the hue that is on the opposite side of a diameter through the centre of a colour wheel. There are at least three other useful definitions of opposite [Fry06] [Har06].

- *Additive complementaries*: two coloured lights that, when mixed, give white.
- *Subtractive complementaries*: two pigments that, when mixed together, produce a grey. In theory, opposites on the artist's and printer's colour wheels (Figure 7(c) and (d)) should do this.
- *Perceptual complementaries*: a colour's opposite is the colour perceived as an afterimage after fixating on the first colour for a significant period of time.

As Harkness shows [Har06], these each give slightly different opposites for any given colour. For example, fixating on Itten's red and then looking away will give a blue-green sensation rather than to the green of the artist's colour wheel [Bri07, Sec.11.3]. So the word "opposite" needs to be defined carefully in order to give a clear answer to our question. This means that we should not expect the Munsell or opponent-colour wheels to have the same colour diametrically opposite blue as do the printer's or artist's colour wheels, because the Munsell and opponent-colour colour spaces were not designed using criteria by which opposite colours necessarily represent complementary colours. Indeed, these colour spaces are non-linear spaces and therefore attempts to use them for accurate colour mixing will fail.

However, we would expect the printer's and artist's colour wheels to have the same diagonally-opposed colours, because they are both constructed by the same principle of subtractive complementarity. We find that they do not: the diagonal opposite of blue is yellow in the printer's colour wheel and orange in the artist's. As the definition of "opposite" is the same in these two wheels, we must consider the definition of "blue".

5.2 What is meant by "blue"?

When asked to imagine a blue, the average person will choose a colour close to the "best, most-typical example" at 10B/4.5. But when asked if a particular colour is "blue", the answer is "yes" for a range from cyan through to indigo (Figure 6). "Blue" can refer to any spectral colour from about 490nm (a greenish-blue, cyan) to 450nm (a purplish-blue, indigo). What we mean by "blue" changes the answers to questions about that colour. As Itten says, "unless our color names correspond to precise ideas, no useful discussion of color is possible" [Itt70, p.30].

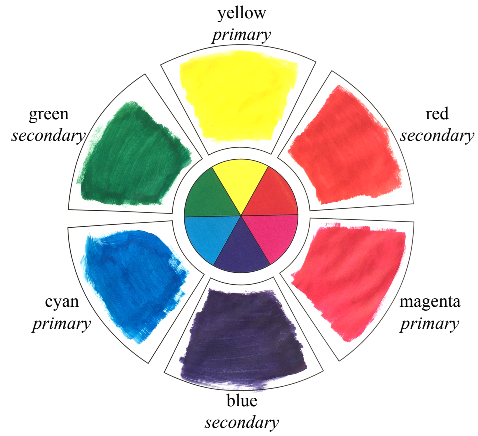

Fig. 8. Mixing real primary inks to produce the three secondaries. Inner ring: primary colour toners mixed on a colour laser printer [Fuji Xerox FX ApeosPort-IV C3375 v3018.103 PS]. Outer ring: primary fluid acrylic paints mixed with a paintbrush [paints from Golden Artist Colors, Inc: Primary Cyan (pigments PW6/PB15:4/Titanium White/Phthalo Blue(GS)), Primary Magenta (pigment PV19/Quinacridone), Primary Yellow (pigments PY3/PY73/PW6/Hansa Yellow Light/Hansa Yellow Medium/Titanium White)].

The answer to "what is the opposite of blue?" depends both on what you mean by "opposite" and on what you mean by "blue". Some of the differences in the "opposite of blue" column in Table 1 are owing to differences in the meaning of "opposite" and some are explained by the word "blue" refering to different hues in the different cases.

5.3 Imprecision in colour naming

More generally than blue, we find that the colour names are imprecise in several cases in our various colour wheels, where the actual principal colour used in the colour system does not match the "best most-typical" example of that colour name. If we consider the colours by how they actually appear, rather than by their basic colour names, we find that it is possible to reconcile a great deal of the apparent differences between the wheels.

Consider the colour wheels in light of the linguistic ambiguity inherent in the colour names and in terms of the true appearance of each colour. In Figure 7, we assumed, as a student might, that each colour represented the "best, most-typical example" of that colour, marked by the crosses in Figure 5. Figure 9 redraws those diagrams to reflect the *actual* colour that is represented by each of the general colour terms. We consider each wheel in turn.

5.4 Opponent systems (CIELAB and NCS), RYGB

In the standard CIELAB system (Figure 9(a)), yellow and blue match their best, most-typical examples, but red and green do not. CIELAB red is a purplish-red; CIELAB green is a cyanish-green [Har06].

By contrast, in the Natural Colour System (NCS), the four principal colours all do match their best, most-typical examples (Figure 9(f)) because NCS is defined explicitly in terms of the colours that an observer would consider to be "pure" red, yellow, green and blue [HST96, p.181] [NCS18].

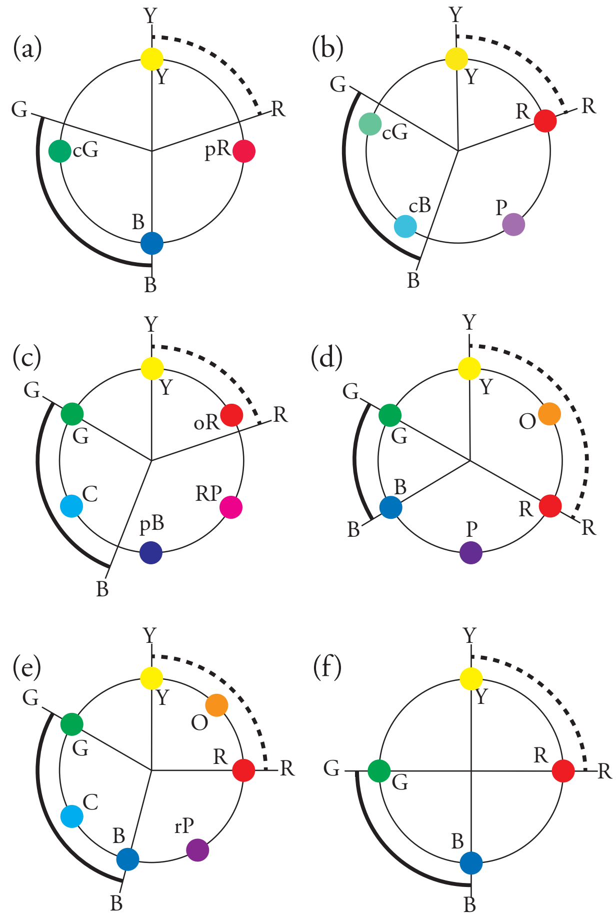

Fig. 9. The colour wheels of Figure 7(a)–(d) and Figure 11(b) redrawn to reflect the *actual* colour represented by each of the principal colour names. An uppercase letter represents the same colour as in Figure 7, a lowercase letter indicates a colour modifier, with "-ish" added to the end of the colour name; for example, **oR** is "orangish-red". Inside each wheel are labels for the actual colours represented by each coloured disc. Outside each wheel are the approximate locations of the best, most-typical examples of **R**ed, **Y**ellow, **G**reen, **B**lue. The thick arc indicates the green-blue angle. The thick dotted arc indicates the red-yellow angle. The six colour wheels are: (a) **CIELAB**, one variant of RYGB; (b) **Munsell**'s RYGBP; (c) the **printer's** colour wheel, RYGCBM; (d) the **artist's** colour wheel, ROYGBP; (e) **Newton**'s ROYGCBV where we have used the correct angles from Figure 10 and applied the colour corrections discussed in the Appendix; (f) **NCS**, a second variant of RYGB in which the colour names match their best, most-typical examples of that colour.

5.5 Munsell, RYGBP

Both the principal green and the principal blue have a cyanish cast to them (Figure 9(b)), so true green and true blue are closer to yellow and purple respectively.

5.6 Printer's, RYGCBM

To assess the printer's colour wheel (Figure 9(c)), consider the colours in Figure 8. This shows two different example sets of CMY inks mixed to make two sets of RGB secondaries. Note the consistency between the two sets of secondaries. Here "green" is close to the "best, most-typical" green, but "red" is an orangish-red, rather than the "best, most-typical example" of a red, and "blue" is far removed from "best most-typical", being a deep purplish-blue: an indigo. So, although these secondaries are informally called "red" and "blue", they are not sitting at the positions in colour space that the average observer would call the "best most-typical example" of those colour names.

5.7 Artist's, ROYGBP

Following Itten [Itt70], the artist's principal colours match their "best, most-typical" examples, by definition, because, in the absence of any other concept, the student will use their internal linguistic definition of the colour to ensure that their red is neither shading towards yellow nor shading towards blue, and likewise for all the other colours (see Section 6).

5.8 Discussion

Consider the six revised wheels of Figure 9. Here, I have indicated the actual hue of each of the principal colours and indicated an approximate location for the "best most-typical examples" of yellow, red, blue and green. In particular, compare the approximate locations of those four colours between the six wheels and compare the lengths of the arcs between red and yellow and between green and blue, though recall that CIELAB, Munsell, Newton and NCS are not metric spaces and so the angles subtended by these arcs give only an approximate indication of the actual distance between two colours.

We find that CIELAB (Figure 9(a)), Munsell (Figure 9(b)), and the printer's colour wheel (Figure 9(c)) are now all very similar. Our linguistic adjustments push all three of these colour spaces close enough to one another that we can see that they are describing much the same thing. Newton's ROYGCBV (Figure 9(e) and Appendix) is a little distorted, with a larger red-yellow angle than those three colour wheels, emphasising the role of orange, but this was an early attempt at a colour system so we can accept it as a rough approximation. We include it because of its continuing influence on children's education about colour. The NCS opponent colour system (Figure 9(f)) is distorted further, but it is designed for colour specification not for colour mixing and it is known to be perceptually uneven: there are more visually distinct hues between red and blue than between yellow and green [Fai05, p.100]. The outlier is the artist's colour wheel (Figure 9(d)) where the red-yellow section is clearly expanded and the blue-green section compressed compared with all the other wheels.

6 Why is the Artist's Wheel Different?

In theory, the artist's RYB and the printer's CMY colour wheels should be identical. Both purport to have primaries that cannot be made by mixing other colours. Both purport to be able to create all hues from the three primaries. Both purport to have diametrically-opposite colours that mix to make grey. However, the CMY colour wheel is demonstrably the correct way to do this, given that these are the colours used in the vast majority of commercial colour printing processes. The underlying theory is that each of the primaries *theoretically* absorbs exactly one third of the visual spectrum. Berns [Ber81, Ch.6], for example, suggests splitting the spectrum into thirds at 500 nm and 600 nm. A theoretical cyan ink absorbs all red and orange light. A theoretical magenta ink absorbs all yellow and green light. A theoretical yellow ink absorbs all blue and violet light. Combinations of these three primaries can produce any hue. In practice, the spectra of the three inks are not perfect squares [Ber81, pp.154–5] [Kip01, Figs.1.4-20,-22], so the range of colours achievable is not as broad as would be possible with perfect theoretical primaries, but we can manufacture inks of sufficient quality to satisfy the vast majority of our printing needs.

The dramatic difference between the theoretically-correct CMY colour wheel and the artist's RYB colour wheel can be explained by considering the mechanism by which the artist's colours are chosen. In Itten's seminal writing on the colour wheel [Itt70], he writes: "... a person with normal vision can identify a red that is neither bluish, nor yellowish; a yellow that is neither greenish, nor reddish; and a blue that is neither greenish, nor reddish... The primary colors must be defined with the greatest possible accuracy." There is no freedom here to allow red to be magenta, because magenta is a red that is distinctly bluish, nor is there freedom to allow blue to be cyan, because cyan is a blue that is distinctly greenish. I hypothesise that Itten is placing his three primaries at or near the "best, most-typical locations" in the Berlin-Kay sense. Itten then mixes his secondaries, which are all also Berlin-Kay basic colour terms. So while Itten says that his hues are "... evenly spaced with complementary colours diametrically opposite each other, " his even spacing is in a linguistic sense rather than a physical one.

Note also how Itten defines his red, yellow and blue. Red is "neither bluish, nor yellowish", defined relative to the other two primaries. But yellow and blue are "neither *greenish*, nor reddish" (emphasis mine), so Itten's three primaries are defined relative to the four principal colours of opponent-colour theory [Bri07, Sec.11.3]. The NCS colour system defines its principal colours in exactly the same way [HST96, p.181], but uses this defining mechanism to create four principal colours rather than the three primary colours of the artist's colour wheel (Figure 9(f) cf. 9(d)).

By having red and yellow as primaries in the artist's colour wheel, orange becomes a natural secondary and, because it is a basic colour term, it is possible to mix orange so that, to the artist's eye, it is neither too reddish or too yellowish, thereby occupying its "best most-typical" position in colour space. With blue in the third of the primary positions, it is obvious from the English Berlin and Kay chart (Figure 5) that the other two secondaries are going to be green and purple, if we wish them to also be basic colour terms. As with orange, it is possible to mix these, as Itten says we should, so that they are well-balanced and not leaning towards the colour on either side, which I hypothesise places them at the "best most-typical" positions.

The substantial difference between the artist's colour wheel and the other colour wheels would not be a problem if the artist's colour wheel, as designed by Itten, were not so pervasive in education about colour.

The challenge with creating the artist's colour wheel is that Itten had two aims that cannot be satisfied simultaneously: he wants his diametrically-opposed colours to be perfect subtractive complementaries [Itt70, p.20] and he wants his primary and secondary colours to be mixed "very carefully" so that, *perceptually*, they do not "lean towards" either colour on either side [Itt70, p.29]. The former is achieved correctly by the printer's colour wheel; the latter pushes the primary and secondary colours to their "best, most-typical locations" in perceived colour space. The fact that the printer's colour wheel and the artist's colour wheel are substantially different demonstrates that these two aims cannot both be satisfied in the same colour wheel[1].

The artist's RYB is thus an approximation to CMY, yet the artist's colour wheel remains by far the most popular colour wheel, outside the technical sphere. This, in spite of the fact that the printer's wheel is technically superior for mixing the widest possible range of colours. We must ask why it is that a colour wheel that appears technically inferior should be so tenaciously held. I hypothesise that the artist's colour wheel's success is owing to its use of the six basic colour terms that correspond to spectral colours: if you are teaching colour theory to children, you will gravitate towards using the colour names with which they are most familiar.

One of the challenges in teaching technical printing is to explain to the student the special role of magenta and cyan, and to describe what they are in terms of the basic colour terms ("reddish-pink" and "greenish-blue" respectively). For example, Gleeson, in her text on the illustration of picture books, identifies magenta with red and cyan with blue [Gle03, p.53], while Cianciolo, writing on the same topic, twice mentions the four process colours, naming them as red, yellow, blue and black [Cia76, pp.61,88]. This is not necessarily a misunderstanding on the author's part but a need to explain the technical concepts ("magenta" and "cyan") in language that is accessible to the general reader ("red" and "blue").

As a framework for teaching colour, RYB does admit the possibility of using colours other than the "best most-typical" and artists over the centuries have used a range of different reds, yellows, and blues as their primaries. However magenta is outside the red zone in the Berlin and Kay diagrams. I hypothesise that the untrained observer has a challenge with accepting magenta as a primary, because it is not intuitively satisfying. Though magenta is the correct colour for printing, it does not fall at one of the optimal points in Berlin and Kay's diagram, being somewhere between red, pink, and purple. Red is much more satisfying, being one of the key colours in Hering's theory of perception. Yellow, by contrast, is both a primary and an optimal point in linguistic colour space, so we have no trouble accepting it. Cyan is a blue but it is not the most typical blue.

There is a further gloss on the use of RYB. Despite it being taught to children as a way of "mixing colours", it would be extremely unusual for a professional artist to have just three colours on their palette. Rather, the artist's colour wheel is used as a framework within which to understand colour relationships. This is because it is not possible to achieve all colours by mixing just a red, yellow and blue; and because having a pure hue allows for consistency of colour not achievable in repeated mixings. For example, Matisse used a palette of 17 colours, van Gogh 9 colours, and

1. It is possible to create narrowband pigments for opposing colours in Itten's scheme, so that the opposing colours mix to grey, but broadband pigments for the primaries do not allow coverage of as large a gamut as CMY.

Fryer shows an example of his own work with a palette of 14 colours [Fry06, p.419]. And, while the colour harmonies of Figure 2 are widely taught, any professional artist or designer will use their own judgment of harmony rather than slavishly depend on this basic framework. Indeed, Itten himself says that different students find different combinations harmonious so that there cannot be a general principle that appeals to all [Itt70, p.23].

7 Conclusion

Some of the apparent difference between the colour wheels can be explained linguistically. The most obvious example is that we recognise that "blue" has a broad spectrum of meanings and that the "best, most-typical" blue is an imprecise approximation to the true colour represented by the word. In the printer's colour space, "blue" is an indigo, in Munsell's colour space it is tending to cyan, in the NCS and artist's colour spaces it is sitting at the "best most-typical" position, and in the traditional rainbow, ROYGBIV, it transpires that "blue" was originally used by Newton to mean "cyan". But all of these are described informally by the single term "blue". Likewise "red" and "green" are used in some colour spaces to refer to colours that are not the "best most-typical" example of the colour.

What can educators conclude from this? Using commonly-understood terms, like "opposite" or "blue", to also have a specific technical meaning leads to problems, unless one is careful to define those terms to have precise meaning. When educating students about colour, we need to be careful to be precise in what we mean when we use terms like "blue". In the printing industry, we already have this precision when talking about the CMY space, because cyan and magenta are not basic colour terms, so our students understand them to have precise meanings, and yellow is a precise term in common usage, because it occupies such a small part of the overall colour space (Figure 5). But terms like red, green, blue and purple all have imprecise meaning in English and we must be careful to ensure that we are defining them appropriately.

There is a remaining challenge, which is that the artist's colour wheel is at such odds with all of the other colour wheels and yet is the first colour system that most people will meet. I hypothesise that one reason for its tenacity is that it is a convenient approximation that allows educators to use six of the basic English colour terms in explaining how colour works.

Appendix
Newton's colour wheel

Newton's seven-colour rainbow is pervasive in English-language education but it is based on shaky foundations. Newton performed some of the earliest scientific work on understanding colour. He had access to some of the earliest optical components that were of good quality and demonstrated that a prism split white sunlight into a spectrum of colours. In Newton's earliest work on this, he names five colours of the spectrum: red, yellow, green, blue and violet [Sha94]. In his later work he augments this to seven colours adding orange (a relatively new word in English) and indigo (which was a recently discovered, imported dyestuff). The addition of these two colours appears to have been driven by his desire to get the spectrum to agree with the notes of the musical scale [New04, p.114]. Goethe critiques Newton for adding orange and indigo and criticises his musical analogy as an attempt to impose on the colours a mathematical order they do not in fact have [Rib85].

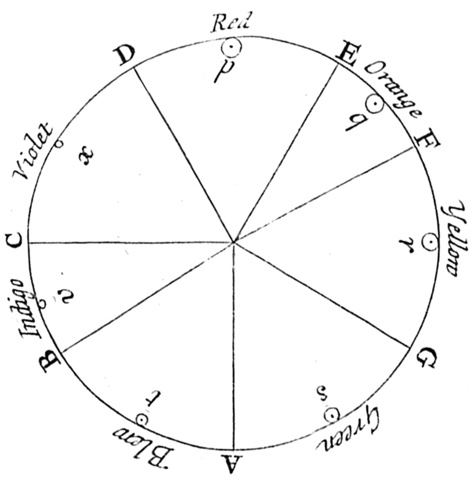

Fig. 10. Newton's colour wheel (adapted from [New04, Book I, Part II, Plate III, Fig. 11]). Notice that orange and indigo have segments of only $30°$ compared to the $60°$ allocated to the five other colours. The uppercase letters $A - G$ are intended to correspond to the notes of the musical scale, with orange and indigo corresponding to semi-tone intervals. The lowercase letters $p - x$ are at the centres of the seven colour arcs. Notice the blue (t) is directly opposite the boundary (E) between red and orange.

To get from a linear spectrum to a circular colour wheel "Newton also notes that purples could be created by combining light from the two ends of the spectrum. . . " [Wal02, p.193] so allowing us to join up the two ends into a circle [Sha94, p.620]. Looking at Newton's own drawings of his colour wheel (Figure 10), we see an oddity: in order to match the tones and semi-tones of a musical scale, Newton gives the new colours, orange and indigo, only half as much space on the wheel as the original five colours. If we take his colour wheel at face value, we see that the opposite of blue is the boundary between red and orange. This is significantly different from any of the modern understandings, where the opposite of blue lies between orange and yellow.

With regard to his use of the colour indigo, "a careful reading of Newton's work indicates that the color that he called indigo, we would normally call blue; his blue is then what we would name blue-green or cyan" [Wal02, p.193]. Finlay points out that, in the eighteenth century, indigo referred to a much wider range of colours than it does today [Fin07, p.340], generated by different concentrations of indigo dye. Taking into account both this information about the meanings of words and also the non-uniform spacing of colours means that a naïve version of Newton's colour wheel (Figure 11(a)) is incorrect and what he meant is much better represented by Figure 11(b), where we replace Newton's "blue" by "cyan" and his "indigo" by our modern "blue". We now find that the opposite of blue is orange-yellow.

How much easier would our explanation of the rainbow

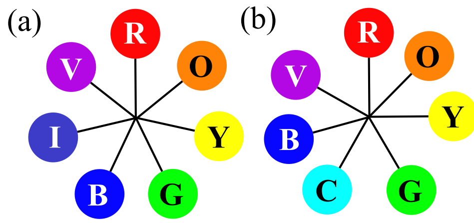

Fig. 11. Two representations of Newton's colour wheel. (a) The wheel as it would be generated from a naïve literal reading of the colour names and from equal spacing around the wheel. (b) The wheel when we take into account that Newton's "indigo" is a modern blue, his "blue" is cyan and his spacing around the wheel is non-uniform (Figure 10).

be if Newton had chosen to stick with his original five colours, or had chosen to introduce cyan as his seventh colour instead of indigo? We may even have been on the way to having a twelfth basic colour term adopted into English, as does Russian. Russian does have seven basic colour terms in its rainbow [Par05]. As it is, indigo is a constant source of confusion in teaching colour in English: children are taught that indigo is a fundamental colour in the rainbow, but most people do not distinguish it as a separate colour. The artist's colour wheel discards it without hesitation: the seven colour ROYGBIV becomes the six colour ROYGBP.

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