

#### Where is Colour Education Now?

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In several important ways colour education today presents not a *simplified* but a *fossilized* version of our current understanding of colour. To explain what I mean I must begin with a short sketch of the development of that understanding.

#### Colour Vision: Trichromacy, Cone Opponency and Hue Opponency (p. 6-8)

The idea that three primary colours, red, yellow and blue, are the ultimate components of all other colours became established progressively over the course of the 17th century. But how could these three primaries be reconciled with Newton's conclusion that the daylight spectrum consists of a contnuous series of rays appearing different colours? Where did that number three come from? One solution was to conclude that Newton was wrong and that the seemingly continuous spectrum is actually made up of physically distinct red, yellow and blue components that overlap to produce the intermediate hues green and orange. The suggestion that colour vision involves three types of visual receptor was first made by Mikhail Lomonosov and George Palmer in the 18<sup>th</sup> century based on this belief that light is physically trichromatic. By this view a mixture of yellow and blue paints appears green because it reflects only the yellow and blue components of light, which stimulate the yellow and blue receptors in the eye, just as they do when mixed to make the green of the spectrum. In this enviably simple view of colour, the primary colours of light-mixing, paint-mixing and human perception all coincide. This idea of a physically trichromatic spectrum predominated throughout the first half of the 19th century through the efforts of the formidable Scottish physicist Sir David Brewster, who convinced himself he could see the red, yellow and blue components of light by viewing the solar spectrum through coloured filters.

Hermann von Helmholtz elegantly and definitively showed that Brewster was mistaken in 1852, and later revived an alternative solution suggested by Thomas Young in 1801. Young had held that the receptor types are three in number, as the number of painters' primaries had previously suggested, but that the spectrum is physically continuous as Newton had believed, and the receptors each respond to a range of wavelengths about a central peak. Young and later Helmholtz postulated that the three receptors evoke red, green and violet fundamental senations respectively that combine to create compound colour sensations. For example, spectral blue is a mix of green and violet sensations, spectral yellow is a mix of red and green sensations, and white is a mix of red, green and violet sensations. Young and Helmholtz had envisioned the three receptors as having broad but well separated sensitivity peaks, but Konig's extensive studies of "colourblind" subjects showed correctly that the so-called red and green receptors overlap greatly and respond through most of the visible spectrum.

Important as this receptoral trichromacy is, there was still one vital piece of the puzzle missing. Ewald Hering disputed Helmholtz's view that yellow and white are compound sensations. Instead he proposed an *opponent* model in which all hue perceptions are combinations of red or green and yellow or blue *unique hues*. For each of these four hues we can imagine a pure version, for example, a yellow that is neither greenish nor reddish, a green that is neither yellowish nor bluish, and so on. Hue opponency is now written in to the standard definitions of the CIE *International Lighting Vocabulary* and is also the foundation of models outside the CIE, notably the Scandinavian *Natural Colour System (NCS)*. In turn the NCS-specified unique hues are employed in converting hue angle to a predicted hue perception (hue quadrature) in modern colour appearance models. Unfortunately most colour education outside the NCS system still fails to address this fundamental aspect of our current understanding of colour.

In the mid-20<sup>th</sup> century it was established that cone cells do not send signals directly to the brain, but rather their signals are compared with each other beginning in the retina in a process called *cone opponency*. It was intially thought that the L/M and S/LM cone opponent responses might correspond directly to the red/green and blue/yellow hue opponent perceptions, but it's now known that these do not align in this way. So at present, though it seems well established that the input to the visual system involves cone trichromacy and *cone* opponency, and that the perceptual output of the visual system involves *hue* opponency, the connection between the two remains uncertain. Together, cone trichromacy and cone opponency detect *variations in the balance of long-, middle- and short-wavelength components* of light across the visual field, and ultimately this information contributes to colour perceptions made up of red/green and blue/yellow hue-opponent components.

#### **Traditional Colour Theory (p. 9-13)**

The defining tenet of traditional colour theory is the idea that there are three primary colours, red, yellow and blue, that all other colours can be mixed from, but which can't be mixed from other colours. This tenet is a fossil of the scientific view of colour demolished by Helmholtz in the mid-19th century. Traditional colour theory still appears extensively in textbooks written for college/tertiary level courses in art and design, as well innumerable books and websites written for painters, designers and other colour users. Historically one of the most influential statements was Johannes Itten's *The Art of Color* (1961). A Google image search for "colour wheel" shows the prevalence of the primaries of "Brewster's theory" that Munsell railed against over a century ago.

The ultimate basis for the supposed unmixability of the traditional primaries is often misunderstood. Don't think for a moment that you can just whip out your modern cyan, magenta and yellow paints and triumphantly prove that red is not a primary colour by "making" red from magenta and yellow paint! The traditional colour theorist will explain to you that the magenta paint already *contains* red (you can see it!), but also contains purple, the complementary of yellow. By adding yellow you didn't *make* red, you merely neutralized the purple and revealed the pure red that was already there (!). Similarly you'll be informed that you didn't make blue by mixing cyan and magenta paint. You can see that the cyan paint already contains blue and green, and that the magenta paint contains red and purple, and of course purple contains red and

blue, so when you added magenta to cyan the red component of the magenta neutralized the green component of the cyan to reveal the pure blue already present in both paints.

Thus these unmixable traditional primary colours ultimately are not colours of paints as such, they are the pure colours that we see *in* the colours of paints. They are an expression of the *unique hues* of modern science, but with one major difference. Whereas the unique hues are thought to be the components of perceptions created by the visual system, the traditional primary colours are assumed to be properties residing and mixing in paints themselves. On this assumption they really are unmixable! We really can't mix a red paint without using paints that are already reddish, we can't mix a blue paint without using bluish paints, and we can't mix a yellow paint without using very yellowish paints.

But we *can* mix a green paint from paints that are not greenish, and that's why there are three traditional primaries and not four. From a scientific point of view we know that a paint we perceive as yellow reflects strongly the long- and middle-wavelength parts of the spectrum and a paint we perceive as blue reflects mainly the short wavelength half. Mixing these paints involves a subtractive process that leaves mostly the middle part of the spectrum, which we see as green. Thus when we mix paints it isn't their *hues* that are mixing. But what if we don't know about all this modern science, and instead subscribe to the fossilized belief that hues reside and mix in the paints themselves? If we can mix a yellow and a blue paint that do not contain green and yet produce a green mixture, it's clear from this perspective that the colour green is not primary, but must be *made of* yellow and blue.

Still, you might argue that although traditional colour theory is not scientifically correct, it's simple and it works in practice. Well, it sort-of works. By eliminating green and distributing the remaining three unique hues symmetrically, we end up with a hue scale that is very unevenly spaced perceptually, moving very rapidly from yellow to green, and very slowly from yellow to red. It also destroys the striking symmetry that an opponent hue scale displays about the yellow-blue axis. We can mix paints of all hues using just a middle red, a middle yellow and a middle blue paint, but the *gamut* (range) of colours we obtain is both disappointingly small and inexplicably misshapen. Why is it that we get high-chroma orange, medium-chroma greens and very low-chroma purples if all colours are made of red, yellow and blue? One way of defending the traditional primaries is to blame this odd and disappointing gamut on the impurity of available primary paints. But then why is it that very impure reds (magenta) and blues (cyan) can mix a larger and more even gamut?

#### The "Split Primary" Theory (p. 14-15)

An alternative approach to defending the traditional primaries argues that we wouldn't expect a middle red, middle blue and middle yellow paint to mix a full range of colours. According to this approach a perfect yellow paint would just reflect yellow wavelengths (which if you were paying attention a few slides ago you'll know isn't true!) and would have no wavelengths in common with a perfect red or blue paint. Colour mixing by this view depends on having primaries containing an impurity or "bias" of an adjacent secondary colour, so we need two paints for each primary, with an impurity or bias in each direction. The theory appears to account for why a palette of six such paints can mix a full range of colours, but can not explain how a CMY palette of a purplish red, a greenish blue and an orange yellow can mix anything! Although the *theory* is completely bogus, a split primary *palette* works well in practice, especially if we choose a magenta paint as our "cool" or purplish red, but largely because it contains cyan and magenta subtractive mixing primaries that with yellow are doing most of the work.

#### The YouTube Theory of Colour Vision (p. 16 -22)

When writing for a general audience, vision scientists often refer to the long-, middle- and short-wavelength cone classes (L, M and S) as red, green and blue cones respectively. While this simplification may seem harmless it unfortunately has been the starting point for a cascade of misunderstandings about human colour vision. To begin with it reinforces the common assumption that hues are properties residing in wavelengths of light, and then understandably leads to the assumption that the three cone types individually detect red, green and blue hues/wavelengths. Together these assumptions lead to the conclusion commonly encountered

in discussions of colour vision on social media that we "only really see three colours". In turn this conclusion has teamed up with the homunculus fallacy to spawn a model of colour vision in which the cone cells send hue signals directly to an observing brain. This model is a veritable fossil collection of outdated views about colour vision, but has achieved the status of orthodoxy on several online platforms.

By this view the spectral hues are "real colours" because they "exist" in the spectrum. When the brain receives a combination of cone signals that could be produced by a "real" colour it "thinks it sees" that colour. Thus the brain "thinks it sees" yellow while we look at a mixture of "red and green wavelengths" because it (somehow) knows that yellow "exists" in the spectrum between red and green. (It's unclear how it knows this since we supposedly can't see yellow "directly"). When our brain "thinks it sees yellow" in this way it is being "tricked" or "lied to"- this mixture of wavelengths is only "fake yellow" – based on the entirely unjustified assumption that the purpose of colour vision is to detect wavelengths of monochromatic light. When the brain receives a combination of "red cone" and "blue cone" signals, which could not be produced by a "real colour" (i.e. a single wavelength), it "makes up" a colour, magenta. Individual explanations add other misconceptions, like cone cells facing the wrong way or the idea that yellow objects reflect only "real yellow" wavelengths. The explanations make no mention of the important concept of hue opponency, and it's difficult to see how this concept could be grafted, without causing great confusion, onto an explanation that already invokes "red, green and blue" signals at the level of the cones.

#### Hue as a Way of Seeing Wavelength Balance (p. 23 - 24)

Hue is not a property of the external world that we "detect" either with red, yellow and blue or red, green and blue colour detectors. Hue is *the way in which we perceive wavelength bias* of lights and of the spectral reflectance of objects. Together, cone trichromacy and cone opponency constitute a device by which we can detect *variations in the relative balance of the long-, middle- and short-wavelength components of light* across the visual field. Not coincidentally, a computer screen is a device that generates light in which the proportions of the long-, middle- and short-wavelength components can be varied at will. Colour education should begin with a thorough exploration of colour as a perception, and a computer screen is a ready-made device for systematically exploring the attributes of perceived colour like hue in the classroom.

Now a computer screen is designed so that when the RGB levels are equal the screen emits light with the same balance of long-, middle- and short-wavelength components as daylight (a specific daylight balance called D65). If there is no long- or middle- or short-wavelength bias relative to daylight we perceive the screen area and the light emitted from it as lacking hue. The hue of a digital colour or of an isolated light is the way in which we perceive a direction of bias among its long-, middle- and short-wavelength components relative to daylight. Students can be led to question the usual presentation of screen colours in terms of "additive colour mixing" of red, green and blue. This seems to work for digital cyan, which looks to be a mix of green and blue, and digital magenta, which looks to be a mix of red and blue. But if we mix red and green in the right proportion we get a colour that looks to contain *neither* red *nor* green. This anomaly can then be explained using the concept of hue opponency. Digital colours can be considered both as light and object colours, so a computer screen can also be used to explore all of the remaining attributes of perceived colour.

#### The Munsell Framework: Hue, Lightness and Chroma (p. 25 - 30)

If anyone tells you that after a hundred years the time has come to retire the framework of hue, lightness and chroma you can tell them that they have no idea how useful the system can be for painters. (Admittedly though, there are still many *painters* who have no idea how useful the system can be for painters!) The prevalence of the hue-lightness- chroma framework over other systems is no doubt because of the primary importance of lightness for painters, both representationally and compositionally.

Traditional colour theory tends to treat the colour wheel and the lightness scale separately, or to integrate them only in a simplistic way as in the colour sphere of Johannes Itten, who ignored Munsell and resurrected 19<sup>th</sup> century conceptions. Spherical models do not represent lightness, as full colours of widely varying lightness are all placed on the equator, or chroma, as the colour scales must be greatly distorted to fit the

symmetrical model. There is a real need for an inexpensive physical model that actually illustrates lightness and chroma instead of this fossilized spherical concept. Fortunately, a suite of free programs by Zsolt Kovacs-Vajna, especially his *drop2color*, are unprecedented in providing painters with three-dimensional computer representations of colorant mixing paths in Munsell space.

The accompanying slides show various ways in which *drop2color* and other programs help the student to visualize characteristic paint-mixing paths in colour space. I like to picture paint mixing as throwing ropes between paints in the Munsell "tree" and ferrying mixtures along the ropes by varying the proportions of the components. For close paints the rope can be pulled straight, but to a good approximation the more distant the paints the more the rope will sag. (This is one reason why it's easier to neutralize a paint using a grey of the same value rather than the more distant complementary). In plan view notice the characteristic mixing patterns for paints close to the ideal subtractive (CMY) primaries (a pattern I liken to an extroverted octopus) and the contrasting pattern for paints close the ideal additive (RGB) primaries (the introverted octopus). These patterns are discussed further on my website www.huevaluechroma.com.

From a painter's point of view the one unfortunate aspect of the Munsell system is the hue scale, which designates as "Purple Blue" paints that we conventionally classify as middle blue and designates as "Blue" paints we generally call cyan. Similarly, "Red Blue" is the painter's magenta, and "Yellow Red" and "Green Yellow" are more awkward than orange and yellow green. A useful modern nomenclature of the Munsell hue scale has been used in a poster by X-Rite based on a proposal by Cal McCamy.

#### The New Anatomy of Colour: Brightness, Colourfulness, Saturation and Brilliance (p. 31 - 33)

The CIE International Lighting Vocabulary defines six attributes of perceived colour: hue, brightness, lightness, colourfulness, saturation and chroma. In addition to these a seventh attribute, brilliance (with its inverse, blackness), has long been used in various forms outside the CIE system, including the NCS System. A very pervasive "fossil" in colour education is the idea that colour has just three dimensions, and with it the idea that chroma, saturation and colourfulness are synonmyms. This may be largely because the CIE definitions were difficult to access until they were made available online a few years ago, and are difficult for the general public to understand without suitable illustrations and explanation.

To understand these terms, consider a stripe of red paint in light and shadow. We see the stripe as maintaining the same *intrinsic* colour – the same hue, lightness and chroma – in shadow and in light. Hue, lightness and chroma are sufficient to describe the colours of objects, including artists' paints.

Nevertheless, the stripe appears brighter and more colourful in the light than in the shadow. Whereas lightness and chroma describe the colour seen as *belonging* to the object, brightness and colourfulness describe the colour of the *light* coming from different areas of the object. In painting we represent variations in brightness and colourfulness by means of variations in the lightness and chroma of our paints.

Because the brightness and colourfulness of the stripe increase in step with each other as the illumination increases, the colourfulness relative to the brightness, called the *saturation*, remains the same. Equal saturation equates to *equal chroma relative to lightness*, so we would expect that the series of paints we would use to depict a variably illuminated object should maintain this relationship and thus radiate from the zero-value point on a Munsell hue page. (In practice these *shading series* are found to wander slightly and on average trend from a point about one Munsell value step below zero). Just as Albert Munsell crystallized the framework of hue, lightness and chroma, the dimensional framework of saturation and brilliance was crystallized (under various names) by another artist and art teacher, Arthur Pope. The framework of hue, saturation and brilliance is an excellent aid to painters in understanding and evoking effects of luminosity and illumination. These attributes of perceived colour and their relevance to painters are discussed in more detail in the pdf of my Munsell 2018 breakout session and poster presentation *Dimensions of Colour for Artists* and in my ISCC International Colour Day 2018 webinar *The New Anatomy of Colour*, a recording of which is available on the ISCC website.

## Colour vision: physical trichromacy



#### Colour vision: physical trichromacy



Sir David Brewster (1781 – 1868)

> Right: From Brewster, A Treatise on Optics (1831)

From this view of the constitution of the solar spectrum we may draw the following conclusions :----1. *Red, yellow,* and *blue* light exist at every point of the solar spectrum.

2. As a certain portion of *red*, *yellow*, and *blue*, constitute *white* light, the colour of every point of the spectrum may be considered as consisting of the predominating colour at any point mixed with white light. In the red space there is more red than is necessary to make white light with the small portions of yellow and blue which exist there; in the yellow space there is more yellow than is necessary to make white light with the red and blue; and in the part of the blue space which appears violet there is more red than yellow, and hence the excess of red forms a violet with the blue.

From Brewster, A Treatise on Optics (1831)





#### Colour vision: receptor trichromacy



Thomas Young (1773-1829)



James Clerk Maxwell (1831-1879)



Hermann von Helmholtz (1821-1894)



Arthur König (1856-1901)



Frequency (not wavelength)

#### Colour vision: hue opponency



1878 Zur Lehre vom Lichtsinne 1920 Grundzüge der Lehre vom Lichtsinn

#### Ewald Hering (1834 -1918)

It is obvious that all colors on the left-hand half of this circle are more or less clearly yellowish or ocher, all those on the right have more or less blueness in common, whereas all those in the upper half are greenish or of varying degrees of green and all colors in the lower half are reddish or red. Accordingly we can divide the color circle into a half that contains *yellow* and one that contains *blue*; or into a half that contains *red* and one that contains *green*.

Each quadrant of such a circle which consists of as many equally clear hues as possible is formed by the *intermediate hues* between two primary colors. Let us take any such intermediate color, for instance an orange, and try to make clear the similarities and differences between the hue of this orange and the adjacent hues on both sides. All hues of this small range are *similar* insofar as (1) they are all reddish, and (2) they are all yellowish, and in fact if we scan the colors in one direction redness increases and yellow decreases, whereas in the opposite direction yellow increases and red decreases. What distinguishes the individual hues in this range is *simply the relative clearness of redness and yellowness*.



Ewald Hering, Grundzüge der Lehre vom Lichtsinn (1920; tr. Outlines of a Theory of the Light Sense, 1964)

#### Colour vision: hue opponency

**Hue:** "attribute of a visual perception according to which an area appears to be similar to one of the colours: red, yellow, green, and blue, or to a combination of adjacent pairs of these colours considered in a closed ring" (CIE, 2011, 17-542).

**Unique hue**: "hue that cannot be further described by the use of hue names other than its own. Equivalent term: "unitary hue". NOTE There are 4 unique hues: red, green, yellow and blue forming 2 pairs of opponent hues: red and green, yellow and blue." (CIE, 2011, 17-1373).



Natural Colour System (NCS) hue circle

 Table 16.2 Data for conversion from hue angle to hue quadrature

	Red	Yellow	Green	Blue	Red
i	1	2	3	4	5
h	20.14	90.00	164.25	237.53	380.14
e.	0.8	0.7	1.0	1.2	0.8
Ĥ,	0	100	200	300	400

Hue quadrature in CIECAM02 (Fairchild, 2013)



#### Colour vision: cone opponency

#### The Three Primary Colors

The three spectrum colors yellow, red, and blue are equidistant from one another on the color wheel. To help you visualize and recall their positions, keep in mind that they can be connected by an imaginary equilateral triangle within the circle (Figure 3-2). These three colors are the basic building blocks of color for the artist; they are called "primaries" because you must have them to start with. You cannot make spectrum yellow, spectrum red, and spectrum blue by mixing any other pigments.

Betty Edwards, Color (2004)

Red, yellow, and blue are the three primaries of the color wheel.

Primary colors are *source* colors, and as such cannot be made through mixtures of other colors: There is no yellow or blue in red, no red or blue in yellow, and blue contains not a trace of either red or yellow.

Jim Krause, Color for Designers (2014)

### THE PIGMENT WHEEL

The mixing or **pigment wheel** is the basis for working with subtractive color; it imparts information about the reactions colors have when they are actually mixed (Figure 2.2). Its **primary colors** are red, yellow, and blue, which are used in combination to form the other hues. The term "primary" tells us that this is a color that cannot be obtained by mixing. When two primary colors are mixed together a **secondary color** (or intermediate color) is the result of the mixture. Yellow and blue mixed together results in green, red and yellow mixed together produces orange, and a mixture of red and blue results in violet (sometimes called purple). Thus the secondaries

Edith Anderson Feisner, Ronald Reed, Color Studies (3rd edn, 2013)

Traditional colour theory



#### Primary Colors

The three colors in the central equilateral triangle, red, blue, and yellow, are the primary colors. They are called "primary" because they cannot be made by mixing any other colors.

Jesse Day, Line Color Form The Language of Art and Design (2013)

The primary colors of pigment are red, yellow, and blue. These are considered primary because they cannot be mixed from any other color. In theory, all other colors can be made from the primaries, with black or white added.

Susan Crabtree, Peter Beudert Scenic Art for the Theatre History, Tools and Techniques (2012)

Primary colours in painting are simply the three colours that cannot be mixed from other colours, that is, red, blue and yellow.

Michelle Roberts, *The Color Book: Keeping it Simple* (Derivan, 2004)

**Primary colors** – red, yellow, blue. These colors cannot be created from any other color.

Tesia Blackburn, Acrylic Painting with Passion (2014)

**Primary colours** All colour originates from the primary colours – red, yellow and blue. These colours cannot be mixed from other colours.

Stan Smith, Oil Painting Workbook (2007)

**Primary Colors:** Red, yellow and blue In traditional color theory (used in paint and pigments), primary colors are the 3 pigment colors that cannot be mixed or formed by any combination of other colors. All

other colors are derived from these 3 hues.

https://www.colormatters.com/color-and-design

Primary Colors: Colors at their basic essence; those colors that cannot be created by mixing others.

http://www.worqx.com/colorcolor\_wheel.htm

Colour Mixing Tip 1. You Can't Mix Primary Colours When combining colours to obtain new hues, there are three basic colours that cannot be made by mixing other colours together. Known as primary colours, these are red, blue, and yellow.

> http://www.visual-arts-cork.com/ artist-paintscolour-mixing-tips.htm

By way of introduction to color design, let us develop the 12-hue color circle from the primaries – yellow, red and blue (Fig. 37). As we know, 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. In examining each color, it is important to view it against a neutralgray background.



About this triangle we circumscribe a circle, in which we inscribe a regular hexagon. In the isosceles triangles between adjacent sides of the hexagon, we place three mixed colors, each composed of two primaries. Thus we obtain the secondary colors:

> yellow + red = orange yellow + blue = green red + blue = violet

I can mix such a gray from black and white, or from two complementary colors and white, or from several colors provided they contain the three primary colors yellow, red and blue in suitable proportions. In particular, any pair of complementary colors contains all three primaries:

> red, green = red, (yellow and blue) blue, orange = blue, (yellow and red) yellow, violet = yellow, (red and blue)

Johannes Itten, The Art of Color (1961)



Selected images from a Google image search for "colour wheel".



## Traditional colour theory



Johannes Itten, The Art of Color (1961 [1973 edn])





# Traditional colour theory

Johannes Itten, The Art of Color (1961 [1973 edn])





Johannes Itten, The Art of Color (1961 [1973 edn])



Paint-mixing paths of *Golden Heavy Body Acrylics* calculated using *drop2color* by Zsolt Kovacs-Vajna



### Traditional colour theory



## The "split primary" theory



Colour mixing theory from Michael Wilcox's *Blue and Yellow Don't Make Green* (1987).

When we mix a blue and a yellow we tend to think that we have made a 'new' color; green. In much the same way as we make dough when flour and water are mixed. This is not the case at all.



If we were to evenly mix a 'pure' blue and a 'pure' yellow we would get black (1 above). This is because blue and yellow actually 'absorb' or 'destroy' each others reflected light. We cannot carry out this experiment because we do not have pure blue and pure yellow to work with. In fact, we have never seen a *pure* blue or a *pure* yellow in pigment form.



What we do have to work with are 'impure' blues and yellows. We can describe them this way because they contain a certain 'amount' of green as well as either blue or yellow. If we now mix a blue containing green with a yellow which also contains green (2. above), it does not matter that the blue and yellow, as such, will disappear, because we are left with the two 'amounts; of green that they contained. This, basically is what happens every time that we mix a blue and yellow together.

## The "split primary" theory



## The "split primary" theory



Colour mixing theory from Michael Wilcox's *Blue and Yellow Don't Make Green (1987)*.



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Colour mixing theory from Michael Wilcox's Blue and Yellow Don't Make Green (1987).





01:45 There three kinds of cone cells that roughly correspond to the colors red, green, and blue.

01:51 When you see a color, each cone sends its own distinct signal to your brain.

01:56 For example, suppose that yellow light, that is real yellow light, with a yellow frequency, is shining on your eye.

02:03 You don't have a cone specifically for detecting yellow, but yellow is kind of close to green and also kind of close to red, so both the red and green cones get activated, and each sends a signal to your brain saying so.

02:16 Of course, there is another way to activate the red cones and the green cones simultaneously: if both red light and green light are present at the same time.

02:24 The point is, your brain receives the same signal, regardless of whether you see light that has the yellow frequency or light that is a mixture of the green and red frequencies.

https://www.youtube.com/watch?v=l8\_fZPHasdo

### The YouTube theory of colour vision



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02:59 There are infinitely many different physical colors, but, because we only have three kinds of cones, the brain can be tricked into thnking it's seeing any color by carefully adding together the right combination of just three colors: red, green, and blue.

### The YouTube theory of colour vision



01:48 So it's not like a photon comes in, and you know, it's 200 nanometers or whatever, and it detects that.

01:53 Instead, you have these cone cells at the back of your eyes that are sensitive to different parts of the spectrum.

O2:01 So when red light comes into your eyes, there's a set of cones that fire and tell your brain you're looking at something red. O2:07 So we'd call those the red cones.

02:10 There's another set of cones that are more sensitive to green, so when there's green light going into your eyes, they fire and they send a message to your brain.

02:16 And there's blue cones, as well.

02:18 So you've got red cones, green cones, and blue cones.

https://www.youtube.com/watch?v=iPPYGJjKVco



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#### (Ri) The Royal Institution @ Published on Feb 13, 201

Why doesn't magenta appear in the rainbow? The answer lies not in physics but in biology.

SURSCOIRE 204

Science presenter Steve Mould demonstrates the strange phenomenon of colour mixing, in which not everything is as it seems. The cone cells within our eyes are responsible for the colours we see, but are only sensitive to Red, Green and Blue light. So how are we able to see so many colours when we can only directly detect three and how do our brains see the colour magenta which doesn't have a wavelength? 02:21 So what about yellow?

02:22 What about when you're looking at yellow light, like that?

02:26 Well in that situation, you don't have a yellow cone.

02:30 So what do you do?

02:31 Well, yellow is quite close to red, so your red cone fires a bit.

02:36 And yellow is quite close to green as well, so your green cone fires a bit.

02:39 So your brain is getting a message from your red cone and your green cone at the same time, and it's deciding, OK well, I must be looking at something in between those two colours, then.

02:49 And that's brilliant, because your brain is perceiving something about the world that it isn't able to measure directly.

02:55 It isn't directly sensitive to yellow light.

### The YouTube theory of colour vision



#### Colour Mixing: The Mystery of Magenta

The Royal Institution ♥ 1M views • 5 years ago CC 03:36 So what about purple?

03:37 What about magenta?

o3:39 Well, what should your brain do if your red cone fires at one end of the spectrum and your blue cone fires at the other end of the spectrum, but your green cone doesn't fire?

03:51 Does it do the same trick? 03:52 Does is think I must be looking at

colour in between red and blue?

03:57 When the colour between red and blue is green, and you're definitely not looking at something green, because your green cone isn't firing.

04:03 So in that situation, your brain invents a colour.

04:06 It makes up a colour, and that colour, is magenta.



1:51 On your retina, you have light sensitive cells called cones that perceive color, red light, green light, and blue light cones...

2:06 .... which means that there is no cone for orange light or yellow light.

2:11 But the crazy thing is that these three cones work together to allow you to see the rest of the colors.

https://www.youtube.com/watch?v=uNOKWoDtbSk

## The YouTube theory of colour vision



2:16 It works like this.

2:18 If I shine the yellow light on your eyes,
2:19 your red cones actually respond a little bit and your green cones respond a little bit, too.
2:24 Then your brain combines those red and green responses to say that's yellow.
2:28 Now, if instead of yellow light, I shine a little red light and a little green light on your eyes, the red cones respond and the green cones respond, and your brain says, red and green, well, that makes yellow-- even if there is no yellow light there.



2:42 This is how your LCD screen tricks you into seeing yellow. It's doing that right now.
2:47 All you're seeing with your eyes is red and green, but your brain is seeing yellow,

### The YouTube theory of colour vision



0:16 This lemon looks yellow to me, and it probably looks yellow to you as well, but not in the same way.

0:23 You see, here in this room, this lemon is "Subtractively Yellow."

0:31 It absorbs all visible wavelengths of light except for yellow light, which it reflects onto my retina.

https://www.youtube.com/watch?v=R3unPcJDbCc



0:37 But the screen that you are using to watch this video doesn't produce yellow light at all.

0:43 In fact, it can only produce red, blue, or green light.

0:50 The really cool, but kind of disturbing thing about this is that here in the room, I am actually seeing "real" yellow light.

0:55 But you are seeing "fake" yellow. Absolutely no yellow is coming off your screen and falling onto your retina.

1:02 But it still looks yellow because it's quite easy to lie to the brain.

### The YouTube theory of colour vision



1:09 Our retinas contain three different types of cone cells that are receptive to color and each one is best suited to detect a certain color.

1:20 One is great for blue, the other is great for green and the third is great for red.1:25 Notice that there is no individual cell

looking for yellow.

1:32 So, the way we actually see yellow happens like this. The wavelength of yellow light falls between the wavelengths of red and green.

1:38 And, so, when an object reflects yellow light onto your retina, both the green and the red cones are slightly activated, which your brain notices and says "well, that's what happens when something's yellow, so it must be yellow."



1:50 All a computer monitor or a mobile phone screen has to do to make you think you're seeing yellow is send a little bit of red and a little bit of green light at you.
1:59 As long as the pixels and the little subpixels on them are small enough that you can't distinguish them individually, your brain will just say "well, I'm recieving some red and some green, that's what yellow things do...hmm...it must be yellow." Even though it actually is not...

## The YouTube theory of colour vision

- 1. Colours exist in the spectrum as different wavelengths (white light "contains" all the colours of the spectrum).
- 2. Our three types of cone cells *detect red*, *green and blue wavelengths* respectively. Thus *we only really see these three colours*.
- 3. The red, green and blue cone cells send signals *direct to the brain*. All colour perceptions are based on combinations of these red, green and blue signals.
- 4. When the brain receives a combination of signals that could be produced by a "real" colour in the spectrum it *"thinks it sees*" that colour.
- 5. Because the purpose of colour vision is to *detect the wavelength of monochromatic light*, when we "think we see" yellow when looking at a "mixture of red and green wavelengths" we are "*being fooled*".
- 6. When the brain receives a combination of red and blue signals that could not be produced by a "real" colour (that is, one that "exists" in the spectrum) it *"makes up*" a colour, magenta.

## Hue as a way of seeing wavelength balance



Cone trichromacy



Cone opponency





## Hues of light

If there is no long- or middle- or shortwavelength bias relative to daylight we perceive the screen area and the light emitted from it as **lacking** hue.

The hue of a digital colour or of an isolated light is the way in which we perceive a direction of bias among its long-, middle- and short-wavelength components relative to daylight.



# Hues of light

If there is no long- or middle- or shortwavelength bias relative to daylight we perceive the screen area and the light emitted from it as **lacking** hue.

The hue of a digital colour or of an isolated light is the way in which we perceive a direction of bias among its long-, middle- and short-wavelength components relative to daylight.



## Hues of objects

If there is no bias among the long-, middle- and short-wavelength components of the spectral reflectance of an object, we perceive that object as **lacking** hue.

The hue of an object is the way in which we perceive a direction of bias among the long-, middle- and short-wavelength components of the object's **spectral reflectance**.



Sunlight Sweet (Streeton, 1890)



Lightness information



Hue and chroma information

# Hue, lightness and chroma





**Colour Mixing Tools** Zsolt M. Kovacs-Vajna Department of Information Engineering University of Brescia

http://zsolt-kovacs.unibs.it/colormixingtools



Hue, lightness and chroma

color2drop

The Color Tree

Illustration from Cleland, 1921

Paint-mixing paths calculated using *drop2color* by Zsolt Kovacs-Vajna



Paint-mixing paths and spectral plots calculated using drop2color by Zsolt Kovacs-Vajna

#### Hue, lightness and chroma



Hue shifts from adding Titanium White, using drop2color by Zsolt Kovacs-Vajna



Paint-mixing paths calculated using drop2color by Zsolt Kovacs-Vajna

## Hue, lightness and chroma



Paint-mixing paths calculated using drop2color by Zsolt Kovacs-Vajna







## Hue, lightness and chroma



#### The new anatomy of colour

- Hue (CIE 2011 17-542)
- Brightness (CIE, 2011, 17-111)
- Lightness (CIE 2011, 17-680) (= [greyscale] value, tone)
- Colourfulness (CIE, 2011, 17-233)
- Saturation (CIE, 2011, 17-1136)
- Chroma (CIE 2011, 17-139)
- Brilliance (inverse of *blackness* of NCS and other systems)

#### CIE International Commission on Illumination Commission Internationale de l'Eclairage Internationale Beleuchtungskommission

CIE (Commission Internationale de L'Eclairage/ International Commission on Illumination), 2011. *International Lighting Vocabulary*. CIE S 017/E:2011. Searchable online at <a href="http://eilv.cie.co.at/">http://eilv.cie.co.at/</a>



## The new anatomy of colour

**Chroma**: "colourfulness of an area judged as a proportion of the brightness of a similarly illuminated area that appears white or highly transmitting" (CIE, 2011, 17-139).

**Colourfulness:** "attribute of a visual perception according to which the perceived colour of an area appears to be more or less chromatic" (CIE, 2011, 17-233).

**Saturation**: "colourfulness of an area judged in proportion to its brightness" (CIE, 2011, 17-1136).

### The new anatomy of colour



Equal saturation equates to equal chroma relative to lightness.



## The new anatomy of colour

#### The new anatomy of colour



*Hue, lightness* and *chroma* are the attributes of colour most familiar to painters, and are sufficient to describe the colours of objects including paints. *Hue, brightness* and *colourfulness* describe the *light* we see coming from objects and evoke by means of the hue, lightness and chroma of our paints. The framework of *hue, saturation* and *brilliance* is an aid to understanding and evoking effects of luminosity and illumination.

## Thank you!



David Briggs, plein air studies, all 9" by 5", oil on board