handprint : color temperature

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color temperature

Blue mountains are distant from us, and so cool colors seem to recede.

J.W. von Goethe

The concept of color temperature or *warm and cool colors* is important to artists yet often poorly understood. This page provides an in depth review of the topic.

Goethe (http://www.handprint.com/HP/WCL/book3.html#goethe) provides the headnote because it was his observation in the *Farbenlehre,* which struck me as ridiculous when I first read it a decade ago, that launched me on my study of color and, by an arduous path, led to the page you are reading now.

I begin with the conventional wisdom about the attributes of , then explain why the effects ascribed to warm colors are not caused by their hue or by optical problems with our eyes but by their typically higher in comparison to other surface colors.

The earliest artistic applications warm and cool appear in the modeling of light in Baroque landscape painting. I argue that the perceptual lies in the mechanism our color vision uses to adapt to changes in the color of natural illumination due to weather and time of day effects that are most obvious in landscape observation.

I develop a definition of , define the warm/cool contrast using , and finally show how these criteria are related to different hues around the hue circle. Finally, I show how the phenomenon of , warm colors that appear only through luminance contrasts, arise because of the limited span of .

These elements of the warm/cool contrast can be summarized as guidelines for , which depend primarily on whether the painting style is landscape or not, and representational or not. Each situation should use warm/cool color contrasts in a different way.

warm vs. cool colors

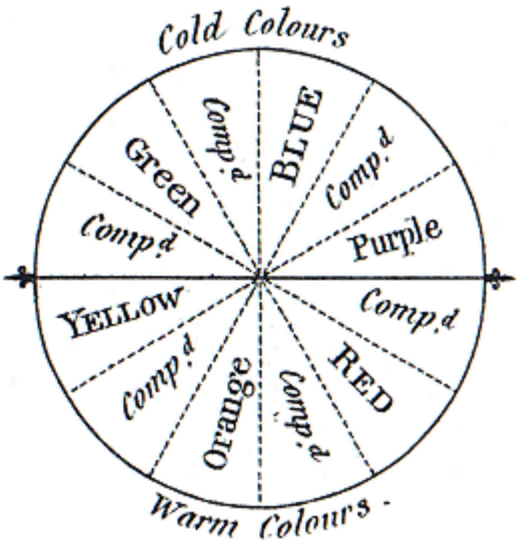
Let's begin at the beginning. The concept of a **warm/cool color contrast** seems to have entered the artistic vocabulary during the 18th century. The earliest attestation in the *Oxford English Dictionary* (1890) for an artistic usage of *warm The canvas glow'd, beyond e'en Nature warm* is from a poem by Oliver Goldsmith dated 1764. *Cold* (the original contrast adjective for *warm*) appears earlier, in an English translation of *Cours de peinture par principes* (1708) by the French art historian Roger de Piles.

Warm and *cold* were, with *dry* and *moist,* terms used from the Middle Ages through the 18th century to describe a variety of animal and physical qualities. *Warm* described animation, exertion, ardent feeling or a complexion glowing with fever; *cold* described a lack of enthusiasm, sociability, life force or energy. There was a long tradition of metaphorical "warmth" from which the artistic usage grew.

color theory

(http://www.handprint.com/HP/WCL/wcolor.html)

Although the warm/cool contrast was familiar to artists since at least the early 18th century, it was to my knowledge first presented within a color wheel by the English artist Charles Hayter, in his *Introduction to Perspective* (1813). This shows that pairs of colors opposite each other on the hue circle are complementary colors (http://www.handprint.com/HP/WCL/color16.html#complement), and that the warm/cool contrast is a "metacomplementary" relationship "the mother of all complementaries" between warm hues (from yellow to red violet) as a group and the cool hues (from yellow green to purple) as a group.



the first warm/cool color wheel diagram

from Hayter, 1813 (sky blue is placed at top, because in Hayter's time it was defined as the "purest" or most fundamental color; note the 19th century contrast with *cold* rather than *cool*)

Whenever you see a tidy geometrical icon in color theory writings, you can be sure that it represents something well cooked but only half baked! Despite the assurance and certainty expressed by Hayter's diagram, there are **four**

questions that the traditional warm/cool usage has not clearly answered:

1. What are the warm (warmest) or cool (coolest) hues?

2. Is every hue in the color wheel either warm or cool, or are some hues excluded as neither warm nor cool?

3. What explains the visual or design effects created by warm or cool colors?

4. Why is the warm/cool contrast fundamental to our visual response to color and to the manipulation of colors in painting?

The rest of this page tackles these questions one by one.

What Are the Warmest (Coolest) Hues? As Hayter's diagram indicates, the most common choice for the **warmest hue is usually an orange or red orange** with a CIELAB hue angle (http://www.handprint.com/HP/WCL/labwheel.html) around 40 to 45. This includes red orange paints (http://www.handprint.com/HP/WCL/palette1.html#redorange) such as perinone orange (PO43 (http://www.handprint.com/HP/WCL/watero.html#PO43)) or pyrrole orange (PO73 (http://www.handprint.com/HP/WCL/watero.html#PO73)), or slightly darker orange red paints (http://www.handprint.com/HP/WCL/palette1.html#orangered) such as naphthol scarlet (PR188 (http://www.handprint.com/HP/WCL/waterr.html#PR188)), pyrrole scarlet (PR255 (http://www.handprint.com/HP/WCL/waterr.html#PR255)), cadmium scarlet (PR108 (http://www.handprint.com/HP/WCL/waterr.html#PR108)). The principal criterion here is that these scarlets are among the most intense pigments available. However burnt sienna (PBr7 (http://www.handprint.com/HP/WCL/watere.html#BS)) is the best choice for a dull red orange among earth orange paints (http://www.handprint.com/HP/WCL/palette1.html#earthorange).

The choice of a red or deep red paint (http://www.handprint.com/HP/WCL/palette1.html#red), such as cadmium red (PR108 (http://www.handprint.com/HP/WCL/waterr.html#PR108)) or naphthol red (PR170 (http://www.handprint.com/HP/WCL/waterr.html#PR170)) is not preferred because these reds are dark valued and contain almost no yellow.

Some artists prefer orange paints (http://www.handprint.com/HP/WCL/palette1.html#orange) such as cadmium orange (PO20 (http://www.handprint.com/HP/WCL/watero.html#PO20)) or benzimida orange (PO62 (http://www.handprint.com/HP/WCL/watero.html#PO62)) with a CIELAB hue angle around 50 to 55. Orange hues are lighter valued, very intense and balanced between yellow and red.

The coolest color is whatever provides the complementary contrast to the warmest hue already selected colors opposite red orange or orange in a visual hue circle, as found in the Munsell Color System (http://www.handprint.com/HP/WCL/vismixmap.html#MUNSELL) or in CIECAM (http://www.handprint.com/HP/WCL/vismixmap.html#CIECAM). These indicate that the **coolest hue is a blue or green blue** with a CIELAB hue angle around 220 to 235. There are few pigments in this region of the color wheel, but they include manganese blue (PB33 (http://www.handprint.com/HP/WCL/waterb.html#PB33)), phthalocyanine cyan (PB17 (http://www.handprint.com/HP/WCL/waterb.html#PB17)) and cerulean blue (green shade, PB35 (http://www.handprint.com/HP/WCL/waterb.html#PB35)). Pigments on the fringes include phthalocyanine blue (green shade, PB15 (http://www.handprint.com/HP/WCL/waterb.html#PB15)) and cobalt teal blue (PG50 (http://www.handprint.com/HP/WCL/waterg.html#PG50)).

The suitable choice of any of these pigments defines a **red orange/green blue** or an **orange/blue** contrast as the axis of the warm/cool effects.

TRADITIONAL

warmest
pyrrole orange
naphthol scarlet

coolest
manganese blue
cobalt teal blue

But artistic practice has not been unanimous. An important and fairly common alternative is to choose **yellow as the warmest hue**. This usually means choosing an intense orange yellow paint (http://www.handprint.com/HP/WCL/palette1.html#orangeyellow), such as hansa yellow deep (PY65 (http://www.handprint.com/HP/WCL/watery.html#PY65)), nickel dioxine yellow (PY153 (http://www.handprint.com/HP/WCL/watery.html#PY153)) or nickel azomethine yellow (PY150 (http://www.handprint.com/HP/WCL/watery.html#PY150)), a dull earth yellow paint (http://www.handprint.com/HP/WCL/palette1.html#earthyellow) such as yellow ochre, gold ochre or raw sienna (PY43 (http://www.handprint.com/HP/WCL/watere.html#PY43)), or an intense yellow paint (http://www.handprint.com/HP/WCL/palette1.html#yellow) such as hansa yellow (PY97 (http://www.handprint.com/HP/WCL/watery.html#PY97)) or cadmium yellow (PY35 (http://www.handprint.com/HP/WCL/watery.html#PY35)) as the warmest pigment. Then a violet blue paint (http://www.handprint.com/HP/WCL/palette1.html#violetblue) (ultramarine blue, PB29 (http://www.handprint.com/HP/WCL/waterb.html#PB29)) or a blue paint (http://www.handprint.com/HP/WCL/palette1.html#blue) (cobalt blue, PB28 (http://www.handprint.com/HP/WCL/waterb.html#PB28) or iron blue, PB27 (http://www.handprint.com/HP/WCL/waterb.html#PB27)) are usually effective as the cool complement. These choices define a **yellow/blue contrast** as an alternative axis of warm/cool effects. It makes all hues containing yellow (from orange red through yellow green) warm colors, and all hues containing blue (from blue violet through blue green) cool colors.

This warm/cool choice is a proxy for the long and short wavelength analysis optimal colors (http://www.handprint.com/HP/WCL/color19.html#sixcolors) identified in my synthesis of surface colors (http://www.handprint.com/HP/WCL/color19.html). Optimal orange (http://www.handprint.com/HP/WCL/color19.html#yellowcyancircuits) is the color produced by the sum of all long wavelength light (above 570 nm), and is closely matched by nickel dioxine yellow (PY153 (http://www.handprint.com/HP/WCL/watery.html#PY153)) or isoindolinone yellow (PY110 (http://www.handprint.com/HP/WCL/watery.html#PY110)). Optimal blue (http://www.handprint.com/HP/WCL/color19.html#sixcolors) is the color produced by the sum of all short wavelength light (below 485 nm), and it is closely matched by ultramarine blue (PB29 (http://www.handprint.com/HP/WCL/waterb.html#PB29)).

This approach is especially suitable when the artist intends to use **yellow as the symbol of light**. This matches our experience of color variations in three ways. First, the hue contrast is aligned with the largest value contrast the lightest saturated hues are yellow, and the darkest hues are blue violet. Second, as , the major visual axis that captures chromaticity variations in natural light (landscape light) extends from yellow to blue. Third, most colors shift toward yellow as the luminance on or through them becomes more intense: blue violets become blue, blues become blue green, greens become yellow green, oranges become deep yellow, and "spectrum" reds become orange. (Purples shift either toward red or toward blue, depending on the balance of the color.) The effects of reflected, filtered or shadowed light transition in the opposite direction, from yellow to red or green blue to blue. Thus, layers of translucent yellow material redden as they become thicker, cyan tropical shallows darken to blue as waters get deeper.

J.M.W. Turner (http://www.handprint.com/HP/WCL/artist05.html) provides some classic examples of this approach. In many of his paintings, the *lightness* of colors is closely aligned with the color temperature (yellow is the lightest color, blue violet or gray the darkest), so lightness and warmth go hand in hand. Jan Vermeer's paintings also show a career shift in color design, from a red/green contrast in his earlier paintings to a more austere, atmospheric yellow/blue contrast in his later works. The palette by Lucy Willis (http://www.handprint.com/HP/WCL/palette4j.html) is a good example among contemporary watercolorists.

ALTERNATIVE

warmest
hansa yellow
hansa yellow deep

coolest
ultramarine blue
indanthrone blue

However, the fact that artists define and use the warm/cool contrast in different ways shows that **there is no such thing as a universally "warmest" color** or "coolest" color, either. Color attributes such as lightness, hue or chroma are inherently defined by context (http://www.handprint.com/HP/WCL/color4a.html) in particular, by the chromaticity of the light illuminating the objects in the image so the best choice of warm or cool colors will depend on the design goals or painting purposes (abstract, expressionist, representational) for which the colors are used.

Is Every Color either Warm or Cool? The second question is whether *every* color should be described as either warm or cool, or only reds and yellows as opposed to greens and blues.

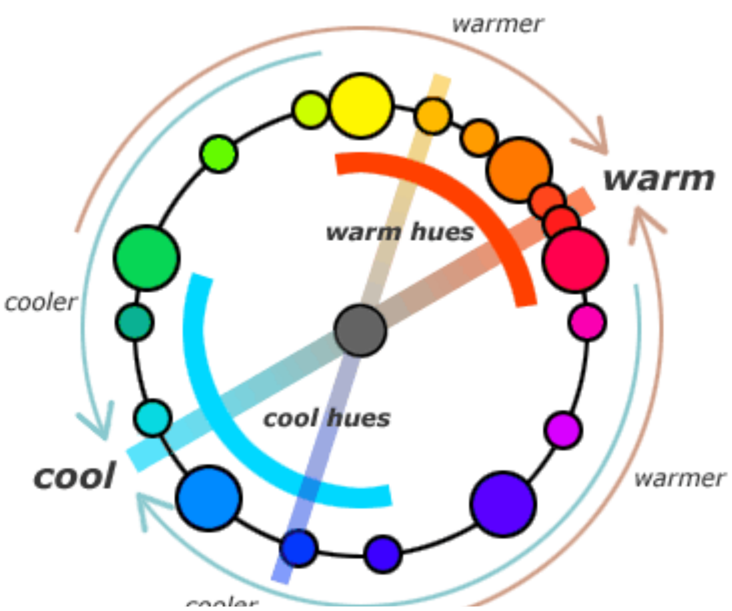
There are two conventions: one assigns an *absolute* quality to a color (*this color is <u>always</u> warm*) or a *relative* quality to a color (*this color is warm <u>in comparison with</u> that color*).

MODERN

warmest
it depends

coolest
it depends

Most color theory texts categorize greens and purples as either warm or cool, because color theory likes things tidy. But I suggest that painters consider the hues from green yellow to green, and from violet blue to violet red, as *fundamentally* neither warm nor cool. In these hues, blue and red, or yellow and green, visibly mix they are warm/cool hybrids. The complementary contrast between green and violet also lacks the stridency of the contrast between red and green or yellow and violet blue. This yields the labeling scheme shown below.



warm vs. cool colors in the color circle

Whatever your views on this fundamental dichotomy, it's common practice and often useful to **describe colors as *relatively* warmer or cooler in comparison with another color**. This simply indicates whether the color is closer to red orange (warmer) or to green blue (cooler) than the comparison color or, closer to yellow or violet blue, if you prefer the alternative yellow/violet blue contrast. Thus, red is a warmer color than magenta, because red is closer to red orange; but both are warm colors in comparison to violet.

These relative comparisons are most often applied to analogous colors (http://www.handprint.com/HP/WCL/tech13.html#analogous) (of similar hue) a "warm blue" (compared to other blues) or a "cool red" (compared to other reds). Thus:

quinacridone red (PR209 (http://www.handprint.com/HP/WCL/waterr.html#PR209)) is a cool red and naphthol scarlet (PR188 (http://www.handprint.com/HP/WCL/waterr.html#PR188)) a warm red

hansa yellow deep (PY65 (http://www.handprint.com/HP/WCL/watery.html#PY65)) is a warm yellow and hansa yellow light (PY3 (http://www.handprint.com/HP/WCL/watery.html#PY3)) a cool yellow

chromium oxide (PG17 (http://www.handprint.com/HP/WCL/waterg.html#PG17)) is a warm green and viridian (PG18 (http://www.handprint.com/HP/WCL/waterg.html#PG18)) a cool green

cobalt blue (PB29 (http://www.handprint.com/HP/WCL/waterb.html#PB29)) is a warm blue and cobalt teal blue (PG50 (http://www.handprint.com/HP/WCL/waterg.html#PG50)) a cool blue cobalt violet (PV14 (http://www.handprint.com/HP/WCL/waterv.html#PV14)) is a warm violet and ultramarine violet (PV15 (http://www.handprint.com /HP/WCL/waterv.html#PV15)) a cool violet.

Occasionally a wider comparison is made across two or more hues, but it is still decided by the **relative distance in a color wheel** between the two colors and the warmest/coolest hue. Hooker's green is *warm* (closer to red orange or yellow) when compared with viridian, but is *cool* (closer to cyan or green blue) when compared with green gold.

It's always helpful to anchor the logic of this abstract color labeling in physical color mixing effects. Thus, the fact that hooker's green is warmer than viridian indicates that we can get a color equivalent to hooker's green by mixing viridian with an orange yellow or orange paint; the fact that it is cooler than green gold indicates that we can get hooker's green by mixing green gold with phthalo turquoise.

What about dull (near neutral) colors? If all colors must be either warm or cool, the common 19th century practice was to assign "gray" to the cool hues (as in a). This is probably because most grays or dark neutral mixtures historically used in painting, including *payne's gray, indigo* and *neutral tint,* have been biased with a blue or green tint.

If colors are judged in relative terms, then a grayed color is either warm or cool using the same "distance in a color wheel" comparison as before. That is, a grayed blue green is warmer than a saturated blue green, because the gray is closer to red orange across the center of the hue circle. In paint mixing terms, some red orange has been mixed with the blue green in order to gray it, and this red orange appears as a warming of the color. (Again, it is always helpful to anchor the warm/cool labeling in color mixing effects.)

In general, all dull cool colors are warmer than their saturation hue match, and all dull warm colors are cooler than their saturated hue match. Thus, burnt sienna is cooler than cadmium scarlet, because it is less saturated (closer to gray).

The same principle applies if you are using the alternative yellow/blue violet contrast: ultramarine blue is made grayer (and warmer) by the addition of some burnt sienna, and burnt sienna is made cooler by adding some cobalt blue.

warm/cool contrast effects

Now we can address the raised above: what explains the visual or design effects created by warm or cool colors? In color theory writings the two most commonly described effects are:

warm colors "advance" in an image that is, they seem to stand out or attract attention, or seem spatially closer to the viewer, while cool colors "recede" or seem to melt into the background: they have a ***depth* effect**.

warm colors are active, arousing or cheerful, while cool colors are passive, restful or subdued: they have a ***mood* effect**.

Visual Associations. color theory typically explains these effects through absurd color associations "ice is blue, and so blue seems cool," or (my favorite), "a distant mountain appears blue, so blue seems to recede from us."

These fictions completely fail to explain the visual effects, because there are numerous and obvious counterexamples. For example, in landscapes the blue sky above us appears much closer than the whitish horizon, so why doesn't blue advance or white recede? If a sunset appears behind those blue mountains in the evening, why doesn't red appear to recede more than blue? On a hot summer's day a noon blue sky radiates far more heat than the reddish sunset, so why isn't blue warm and red cool? Why don't we say "snow is white, so white seems cold"? Or why is red warmer than white, if *white hot* is much hotter than *red hot?* It's astonishing that color theory writers have repeated these nursery rhymes, generation after generation, without any regard for the facts.

Indeed, thoughtful artists rejected this color theory nonsense almost from the beginning. Here for example is John Ruskin (http://www.handprint.com/HP/WCL/book4.html#ruskin), writing in 1862 about the depth effect:

It is a favourite dogma among modern writers on colour that 'warm colors' (reds and yellows) 'approach,' or express nearness, and 'cold colours' (blue and grey) 'retire' or express distance. So far is this from being the case, that no expression of distance in the world is so great as that of the gold and orange in twilight sky. Colours, as such, are ABSOLUTELY inexpressive respecting distance. It is their quality (as depth, delicacy, etc.) which expresses distance, not their tint [hue].

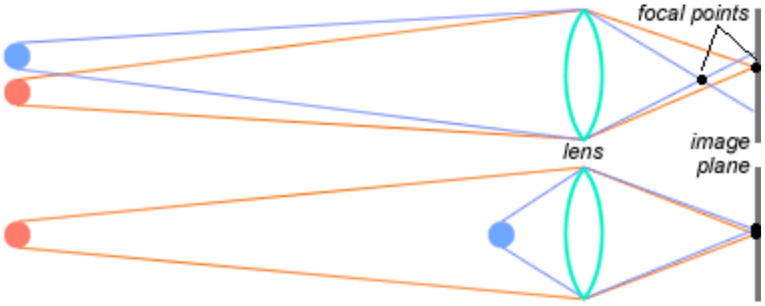
An Optical Illusion. Undeterred by Ruskin's critique, Joy Turner Luke (http://www.handprint.com/HP/WCL/book3.html#luke) offers an explanation for the depth effect that has become popular recently: warm colors are "advancing" because their focal length is longer than cool hues, which is the cause of chromatic aberration (http://www.handprint.com/HP/WCL/color1.html#aberration).

All hues cannot be perfectly focused at the same time. The eye focuses slightly differently on long wavelengths (reds) than on short wavelengths (blues). The lens becomes slightly fatter and more curved to focus on red in comparison to when it is focusing on a blue or green. ... When the eye focuses on nearby objects (http://www.handprint.com/HP/WCL/color1.html#lens) it makes a similar, but larger, change than it does when focusing on red; ... the muscles that control the lens are most relaxed when we gaze off into space. This small difference in focus may account *for the fact that blue and green seem more relaxing and to recede slightly in space*.

This explanation doesn't work for three reasons. First and most important, our eyes are adapted in many ways to eliminate chromatic aberration (http://www.handprint.com/HP/WCL/color1.html#edges) from visual experience. Depth perception is critical to primate survival, and objects that "advance" or blur because of their surface color would destroy that acuity. We simply never see aberration effects, unless they are produced by cheap artificial optics. The focusing of our eyes, the appearance of objects and our **color associations cannot be influenced by optical effects we never see**!

Second, optical accommodation (the focusing of the lens) is an extremely weak depth cue (note Luke's use of "slightly" and "small"). In studies that have looked at various depth cues (http://www.handprint.com/HP/WCL/perspect1.html#cues), optical accommodation to object distance (even though it is a "larger change" in the lens) has an inconsequential effect on depth judgments for objects more than a few feet away.

Finally, in everyday experience we see red and blue objects together, as part of a unified, three dimensional world. Luke's "relaxation sensation to invisible aberration" could only be experienced by focusing on monochromatic lights viewed in isolation first a pure "red" pattern and then a pure "blue" one. And in that context **humans are nearsighted to blue light**.



chromatic aberration and focal length

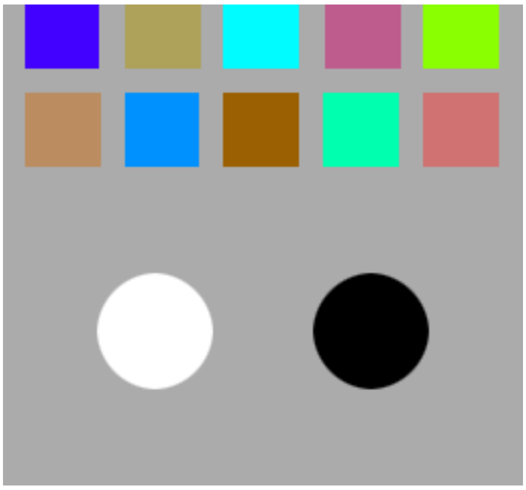
humans are nearsighted to "blue" light, which means an object comes into focus as it moves closer to the eye

The difference in the angle of refraction between "red" and "blue" light is equivalent to an extremely large difference in the distance of two objects, assuming no accommodation occurs in the eye (diagram, above). That is, if you cover one eye and focus on a line grating of monochromatic *"red" light* 100 yards away, a line grating of monochromatic *"blue" light* just *two feet* away would be in focus at the same time. Wherever we looked, our experience of the world would be of near, in focus blue objects or refractions popping out of a field of view anchored on distant, in focus warm objects.

This separation is visible in rare situations, such as an ultraviolet light viewed in darkness: the physical source, which appears in shades of pink or red, is surrounded by an unfocused, but apparently closer, violet nimbus. But this peculiar effect is clearly unusual, so it too cannot provide the hypothetical associations claimed to produce warm/cool contrast effects.

Lightness and Chroma. OK, so what *does* explain the qualitative differences between warm and cool colors? As with any complementary color contrast, lightness and saturation strongly influence (http://www.handprint.com/HP/WCL/color4.html#simultaneous) our color judgments, and in my view **lightness and saturation explain the depth and mood effects** associated with warm or cool colors. In fact, Alfred Munsell (http://www.handprint.com/HP/WCL/color7.html#munsell) noted the "advancing" effect of light valued and saturated colors and developed principles of color harmony around them.

The proof is that when the lightness and/or chroma of warm colors are made less than the lightness and/or chroma of their cool complements, those special warm color depth and mood effects either disappear or shift over to the cool colors!



warm color effects caused by lightness and/or chroma

cool colors can easily appear "advancing" or "arousing" if they are lighter and/or more intense than the warm colors around them; a white disk appears "closer" than a black disk

But what makes lightness and saturation "attention getting" or "advancing"? The *luminance:* they are the most luminous or chromatic objects in the visual field, and our visual system perceives extreme brightness or chroma as similar.

Vision continually isolates contrast or novelty (http://www.handprint.com/HP/WCL/color8.html#weave) wherever it appears, as a primitive strategy to identify unusual (attention getting) features in the environment and bring them (advancing) to our attention. Even in an urban consumer environment, intensely saturated colors are infrequent in our routine visual experience. We occupy a fairly gray world, colorimetrically speaking: saturated colors stand out because they are unusual.

I think the conventional wisdom about warm colors evolved primarily from comparisons between . In general, **warm colored pigments achieve a higher chroma and lighter value** than their cool complementary equivalents. (Ultramarine blue is a spectacular exception.) A saturated yellow or orange paint is much lighter valued and more intense than any green or blue paint. But if the yellow or orange is mixed with black so that its lightness and chroma are matched to a complementary iron blue, the color is transformed into a raw umber or burnt umber. And I have never heard anyone claim that brown is "advancing," "attention getting," "cheerful" or "arousing"!

Most of the warm/cool color effects do not appear in color comparisons made with single wavelength or prismatic colors. For example, "violet" monochromatic light has the highest saturation (http://www.handprint.com/HP/WCL/color2.html#chromadiscrim) of any hue and appears extraordinarily "advancing" and "arousing" in comparison to "yellow" light, which is bland and dull. Just the reverse is true in paints.

Because cool colored paints are typically darker and less intense than their warm complements, they make effective **background colors** for warm colors. The warm colors capture our attention and seem to stand out from the cool background; like the setting for a jewel, the background provides an enhancing contrast. But these are jewels of chroma and lightness, not hue. The same arousing, advancing contrast appears in the last fiery orange leaves that remain in a tree of autumnal brown even though the red orange and brown are both warm colors and are in fact the same hue.

the origin of warm/cool

By assigning warm color to lightness and chroma, it might seem that the warm/cool contrast is illusory, just a crude way to summarize the lightness and saturation differences between different hues.

But that's the wrong conclusion. The depth and mood effects were grafted onto the warm/cool contrast by late 18th and 19th century "color theorists"; they were not part of the contrast as it was applied in Baroque landscape painting. So we still have the to answer: why is the warm/cool contrast fundamental to our visual response to color and to the manipulation of colors in painting?

The first step to an answer is that the **warm/cool contrast originates in diurnal or climatic changes in illumination**, specifically as seen in landscape settings. Thus the *Oxford English Dictionary* describes 18th century usage to include:

Cold *- applied to tints or colouring which suggest a cold sunless day, or the colder effect of evening; esp. to blue and grey, and tints akin to these.*

Warm - suggestive of warmth, said especially of red or yellow ... to become 'warmer' or more ruddy: "On a bright morning of July, when the grey of the sky was just beginning to warm with the rising day".

These and similar 18th century sources, unpolluted by later color theory misconceptions, show clearly that the *warm vs. cool* contrast originated in observations of the **changing illumination** produced by sun and sky. Specifically:

changes in the sun's altitude during the day cause the color of daylight to shift from a cool (bluish) tint at high noon to a warm (yellowish to reddish) tint after sunrise or before sunset

changes in the sun's declination cause seasonal changes in the sun's maximum elevation above the horizon, causing the average illumination and temperature to increase from winter to summer

the atmosphere produces changes in illumination intensity and color through the filtering effects of smoke, dust, water vapor and clouds.

The examples (right) illustrate the changes in natural light from dawn through midday to late afternoon. (These changes are best observed through the window of a darkened room, as Monet did when he painted his series of Rouen Cathedral (http://www.ibiblio.org/wm/paint/auth/monet/rouen/) facades.) The color changes are clearly from warm (yellow) to cool (blue). As the sun declines in the sky, the light dims and the sky color shifts from deep blue to cerulean; in surface colors, reds and yellows become more saturated, yellow greens become warmer and lighter valued, and blues or blue greens become grayer and darker.

color changes across daylight phases

by Hiroshi Yoshida

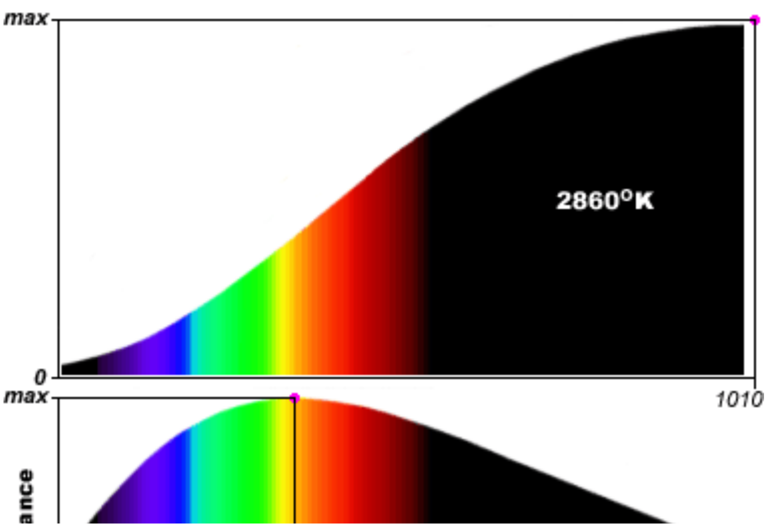
The Japanese artist Hiroshi Yoshida made a fine set of three woodblock prints illustrating these color effects (above).

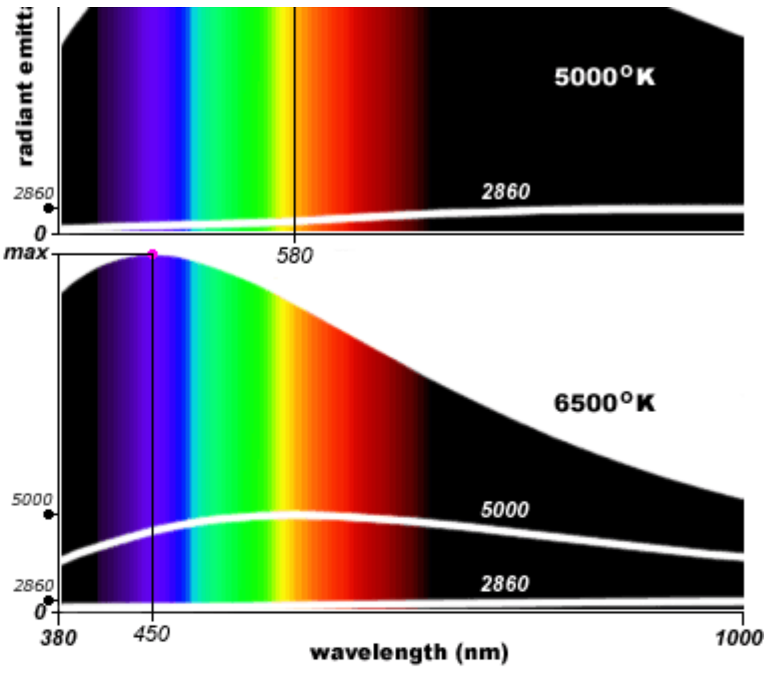
These changes physically occur because the daylight spectral power distribution (http://www.handprint.com/HP/WCL/color1.html#dayphases) contains different proportions of "red", "yellow" and "blue" wavelengths at different times of the day, different seasons of the year and different geographical locations, and under different atmospheric conditions. These variations in the color of the illumination mix subtractively (http://www.handprint.com/HP/WCL/color10.html#surfaceshadow) with surface colors, producing familiar changes in the appearance of our environment. Hues appear to shift warm or cool, colors become more or less saturated, lighter or darker, and complementary shadow colors (http://www.handprint.com/HP/WCL/color10.html#compshadows) change from violet to blue green.

Blackbody Color. The obvious next step is to find a method that can describe or define the relative amounts of yellow or blue bias in a "white" light. A simple way to do this, for natural light and most "white" artificial lights, is by the light's **blackbody temperature**.

In 1900 the Austrian physicist Max Planck mathematically described the spectral power distribution (http://www.handprint.com/HP/WCL/color3.html#radiometry) that would be produced at different temperatures by a perfectly radiating object, called a "black body" because no light would *reflect* from it. (This work led to the development of quantum mechanics, which won Planck the Nobel Prize in 1918.)

These **blackbody curves** approximately match the spectra radiated by many natural light sources, including heated metals, electrical discharges and stars. In all these cases, an entire spectral emission curve (http://www.handprint.com/HP/WCL/color3.html#colorimetry) can be specified by its blackbody temperature alone.





blackbody spectral emittance curves

for temperatures of 2860°K, 5000°K and 6500°K, corresponding to CIE illuminants **A**, **D50** and **D65**; as the blackbody temperature increases, the peak emittance increases and shifts from infrared to ultraviolet wavelengths

Shown above are the blackbody curves corresponding to three standard "white" illuminants published by the CIE (http://www.handprint.com/HP/WCL/color7.html#CIELAB). They illustrate the **three characteristics of all blackbody radiation**: (1) a continuous, smooth curve with a single peak emittance; (2) a shift of the peak emittance as temperature increases, from a peak in the far infrared (7200 nm) for a blackbody at room temperature to a peak in ultraviolet (30 nm) for a blackbody at 100,000°K (degrees Kelvin); and (3) an enormous increase in total radiant flux as temperature increases.

color changes in daylight

(top) noon; (bottom) late afternoon; note change in the sky color

color changes in daylight

(top) morning; (bottom) midday diurnal color changes are best observed through the window of a darkened room

If we convert the blackbody emittance to lumens (http://www.handprint.com/HP/WCL/color3.html#photometry), then standardize the vast energy differences to get light profiles of equal luminance, these *relative* spectral emittance profiles (or **illuminants**) can be assigned a hue and chroma location in a CIE chromaticity diagram, just like any other colored light. The changes in the shape and peak energy of the blackbody curves then produce a **characteristic color sequence** as temperature increases a curved line called the **blackbody locus** (right).

The essential features of the blackbody locus are: (1) the curve is closest to the equal energy white point at a temperature of about 5800°K; (2) above 5000°K the curve is nearly straight; (3) this straight portion is aligned from blue to yellow (approximately from 470 nm to 575 nm); (4) below 4000°K the curve arcs sharply into orange and red, and becomes much more saturated, as temperature decreases; (5) an equal temperature difference defines a smaller color difference as the blackbody temperature increases; and therefore (6) blackbody radiation never reaches a violet or purple hue: at an infinitely high temperature, the blackbody chromaticity has a dominant wavelength of about 470 nm (CIELUV hue angle of 249).

Correlated Color Temperature. The blackbody locus provides the method necessary to specify the color of almost any naturally occurring light source. The temperature (curve shape) of the blackbody is adjusted until its standardized spectral emittance curve produces a *visual* or metameric match (http://www.handprint.com/HP/WCL/color1.html#metamers) between the blackbody and light source their chromaticity points are the same. Note that the match is not between the *shape* of the two spectral emittance curves, but between the *apparent color* of the two curves as they appear, at equal luminance, to a normal observer. Then the temperature of the blackbody curve, expressed in degrees Kelvin (**K**), is the **correlated color temperature** (abbreviated **rK** or **CCT**) of the matching light.

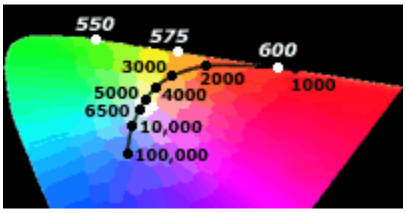
The blackbody temperature has proven very useful to specify the chromaticity of a wide range of artificial "white" lights and natural daylight phases, as summarized below. Note that an equal temperature change produces a smaller color change at higher temperatures.

correlated color temperatures
for common illuminants and light sources

rK° color correlated illuminant or light source 1000 lower limit of blackbody curve 1850 candle flame 2000 sunlight at sunrise/sunset (clear sky) 2750 60W incandescent tungsten light bulb 2860 **CIE A**: 120W incandescent light bulb 3400 photoflood or reflector flood lamp 3500 direct sunlight one hour after sunrise 4100 **CIE F11**: triband fluorescent light 4300 morning or afternoon direct sunlight 5000 white flame carbon arc lamp 5003 **CIE D50**: warm daylight illuminant 5400 noon summer sunlight 6400 xenon arc lamp 6500 average summer daylight 6504 **CIE D65**: cool daylight illuminant 7100 light summer shade 7500 indirect northern skylight 8000 deep summer shade 9300 white point of a CRT (television screen) 10640 clear blue sky **Sources**: Mitchell Charity, MIT; Kodak USA.

Note: Color samples grossly exaggerate the chromatic contrast and drastically reduce relative luminance for purposes of visual illustration.

To facilitate the comparison of color samples within modern color models (http://www.handprint.com/HP/WCL/color7.html), a series of CIE standard illuminants (http://www.handprint.com/HP/WCL/color1.html#dayphases) are commonly used to define the white point (http://www.handprint.com/HP/WCL/color6.html#whitepoint) in a chromaticity diagram (http://www.handprint.com/HP/WCL/color6.html#CIE1964). Changing the white point in a chromaticity diagram changes the predicted and actual distribution of colors and the calculation of color matches (metamers).



blackbody locus in the CIE UCS
chromaticity diagram

adapted from Hunt (2004)

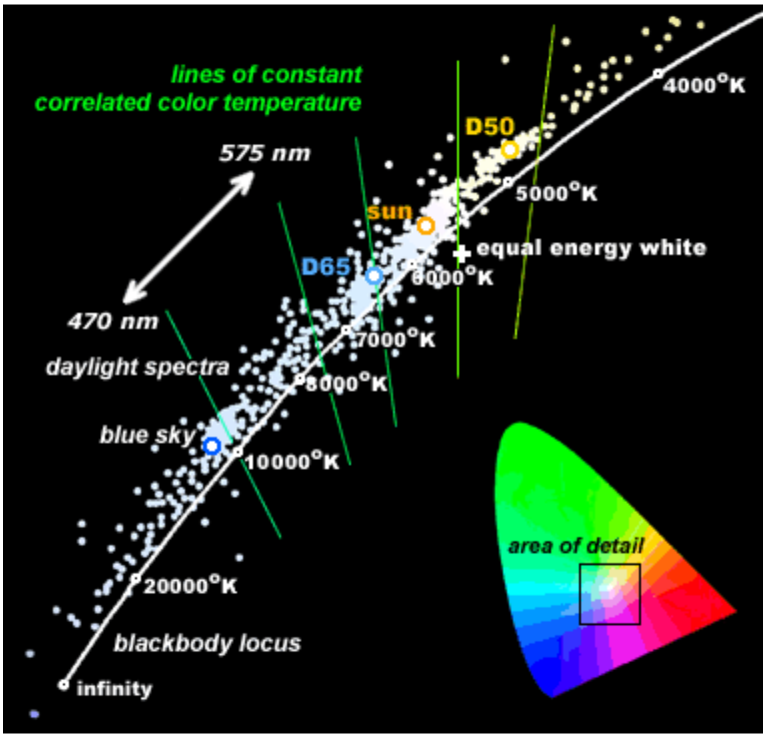
The CIE standard illuminants are based on averaged photometric measurements that characterize common light distributions. The 2860°K (**A**) illuminant represents light from a standard domestic incandescent light bulb; the 5000°K (**D50**) illuminant represents a warm daylight distribution and is preferred in graphic arts applications, and the 6500°K (**D65**) illuminant represents a cool daylight distribution that is preferred for industrial colorimetric applications (for example, matching automotive colors or architectural paint colors).

Notice the fact inconvenient for color theory and sometimes confusing when using CCT values in lighting and photography: as the temperature becomes warmer, the color becomes *cooler!* To avoid confusion, photographers instead use the **mired** (**M**), defined as:

M = 1,000,000/rK

The mired has two desirable properties: values increase as the color becomes warmer (diagram, right), and an equal numerical difference on the mired scale represents an approximately equal visual change in the color temperature across the practical range of CCT values.

Solar & Daylight Color. How well do correlated color temperatures describe the chromaticities of actual landscape illumination? The diagram below shows that the blackbody locus closely parallels the aggregate chromaticity variations across a large sample of daylight spectra (http://www.handprint.com/HP/WCL/color1.html#dayphases) the colors of natural light, measured in different sky directions across different seasons and geographic regions at different times of day.

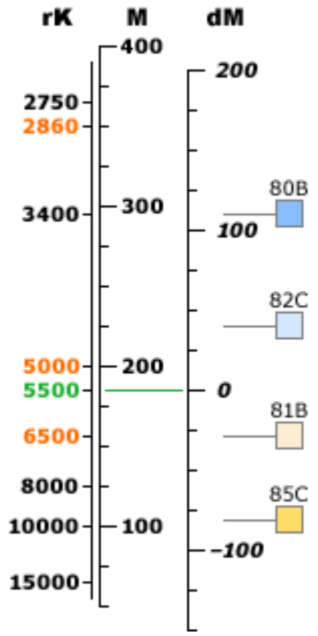


loci of daylight and blackbody spectra

chromaticities of daylight spectra measured by Budde (1963), Condit & Grum (1964) and Henderson & Hodgkiss (1963), CIE illuminants **D50** and **D65**, and solar CCT (5780°K) in the CIE 1931 Yxy chromaticity diagram (http://www.handprint.com/HP/WCL/color6.html#CIE1964); adapted from Wyszecki & Stiles (1982)

In general there is an extremely close fit between the daylight and blackbody curves. This is not surprising, because the solar spectrum is one of many natural light sources that resemble a blackbody radiator. But the most essential point is that the blackbody locus describes the **entire sequence of landscape**

illumination across diurnal and seasonal cycles.



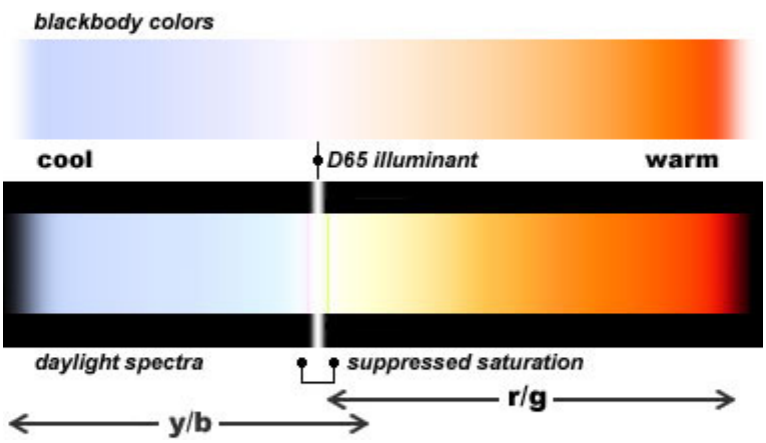
blackbody (rK), mired (M) and
mired deviation (dM) values

mired deviations specify wratten filters used to neutralize light temperature for color film balanced at 5500°K; these filters are visual complements of the blackbody color

However, there is one problem. Compared to an "unbiased" or equal energy (http://www.handprint.com/HP/WCL/color6.html#whitepoint) illuminant, the blackbody locus and the path of all daylight spectra are **shifted toward green** by a small, consistent amount. This occurs because the equal energy illuminant is perfectly flat, while the daylight spectra are typically near the center or short wavelength end of the spectrum. When these chromaticities are reproduced at luminances matching your computer screen, they produce a distinct yellowish green or bluish green tint (right); in fact, the dominant wavelength for sunlight is about 530 nm. Sunlight is not yellow, it is a very pale green!

Can the correlated color temperature describe lights that do not *exactly* match a blackbody chromaticity? The answer is yes, provided the color difference is not large. We simply determine the **closest matching CCT** to the light we want to describe. In a uniform color space, such as the CIE 1976 UCS (http://www.handprint.com/HP/WCL/color7.html#CIE1976uv), a line through the light's chromaticity that is *perpendicular* to the blackbody locus passes through the closest matching CCT value. In a nonuniform color space, such as the CIE 1931 **Yxy** chromaticity diagram used above, these lines (shown in green) are not perpendicular to the blackbody locus but slanting to it.

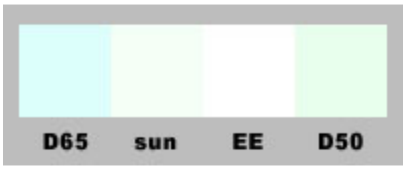
The subtle chromaticity differences between the blackbody curve and the aggregate swath of daylight spectra can be compared in the **daylight color series** shown below. This represents the actual *colors of light* that mix with and alter landscape surface colors.



blackbody and daylight color series

chromaticities of blackbody spectra under **D65** adaptation; adapted from Charity (1997)

The major difference between the blackbody and daylight color series (when defined against a **D65** "white" standard) is the visibly increased "green" component in the daylight colors from deep yellow to white, and from white through middle blue, which produces the noticeable yellow or cerulean tints around daylight colors close to white. These colors appear because "green" light shifts all "red" wavelengths toward yellow and all "blue" wavelengths toward blue green (cerulean).



chromaticities of CIE illuminants when eye is adapted to equal energy "white" (EE)

The yellow is visible in afternoon sunlight, especially in shafts of light into a darkened room, and in this range does not match the orange color of the blackbody spectrum. Ceruleans and very subtle greens are often visible in the sky close to the horizon, especially around sunset when the "violet" component of daylight is heavily filtered. At these times the low sky can appear to shade from a grayish deep yellow into scarlet (photo, right).

It is intriguing that green and rose hues (shown in the diagram immediately around the white point) appear in the afterimage colors of specular reflections, and commonly in the glint of iridescence or refraction colors in water and high altitude clouds near the sun, and the rose colors of dawn. These are subtle shifts in "white" color that are not within the daylight series of colors but are perpendicular to it (along a magenta/green dimension).

The artist can only marvel that the solar light and atmosphere can weave such a narrow chromaticity path and yet create so many landscape color changes and light contrasts. The color variations between dawn and sunset, or the sky seen from a seagoing ship and a mountain peak, or a desert sky before and after a cleansing cloudburst, or the light of spring and fall, or noon and twilight, or the colors of rainbow and iridescent sundog, are a source of abiding pleasure and fascination for landscape painters.

Lighting "Mood" Depends on Luminance. By focusing on the chromaticity of light we have ignored what is its most important attribute the intensity (illuminance (http://www.handprint.com/HP/WCL/color3.html#illuminance) or luminance (http://www.handprint.com/HP/WCL/color3.html#luminance)) of the light source. The actual **light color depends on light intensity**, especially for chromaticities close to white, which means lights with the same CCT can have a very different visual impact depending on how bright they are.

The CCT does not literally stand for a *specific color,* only for a color tendency or color bias; the apparent color of a light will not necessarily match the "color" of its CCT. In addition, luminance affects our visual response. For objects at low to moderately high luminances, the blackbody color sequence seems to correspond to our experience of heated metals from the feeble red to yellow glow of heated iron. But metals heated above 1700°K appear to be a brilliant white, even though this "white" might be equivalent to an "orange" CCT of 2000°K or little more.

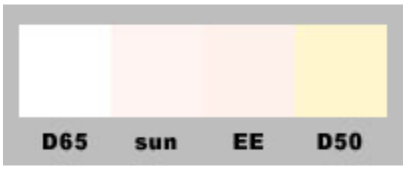
natural display of the

daylight color series

looking east during a Maine sunset

Solar light does not appear to be green, but either white or faintly yellow, for three reasons. First, our eyes easily adapt to the *total* daylight illumination as the standard for "white" light, and this adaptation is to a white point that resembles one of the CIE daylight illuminants, usually **D65**, that are slightly cooler or bluer than direct sunlight, which by contrast appears a pale amber or orange. (The effect is enhanced if a shaft of sunlight is observed within a darkened room.) Second, illuminating green, orange or red surface colors with more intense light appears to shift the color toward yellow, and to shift yellow surface colors toward white, as a result of changes in the proportional response of the **S** cones relative to the **L** and **M** cones at different luminance levels, and these shifts cause the illuminant to appear warm. Finally, the "white" appearance occurs for the same reason that very luminous hot metals, such as the filament in a domestic tungsten bulb, appear "white": the feeble "yellow" or "yellow green" chromaticity is swamped by the light intensity.

The joint effect of adaptation and illuminance level explains why the same incandescent lighting appears "white" to someone inside a room at night, but appears "yellow" when the light is viewed on a window shade from outside. Similarly, a television screen or computer monitor, which typically has a white point approximating 6500°K, appears to produce a balanced light to the viewer in a darkened room indoors, but glows with a distinctly bluish tint when viewed on a window screen from outside.



chromaticities of CIE illuminants when eye is adapted to noon daylight (D65)

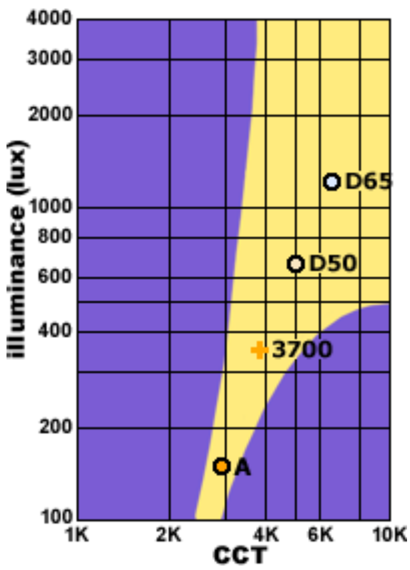
However, even when all the illumination comes from a single light source with a constant relative spectral power distribution, and chromatic adaptation is therefore minimal, **illuminance changes produce contrasting mood effects**. We commonly experience these variations in invigorating effect of a bright sunny day (high CCT, high illuminance) in contrast to the gloomy, cold demeanor of a heavily overcast day (high CCT, low illuminance), or the intimate or comforting effect of candlelight or a night campfire (low CCT, low illuminance) in contrast to the motivating or clinical effect of indoor task illumination (low CCT, high illuminance).

A study by A. Kruithof (graph, right) suggests that an incandescent (tungsten or halogen) source matching illuminant **A** provides "pleasing" illumination between 100 to 300 lux; sources that are rated cooler (higher CCT) should be used at proportionately higher illuminances (above 300 lux). Recently Steven Weintraub (http://www.solux.net/ies_files/MuseumLightingStudy.pdf) and colleagues determined that museum and gallery displays of many different styles of paintings were perceived as most attractive under a CCT of about 3700°K across 50 to 2000 lux, with the "white" appearing CCT values rising from about 3500°K to 3900°K across this illuminance range. A similar study by found preferred CCT values of around 3600°K at illuminances between 200 to 300 lux. Note that cooler source CCTs would be preferred at illuminances near daylight levels of illumination (above 30,000 lux).

To my knowledge these effects have not been explained. The illuminances used in these studies (up to 10,000 lux in Kruithof's study) span the range where mesopic rod intrusion (http://www.handprint.com/HP/WCL/color4.html#rodintrusion) would be a likely explanation, but if low light adaptation shifts the white point from the photopic to scotopic sensitivity peaks (from 555nm to 510nm) then low (reddish) CCTs should appear *warmer* rather than perfectly "white". It may be that exposure to the diurnal cycle during development causes the visual system to associate the white balance with average illuminance levels, so that chromatic adaptation anticipates "warm" (sunset) spectral distributions to be relatively dim (http://www.handprint.com/HP/WCL/color4.html#lightrange). In any case, I believe the baseline perceptual "white" comparison should not be a form of blackbody radiation but a true equal energy illuminant (http://www.handprint.com/HP/WCL/color6.html#whitepoint).

These variations explain why different CCTs are accepted as the best white standard for different lighting or colorimetric applications. Lighting with a CCT of 3500°K or less is considered "warm" and is used in the subdued lighting of restaurants or bars, while lighting at 4000°K is considered an attractive "white" for kitchen or office lighting, which is usually above 200 lux. The range of daylight that appears as "white" does not go much below 3500°K, but a photoflood or high wattage incandescent bulb, with a CCT below 3500°K, can appear perfectly "white", especially at night or when it is the only light source.

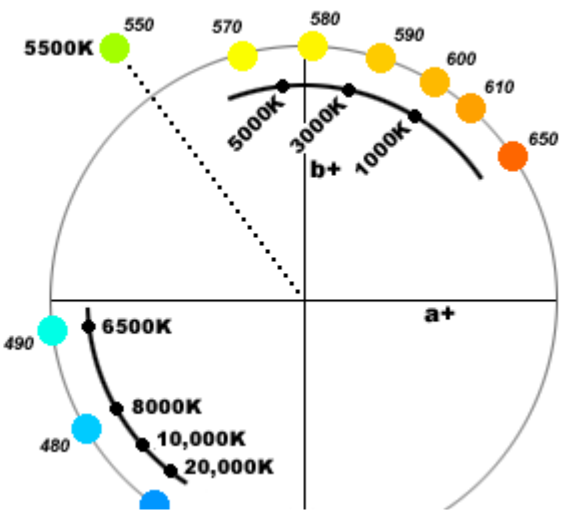
Daylight and the Warm/Cool Contrast. We now have ample evidence and context to link the variations in landscape light to the geometry of color vision.

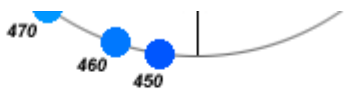


"preferred" light intensity for different illuminants yellow shows zone of preferred intensities for each CCT; adapted from Kruithof (1941), Weintraub (2004)

Just as light/dark adaptation (http://www.handprint.com/HP/WCL/color4.html#sensitivity) is a visual adaptation to diurnal variations in light intensity, the y/b opponent function (http://www.handprint.com/HP/WCL/color1.html#dipict) appears to provide the primary chromatic adaptation (http://www.handprint.com/HP/WCL/color4.html#chromaadapt) to diurnal changes in the yellow/blue (http://www.handprint.com/HP/WCL/color1.html#bluewgts) balance of daylight. The r/g opponent function (http://www.handprint.com/HP/WCL/color1.html#tripict) provides adjustments in the relative balance of the **L** and **M** contribution to the **Y** component of the y/b function, which restores the perception of "pure white" illumination as light shifts farther into the "red" wavelengths.

In the , the arrow indicating the direction of "yellow" wavelengths (around 575 nm) shows that the y/b opponent function can easily compensate for the daylight shifts in chromaticity down to about 5000°K. But under extreme "blue" or "red" (late afternoon) daylight phases **the r/g function is also involved**. This is easier to see if the chromaticities of daylight CCTs (disregarding their typically low saturation and huge differences in luminance) are shown as hue angles on the CIECAM chromaticity plane.





color analogs to daylight spectra chromaticities

the hue of blackbody temperatures illustrated as spectral locations on the CIECAM a*b* plane (http://www.handprint.com/HP/WCL/color2.html#huespace)

This diagram allows comparison of the color shifts in natural light with the traditionally defined : the match is quite good. It also suggests the relative contributions of the r/g and y/b opponent functions in chromatic adaptation. The y/b function makes the major adjustments around the average solar "white", while the r/g function tracks hue changes at lower temperatures. In video production, there are analogous Y/B and R/Y controls to adjust the image *white balance;* digital artists use green/magenta, red/cyan and yellow/blue controls that change the balance between the three complementary contrasts that define the secondary color wheel (http://www.handprint.com/HP/WCL/color13.html#secondary).

Warm hues (matched by CCTs below 5000°K) are smeared across the hue range from yellow to red; cadmium pigments (http://www.handprint.com/HP/WCL/pigmt1b.html#cadmium) represent this range very well. The daylight CCTs above 6500°K start at a teal blue and shift to a middle blue at 10,000°K; this range is represented by cobalt pigments (http://www.handprint.com/HP/WCL/pigmt1b.html#cobalt).

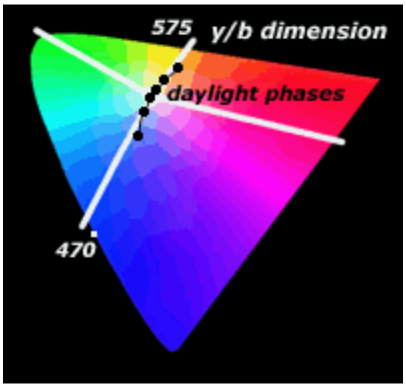
The color of the clear sky (skylight) varies substantially by geographic latitude, altitude, season, humidity, distance from the zenith, time of day and concentration of atmospheric ice, dust or smoke. The distribution of chromaticities is again roughly parallel to the blackbody locus, but the average sky chromaticity is usually above a CCT of 10,000°K, corresponding to a dominant wavelength of about 470 to 475 nm (CIELUV hue angle (http://www.handprint.com/HP/WCL/color2.html#vizluv) of about 235° to 245°). The best paint matches to the typical blue sky color are a dulled cobalt blue (PB28 (http://www.handprint.com/HP/WCL/waterb.html#PB28)) or iron blue (PB27 (http://www.handprint.com/HP/WCL/waterb.html#PB27)), both visual complements of orange yellow.

The luminance of sky colors vary widely. As an upper bound, cumulus clouds that appear "pure white" have an albedo (reflectance) of around 70%-80%, equivalent to a light gray; it is the luminance contrast with the surrounding darker sky that makes them appear white. The sky typically appears relatively dark, with a luminance near the zenith that approximately matches a middle gray (reflectance 30%). Again, moderately diluted cobalt paints reproduce these values well.

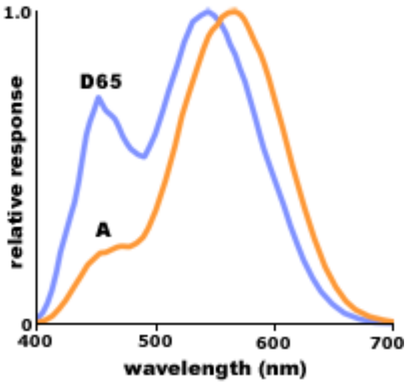
The hue of daylight or direct sunlight never reach a blue violet or purple, although these sometimes appear during twilight as a result of subjective adaptation or complementary contrast effects.

Color Rendering Index. The orientation of the lines of constant CCT (above) shows that artificial lights with the same CCT can have a definite yellow, green, blue or purple tint, even though rated as "white" lights. This ambiguity is introduced in two ways: (1) by defining CCTs as metameric matches (http://www.handprint.com/HP/WCL/color1.html#metamers) between a blackbody curve and a light, which can ignore radical irregularities in the spectral curve of the light, and (2) by defining CCTs as the *nearest blackbody chromaticity* to the chromaticity of the light, even when there is a visible color difference between them. Lights with the same CCT and even the same "white" chromaticity can have very different spectral emission curves, which will produce different appearances in surface colors.

These differences represent the **color rendering** quality of a light. The *color* *rendering index* (CRI) is a numerical rating of how closely the color appearance of surfaces viewed under the light matches the color appearance of the same surfaces viewed under a blackbody light of the same CCT. It is calculated by averaging the colorimetric differences (if any) between the reflectance of 8 to 14 standard colors as illuminated by the test light and a correlated light source of equal luminance and a flat, smooth emission profile, after chromatic adaptation to each light.



the warm/cool contrast and the opponent dimensions



relative visual response to illuminants A and D65

Fluorescent lights generally have reduced CRIs. They emit a **broken spectrum** that has an undulating shape across the spectrum and contains very high, sharp spikes at specific wavelengths (right). These hardly match the smoothly curving, domed curve of a blackbody spectrum, and the surface color reflectances at the "spike" wavelengths are grossly inflated in the total color appearance, producing a greenish or bluish cast that has an especially dulling effect on warm colors. "Cool white" fluorescent lights have a CRI from 65 to 85, "daylight" fluorescents around 80, and "warm white" fluorescents from 55 to 75. Metal halide bulbs range from the mid 60's to the mid 90's; and those beloved sodium vapor lamps, which transform all colors into a yellowish, cadaverous gray, have CRIs close to zero.

The best light sources are those that make all colors all hues at all levels of chroma and lightness appear "natural" or completely untinted. These are broadband, smooth spectral power distributions with chromaticities close to the daylight spectral path: incandescent lights (tungsten or halogen lights), propane lanterns, carbon or xenon arc lamps, burning magnesium. Incandescent or tungsten halogen bulbs all have a CRI of 100 and deliver a "true" color balance.

How can a light source that has an off white or "warm" color (such as a 120 watt incandescent bulb at 2860°K) still have a CRI of 100? As long as the light approximates a high temperature blackbody source, it generates light across the entire spectral range without spikes or gaps, and our eyes will be able to preserve the perception of "white" illumination by chromatic adaptation. That adaptation is the origin and principal basis of our warm/cool color sensitivity.

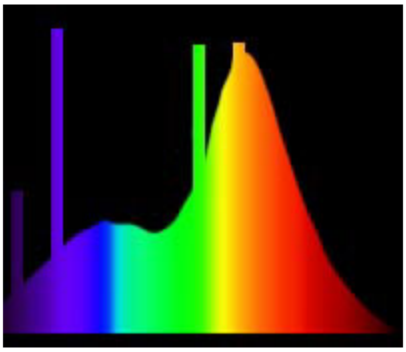
The Univerity of Nebraska-Lincoln hosts a simple blackbody curve simulator (http://astro.unl.edu/naap/blackbody/animations/blackbody.html) that calculates the emittance spectrum and peak energy for a blackbody from 3000°K to 25,000°K. Mitchell Charity (http://www.vendian.org/mncharity/dir3/blackbody/) has posted several useful pages on blackbody colors with links to additional resources.

the warm/cool contrast in paints

I have explained why lightness and chroma are responsible for the "advancing" (spatial depth) or "arousing" (mood) effects attributed to warm colors, and why the warm/cool contrast is a visual adaptation to changes in natural *light*. The last piece of the puzzle is to explain how the warm/cool contrast appears through our perception of *surface colors* such as paints.

Unfortunately no modern color model (http://www.handprint.com/HP/WCL/color7.html) represents the warm/cool contrast as a distinct dimension of color perception, so the answer has to expressed in terms of paint reflectance curves (http://www.handprint.com/HP/WCL/color3.html#reflectance) and their colormaking attributes (http://www.handprint.com/HP/WCL/color7.html#hsv).

The warm/cool contrast is also fundamentally a color judgment, not a color sensation: it is a judgment about the *relative* quality of light, color in comparison to our notion of a pure white.



spectral emission curve of a fluorescent "daylight" bulb with a CCT of 4370°K

from Wyszecki & Stiles (1982)

Green Is Neither Warm Nor Cool. If we compare the visible spectrum (http://www.handprint.com/HP/WCL/color1.html#visiblespectrum) to the shown above, we immediately notice a glaring omission: there is **no "green" in the daylight color spectrum**.

The reason is that most noon , with CCTs between 5800°K and 5000°K, are actually slightly green in hue (right, and). Green is also the range of maximum reflectance in *chlorophyll* (which absorbs only short and long wavelength light) and therefore is the color of landscape vegetation. Green is not perceived as a sky color.

This green hue is briefly visible in the positive afterimage (http://www.handprint.com/HP/WCL/color4.html#posafter) caused by glancing at the sun or staring at its reflection in a dark glass or water; but we are adapted to accept it as "white" light. (The afternoon sun appears yellow because atmospheric filtering has reduced its brightness and begun to shift the color toward red.)

As a result green is neither warm nor cool, because it is (at high luminance) associated with solar light and our perception of the white point (http://www.handprint.com/HP/WCL/color6.html#equalenergy) or an equal balance between short and long wavelengths of light. So the warm/cool contrast is fundamentally a judgment of the balance in a light mixture between the wavelengths shorter than green (*blue* and *violet*) and longer than green (*yellow* and *red*).

Reflectance Criteria for "Warm" Colors. The next point is whether there are consistent attributes in the reflectance of surface colors perceived as warm or cool. There are, in particular for "warm" colors. These are apparent in the difference in color perception between lights and surfaces (http://www.handprint.com/HP/WCL/color3.html#related).

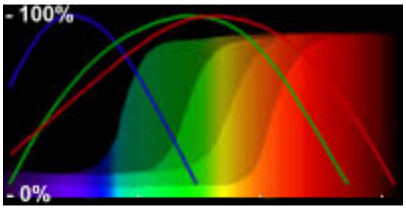
For all parts of the *emitted spectrum* that is, for colors of *lights* the relative saturation increases as the wavelengths of light are limited to a narrower band of color. At the extreme, a spike of single wavelength (monochromatic) light is the most saturated color stimulus physically possible for any hue at any brightness. And this is true no matter whether the hue is red, orange, yellow, green or blue.

Despite this, we find in artistic practice the consensus that only lights in the hue range from red through yellow to white are considered *warm*. A green or blue light, by itself or as the source of illumination in an architectural space, is not identified as warm and may even be termed cool. So although chroma or saturation may explain the effect of warm colors, it does not by itself define an essential warm or cool color attribute. The same reasoning applies to the brightness or lightness of a color.

However, for *reflected colors* the colors of the real world the perception of chroma is more complex. As we saw in the discussion of optimal color stimuli (http://www.handprint.com/HP/WCL/color3.html#optimalstimuli), the maximum possible chroma for a surface color is defined by its lightness or total reflectivity, which means as colors become *lighter* they necessarily become *duller*. So the general rule (http://www.handprint.com/HP/WCL/color3.html#colormakingchroma) for hue purity in surface colors should be: **high saturation signals high reflectance within a limited part of the spectrum**, although this means intense surfaces will also be relatively dark surfaces; pastel (light valued) colors typically have muted saturation.

But for *warm surface colors* even this rule does not apply: **warm surface colors retain chroma across increasing lightness**. This is apparent in the diagram of MacAdam limits (http://www.handprint.com/HP/WCL/color3.html#maxchroma): purple, blue or green hues contract toward the white point (become less saturated) as lightness increases, but for hues from yellow green through red the maximum chroma boundaries remain at maximum saturation, along the spectrum locus although the range of hues gradually contracts toward yellow.

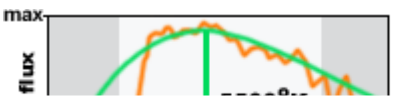
The reason for this unique quality is what I call the **"warm cliff" reflectance curve** that is characteristic of all saturated red, orange and yellow paints. Invariably, **all intense warm hues have three reflectance attributes**: (1) a distinct "cliff", or abrupt increase in the reflectance curve between "cyan" and "orange", (2) consistently high (90% or above) reflectance on "red" side of the cliff, and (3) consistently low reflectance (20% or less) on the "blue" side of the cliff. This locates warm colors in the hues from deep red to light yellow (approximately CIELAB hue angles 30° to 90°)

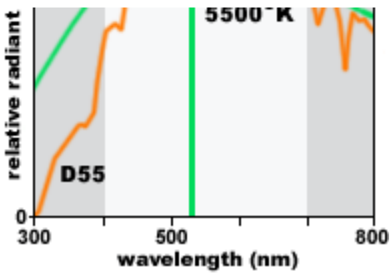


the "warm cliff" reflectance curve

(a sampling of intense red to yellow pigments (left to right): hansa yellow light PY3, hansa yellow deep PY65, perinone orange PO43, naphthol red deep PR170)

This sampling of reflectance curves shows how consistent this "warm cliff" is across all highly saturated warm color pigments, from lemon yellow (hansa yellow light, PY3 (http://www.handprint.com/HP/WCL/watery.html#PY3)) to deep red (naphthol red deep, PR170 (http://www.handprint.com/HP/WCL /waterr.html#PR170)). These curves roughly bracket the wavelengths where there is a "plateau" in the photopic light sensitivity (http://www.handprint.com /HP/WCL/color1.html#psf) curve, which means that luminances in this range will appear brighter than equal radiances at higher or lower wavelengths.





daylight spectral power distribution and blackbody curve at 5500°K

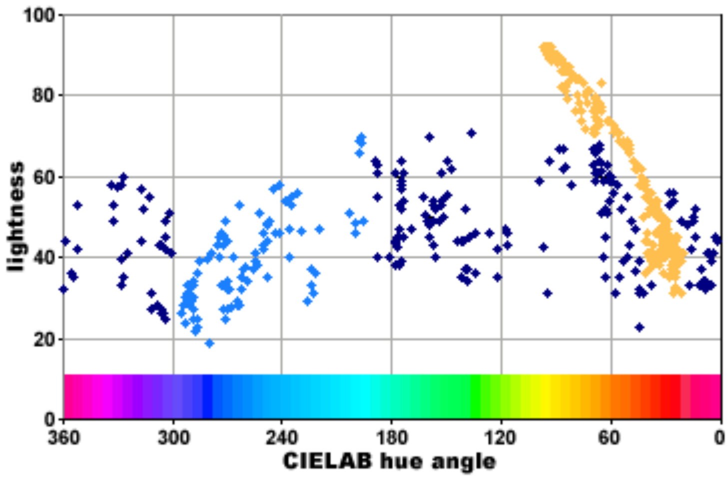
D55 curve from
Wyszecki & Stiles (1982)

If we examine the average chroma of different watercolor pigments (in the artists' color wheel (http://www.handprint.com/HP/WCL/cwheel06.html)), the highest available chroma appears in red to red orange hues. Comparison of these reflectance curves with the idealized warm profile for a matching optimal color stimulus (right) shows how closely intense red, orange, yellow and yellow green pigments match the ideal and therefore can reach a chroma nearly equal to the chroma of monochromatic lights.

The key feature here, in awkward language, is that **warm colors can retain saturation sideways** increasing the *width* of the wavelengths of maximum reflectance does not lower the saturation of the color. No other surface hues have this property.

Warm and Cool in Paints. Now consider the effect this warm cliff must have on the lightness of different warm hues. As we read these reflectance curves from right to left, it is as if a luminosity curtain were being drawn back from a window of light, revealing more and more reflectance as the apparent hue shifts from deep red to orange to yellow. There is a **close relationship between lightness and hue** for intense colors across the warm color span.

We can see this clearly if we plot the measured lightness of commercial watercolor paints (http://www.handprint.com/HP/WCL/waterfs.html) against their hue angle in the CIELAB color space. (Use this chart (http://www.handprint.com/HP/WCL/labwheel.html) to identify the pigments located at a specific CIELAB hue angle.)



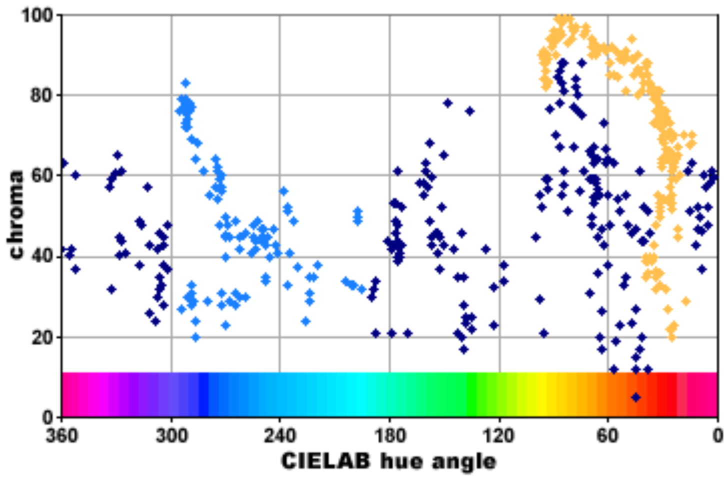
masstone lightness and hue angle

CIELAB **L*** and **h** measured in 600 commercial watercolor paints displayed at maximum chroma

The line of yellow colored points on the left spans the warm colors from hue angle 20 (**quinacridone pyrrolidone**, PR N/A (http://www.handprint.com/HP/WCL/waterr.html#PR%20N/A)) to hue angle 95 (**cadmium lemon**, PY35 (http://www.handprint.com/HP/WCL/watery.html#PY35)). (The dark blue points above this curve at left are lighter valued rose pigments; those below the curve are earth pigments and dull synthetic organic pigments such as perylene maroon.) This curve peaks at a light or lemon yellow, because the lightness of light yellow paints is around 95 and white paints (http://www.handprint.com/HP/WCL/waterw.html#PW4) are at 98. Increasing the reflectance further quickly causes yellow to desaturate into white as the warm cliff crosses into the darker "blue" and "violet" wavelengths.

The chart also shows a reverse relationship between lightness and chroma in the most intense cool colors, shown in pale blue from approximately hue angle 200 (**cobalt teal blue**, PG50 (http://www.handprint.com/HP/WCL/waterg.html#PG50)) to hue angle 290 (**ultramarine blue**, PB29 (http://www.handprint.com/HP/WCL/waterb.html#PB29)). The saturated blue hues *lose* lightness as the hue shifts from "blue green" toward "violet".

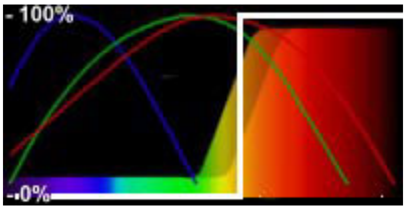
This is obvious if we plot the *chroma* of these paints in relation to their hue, which shows that as warm pigments lighten (from red to yellow) and as cool pigments darken (from turquoise to violet), they both increase in chroma. But the **range of chroma** is greater, and the maximum lightness of chroma is much higher, for warm colors in comparison to all other hues. This **contrasting relationship between lightness and chroma** is partly why the warm hues have qualitatively opposite effects in color experience.



masstone chroma and hue angle

CIELAB **C** and **h** measured in 600 commercial watercolor paints displayed at maximum chroma

If we just multiply the lightness of a color by its chroma, the highest values are in the warm colors around CIELAB hue angle 30 (roughly from pyrrole red, PR254 (http://www.handprint.com/HP/WCL/waterr.html#PR254) to pyrrole orange, PO73 (http://www.handprint.com/HP/WCL/watero.html#PO73)), which includes many brands of cadmium scarlet. In those hues specifically, the edge of the reflectance cliff is right on the wavelength of maximum sensitivity for the **L** cones, while its base is at the wavelength of maximum sensitivity for the **M** cones. Throughout this hue range, for maximally intense colors, there is no significant output from the **S** cones.



theoretical and actual red orange reflectance curves

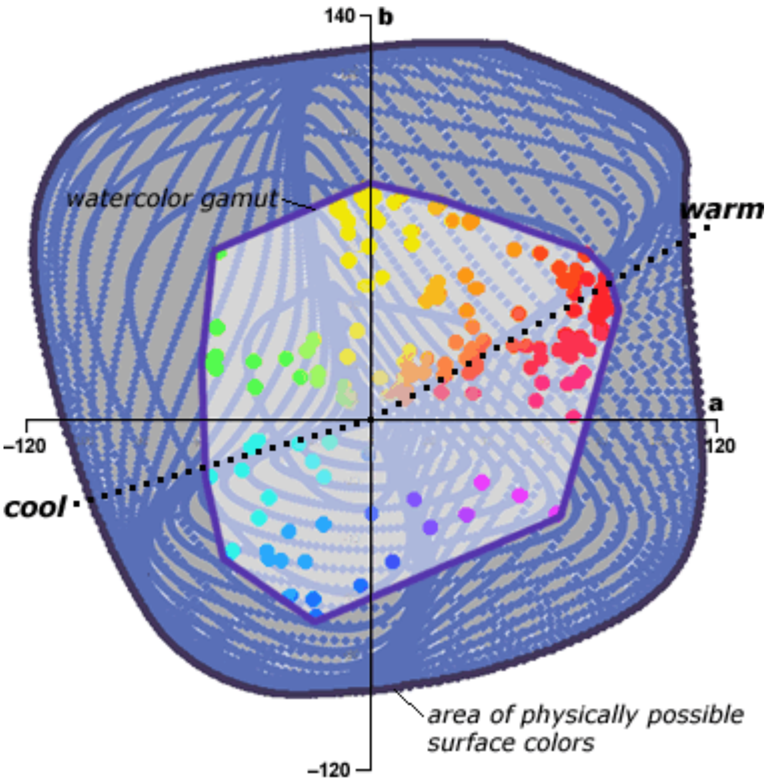
optimal color in white;
pigment curves in color bracketing CIELAB hue angles 32 to 48

Reflectance Criteria for "Cool" Colors. By examining these pigment plots, and partly by reversing the "warm" color reflectance attributes, I can suggest that **all cool hues have three reflectance attributes**: (1) a "cliff" in the reflectance profile located between "cyan" and "yellow"; (2) high or maximum reflectance from this cliff into the "blue" end of the spectrum; and (3) minimum or no reflectance from this cliff to the "red" end of the spectrum. The only qualification is that the "violet" wavelengths (below ~460 nm) must be excluded from the judgment, as these stimulate the **r+** opponent function (as shown here (http://www.handprint.com/HP/WCL/color2.html#opponentcurves)) and therefore appear to contain some "red" light. This locates cool colors in the hues from bluish green to deep blue (approximately CIELAB hue angles 180° to 270°).

This implies that, for cool hues, the cone response profile is always **S** > **M** > **L**. (Note that, for surface warm hues, the reverse is not always true, because **L** and

M can be added together without substantially reducing the chroma of the color, whereas a blue green formed by **S**+**M** is always duller than a blue from **S** alone.) In cool hues, adding **L** output acts subtractively on the **M** output and thereby reduces the saturation of the color. In other words, as the **S** output increases, the color effect of **L**+**M** changes from luminance increasing to chroma reducing (as explained).

Warm/Cool in Color Space. Finally, we can compare the actual chroma of modern artists' pigments with the gamut of optimal colors (http://www.handprint.com/HP/WCL/color3.html#optimalstimuli), which have the *maximum physically possible* chroma of any surface color that does not fluoresce. The diagram shows this comparison on the CIECAM $a_C b_C$ plane (http://www.handprint.com/HP/WCL/camwheel.html).



artists' pigments and optimal color limits on the CIECAM $a_C b_C$ plane

gamut. This suggests that our perception of chroma and saturation is adapted to, or habituated within, the limits of physically possible surface stimuli even though these stimuli are essentially theoretical or "ideal" and are not found in nature.

The optimal color limits may be closest to the pigment limits along the orange/blue direction of the color space because this is the direction of variation in daylight phases. It is interesting that two ridges in the optimal color surface roughly correspond to the warm/cool contrast (red orange to blue green). Since surface colors appear as the subtractive mixture of the surface and illumination spectral profiles, changes in light chromaticity will have the strongest effect on colors in this direction. It is unclear how much of this structure develops in response to the *naturally occurring* variations in daylight and how much is "hard wired" in the opponent functions (http://www.handprint.com/HP/WCL/color2.html#opponentcurves).

Our perception of surface chroma does not correspond to the maximum saturation possible in blue or purple hues of monochromatic light. However, extremely intense blue or purple substances may be hard to form for basic chemical reasons, and would therefore not appear in the domain of natural colors. The pigment examples probably capture the range of color experience produced by physical materials under natural light.

What about Purple? Finally, all the evidence discussed above suggests that **violet is neither warm nor cool**. I argued above that green is neither warm nor cool because the gamut of daylight spectra contains , and the same is true for violet or purple in all blackbody curves no matter how intense a blackbody radiator, it never achieves a color beyond blue violet.

As the green/purple dimension is perpendicular to the warm/cool contrast (defined on red orange), these hue seem unrelated to color temperature. In fact, a magenta/green (http://www.handprint.com/HP/WCL/color4.html#rodintrusion) contrast seems to be associated with different levels of brightness adaptation, and is therefore related to changes in the illuminance, not changes in the light's spectral profile.

Exclusion arguments can also be based on reflectance curves. The reflectance curves of blue green and blue pigments (http://www.handprint.com/HP/WCL/IMG/RC/blue.html) do not conform to *any* of the characteristic of warm hues a warm cliff reflectance profile, maximum reflectance on "red" side of the cliff, and no reflectance on the "blue" side. Rather, they have subdued "hump or bump" profiles, maximum reflectance in the short wavelengths, and no reflectance in the "red" wavelengths. This makes them visual complements to the warm colors. In contrast, the reflectance curves of violet pigments (http://www.handprint.com/HP/WCL/IMG/RC/magenta.html) and green pigments (http://www.handprint.com/HP/WCL/IMG/RC/pg7.html) show some of these warm color attributes but not others. So those hues do not clearly belong on either side of the warm/cool contrast.

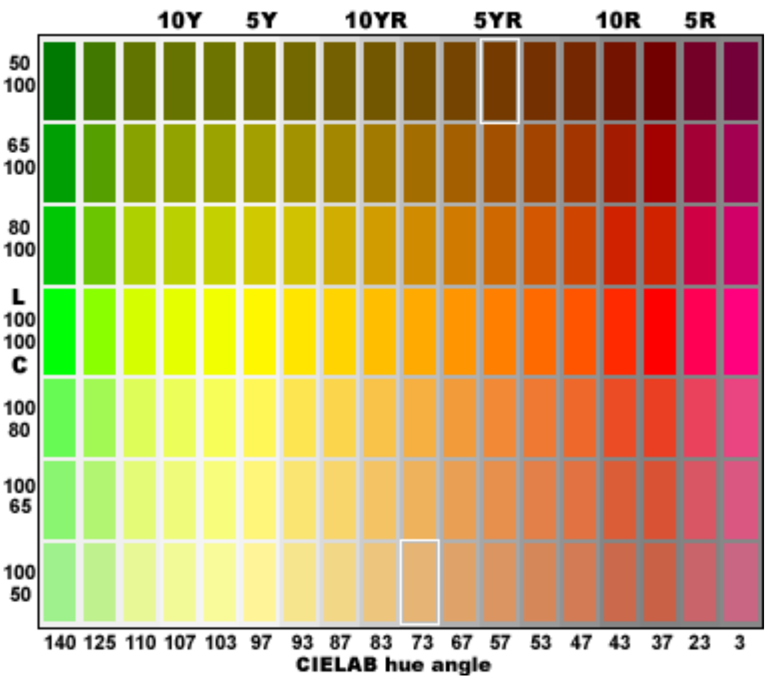
In paints, then, **warm colors are limited to the range from deep red to light yellow**. If we consider only colors that violate *all three* criteria, then **cool colors are limited to the range from blue green to deep blue**. This means, as argued elsewhere (http://www.handprint.com/HP/WCL/color4.html#qualitative), complementary color effects that involve green vs. purple should be qualitatively different from the contrasts around warm vs. cool colors.

unsaturated color zones

A major feature of the warm/cool color contrast is that certain kinds of lightness or chroma contrast cause perceptually unique colors to appear among reds and yellows but not among blues, greens or purples. These new colors are *brown, ochre* and *green gold*.

They cannot be produced by manipulating the brightness or colorfulness of an isolated *red*, *orange* or *yellow* color area; they only appear in the contrast between related colors (http://www.handprint.com/HP/WCL/color4a.html#relatedview). Yet they appear perceptually very different from the saturated hues: brown looks nothing like orange, and green gold nothing like yellow.

I've called these **unsaturated color zones**. (There doesn't seem to be a standard name for them; some texts refer to them as "grays".) The chart below suggests the color variety they produce, in comparison to two shades of green.



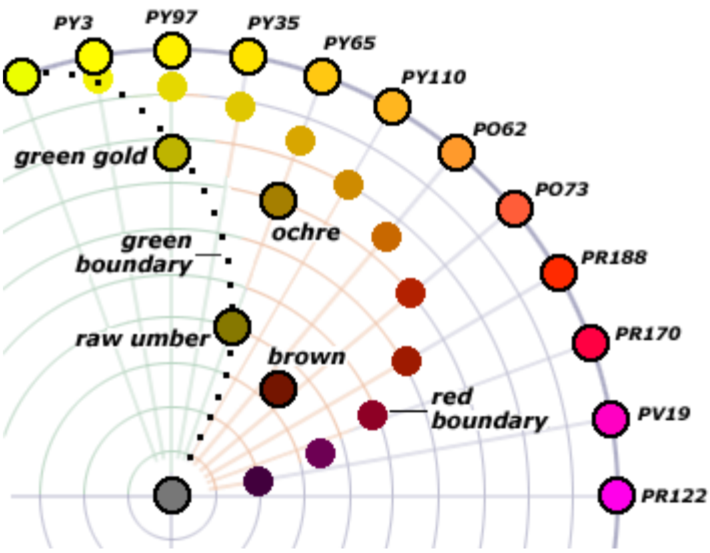
unsaturated color zones

warm colors at optimal lightness (**L**) and chroma (**C**, middle row), with reductions in lightness (top three rows) or in chroma (bottom three rows) to 80%, 65% or 50% of the optimal values; focal locations of *green gold*, *ochre* and *brown* are outlined

In fact, as shown above, these colors can be produced by reducing either the lightness or chroma of the pure hue, although **lightness has a greater impact than chroma** across all hues, and lightness contrast is most important and chroma contrast least important in light yellow hues.

Boundary of Unsaturated Color Zones. The unsaturated color zones only appear within a limited span of the color wheel, roughly centered on the warm end of the at a CIECAM hue angle of about 35°. This splits the color wheel into two parts: the relatively small area between red and yellow where the unsaturated color zones appear, and the much larger circuit of violets, blues and greens where they do not.

The diagram shows the approximate extent of these browns, ochres and green golds as a proportion of the lightness of "pure" (most saturated) colors in a typical artists' color wheel, which puts the pure pigments at the circumference. Color markers are indicated by pigment color index name. The boundary of the unsaturated color zones defines an involute starting at the neutral tone for a magenta, increasing rapidly in relative lightness through the reds and red oranges, and finally intersecting the most saturated yellow green color at a hue angle of around 110°. The approximate location of focal brown, ochre and green gold are shown for reference.



unsaturated color zones in a generic color wheel

boundary of unsaturated colors as a proportion of the lightness of pure pigment color, at hues anchored by common pigments

The boundary is difficult to summarize in terms of chroma or saturation changes. The gist is that:

Mixing the pure color with white *never* produces these new colors; it only produces a pastel or *tint* of the color and typically shifts the hue as well (toward yellow for oranges or deep yellows, toward violet for reds and bluish reds).

Mixing the pure color with black ("lightness boundary", above) *always* produces these new colors, as it reduces both lightness and chroma; the impact of added black is strongest in light yellows (where a 5% reduction in lightness will shift the pure color into green) and weakest in bluish reds.

Mixing the pure color with a gray of equal lightness ("chroma boundary", above) *typically* produces these new colors, as it reduces chroma only; the effect is strongest in hues from yellow to scarlet. Added gray does not produce a categorical change among light yellows, as these already have a lightness close to white.

An interior boundary between the unsaturated colors with a reddish or greenish appearance crosses underneath all yellows and turns toward the achromatic center of the color wheel at around a hue angle of 60°, approximately the location of isoindolinone yellow (PY110 (http://www.handprint.com/HP/WCL/watery.html#PY110)) or nickel dioxine yellow (PY153 (http://www.handprint.com/HP/WCL/watery.html#PY153)). Colors near this **green boundary** have a greenish appearance (for example, raw umber or green gold) will usually shift back to a yellow appearance if sufficiently diluted or mixed with white.

A variety of color labels have been attached to various shades or tones within the unsaturated color zones in the CIECAM a_Cb_C plane (http://www.handprint.com /HP/WCL/cwheel06.html). This table provides a guide.

unsaturated color zones *CIECAM*
*hue anglepure color **J****
- *pure color namereduced lightness **J***
- *new color names* 90>90 - med. yellow70 - **green gold**
50 - **olive**
30 - green gray 7075 - deep yellow60 - **yellow ochre**
50 - mars yellow
30 - **green umber** 5065 - orange50 - **gold ochre**
30 - **raw umber** 3050 - scarlet45 - burnt orange
40 - **burnt sienna**
35 - **venetian red**
30 - **burnt umber** 2040 - deep red30 - **maroon**
20 - mars violet *J = CIECAM lightness. Unsaturated color zones only appear in surface (related) colors at moderate to low lightness (moderate to high contrast with white surface luminance).

As with any color, the label applies to a category or cluster of similar colors that are centered on a focal color (http://www.handprint.com/HP/WCL /color2.html#focalcolors) with a **specific lightness, chroma and hue**. Just lightness or chroma by itself does not adequately locate the color changes. For example, an extensive study by Bartleson put the focal color of "brown" at around Munsell **5YR 3/6**, which corresponds to a CIECAM (http://www.handprint.com /HP/WCL/color7.html#CIECAM) **JCh** of about 25, 32 and 52°, respectively very near the location of burnt umber (PBr7 (http://www.handprint.com /HP/WCL/watere.html#BU)).

The difficulty for artists who want to mix an unsaturated warm color is that they must recognize a specific brown not simply as an orange hue, but an orange of a specific lightness and chroma. Because hue is very hard to identify in unsaturated warm colors, this results in a lot of fruitless mixing back and forth to create a specific dull warm hue from more saturated paints a problem that is most commonly encountered when mixing skin tones (http://www.handprint.com/HP/WCL/tech35.html#skintones).

What Causes Unsaturated Color Zones? The subjective qualities of the unsaturated color zones are barely mentioned in the color vision literature. Joy Turner Luke (http://www.handprint.com/HP/WCL/book3.html#luke) explains the "strange case of yellow and brown" this way: *"Apparently when the combined response from the* ***L*** *and* ***M*** *(Y) cones is below a certain level, perception is more affected by the signal from the L-M channel than the signal from the Y-B channel."*

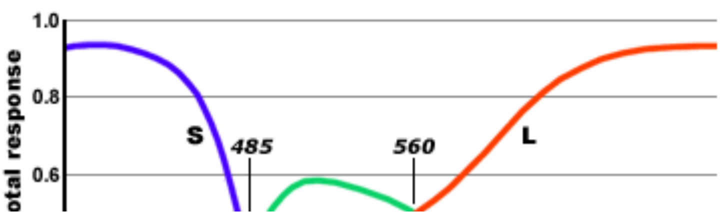
This offhand explanation doesn't do the job. Why do green golds, ochres, siennas, umbers and maroons **only appear in related color judgments**, if the r/g and y/b opponent functions (http://www.handprint.com/HP/WCL/color2.html#opponentcurves) also apply to the perception of unrelated light colors? And why does the signal from the "L-M channel" affect only the appearance of reds and yellows, and not symmetrically the appearance of greens, when the **y/b** ("Y") response is "below a certain level"?

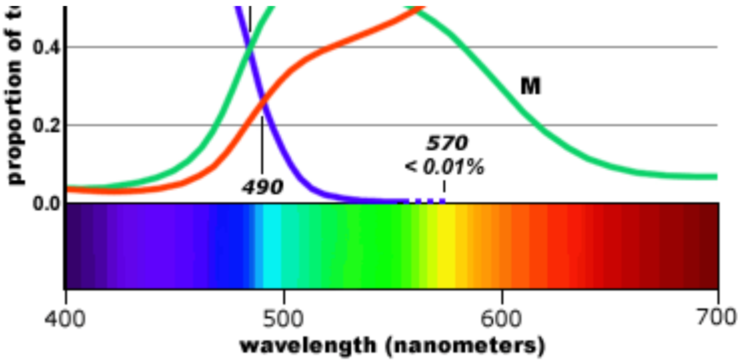
The starting observation is that unsaturated color zones are produced by the **lightness contrast** that characterizes the related colors (http://www.handprint.com/HP/WCL/color4a.html#relatedresponses) of reflecting surfaces. This makes green golds, ochres and browns behave in the same way as grays: they only appear through lightness contrast.

The example at right shows that the same color area can appear *brown* when viewed with a high luminance contrast (white) background (diagram, right bottom), but will appear *yellow orange* if the luminance contrast is substantially eliminated by the appearance of shadow (diagram, right top). The reverse is also true: an orange surface can be made to appear brown if the luminance of surrounding color areas is substantially higher. A similar effect appears in yellows and scarlets. The **unsaturated color zones are produced by luminance contrast**. They are not intrinsic to a specific combination of trichromatic outputs or opponent functions.

What causes this odd color change? The key factor is the span of the **S cone sensitivity**, which at wavelengths above ~570 nm ("greenish yellow") is less than 0.01% (http://www.handprint.com/HP/WCL/color1.html#normlogconesens) of the peak **S** cone response (or 1 part in 15,000 of the total chromaticity signal). Compare this to intuitive benchmarks for "invisible" light: in the Stockman & Sharpe (http://www.handprint.com/HP/WCL/color1.html#logconesens) cone fundamentals, the **S** cone sensitivity at 570 nm is less than 2% of its sensitivity at 400 nm, the conventional short wavelength boundary of the visible spectrum, and it is less than 0.05% of the *combined* sensitivity of the **L** and **M** cones at 700 nm, the conventional long wavelength boundary of light.

When a luminance contrast reduces the **S** cone weighting in the "green" and "blue" wavelengths (because the cones are adapted to respond at the higher luminance of surrounding surfaces), the extremely small **S** cone signal is pushed below the detection threshold, and our eyes become functionally dichromatic (http://www.handprint.com/HP/WCL/color1.html#dichromat) in "yellow" to "red" wavelengths. In effect, **brown signals a contrast induced colorblindness** (tritanopia (http://www.handprint.com/HP/WCL/colorb.html)) in normal vision.

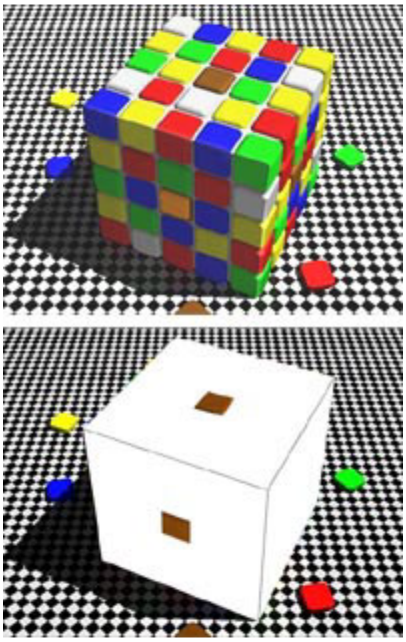




cone mixture curves across spectral hues

curves show the proportion of the total chromaticity information contributed by equal area 10° cone fundamentals (http://www.handprint.com/HP/WCL/color1.html#areaconesens)

This **divides the spectrum into two parts** (above): the monochromatic hues where the **S** cone outputs do or do not significantly contribute to color discrimination. In long wavelengths (yellows and reds) *only the **L** and **M** cones* can be used to discriminate spectral hues.



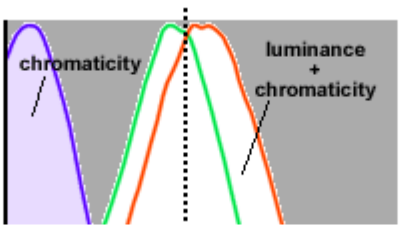
color and lightness induction in a "brown" colored tile from Purves & Lotto (2002)

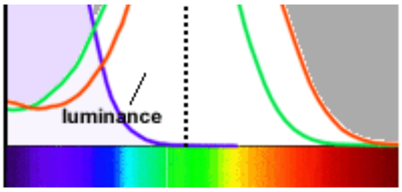
A background issue is that the maximum chromatic intensity of a surface color is uncoupled from lightness (http://www.handprint.com/HP/WCL/color3.html#maxchroma) in warm colors, in the sense that increasing the luminance of a warm surface color does not significantly reduce its chroma (as happens in all green, blue, violet and magenta colors). This is because, lacking outputs from the **S** cones, the **L** and **M** cones must provide both luminance (**L+M**) and chromaticity (**LM**) information (diagram, right). Adding any short wavelength reflectance increases both the lightness (**L+M**) *and* shifts the hue toward white instead of green, because the **S** cone provides separate chromaticity input.

In this predicament, the visual system apparently imposes a chromatic induction (in comparison to the luminance of a "white" standard) that assigns a different perceptual quality to long wavelength (**Y**) luminance that is near, or alternately much below, the luminance value expected for a ("warm cliff") reflectance of matching hue.

So experienced "hue" becomes dominated by lightness contrast. However, the reflectance profiles of yellows or reds can become *darker valued* (the lightness contrast with white is increased) in two different ways:

blacker, meaning that the maximum reflectance in the reflectance profile is reduced well below 100%, even though the transition from minimum to maximum reflectance displays the abrupt reflectance profile (reduced "vertical" reflectance in the "yellow" and "red" wavelengths).





contrasting sources of luminance and chromaticity in warm vs. cool colors

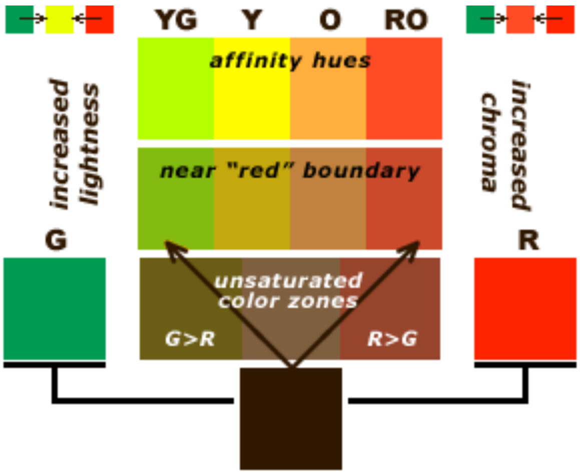
redder, having maximum reflectance that is close to 100%, but having the "warm cliff" reflectance transition shifted far into the long wavelengths where the **L** and **M** cone sensitivity is much weaker (reduced "horizontal" reflectance in the "yellow" to "red" wavelengths). This is revealed by the way the spectrum locus dives toward the achromatic center (becomes darker) along a constant hue angle or black limit (http://www.handprint.com/HP/WCL /color2.html#yellowcyancircuits) at around CIECAM hue angle of 33°; diagram, right.)

The combined effects of decreased hue sensitivity and the ambiguous interpretation of darkened color (increasing blackness or redness) means there is a **disproportionately large number of metamers** among dark, dull, red or yellow surface colors a third perceptual justification for unsaturated color zones.

How does color vision represent these ambiguities? Just as it does in tritanopia by anchoring the hue sensation in the **opponent balance between red and green** (the r/g opponent function (http://www.handprint.com/HP/WCL /color2.html#opponentcurves)).

Recall that, at high reflectance with a "warm cliff" profile, a roughly equal mixture of red and green produces the perception of yellow (http://www.handprint.com /HP/WCL/IMG/RC/yellow.html). Yellow is the perceptual token for a surface color that approximately balances the **r/b** function at high surface reflectance. Any **yellow is a signal of *both* high chroma *and* high reflectance** in warm surface colors, which means the color is near or above the shown above.

Increasing the lightness and/or chroma of any color from yellow green through scarlet takes it toward its affinity hue (diagram, below) and produces a clear perception of the proportion of yellow hue in the color. Adding any **S** cone response shifts the color toward white (or green), so whiteness or greenness becomes the warm color signal for short wavelength reflectance yellow and blue really do make green.



the r/g balance in unsaturated warm colors

For darkened colors below the red boundary, as chroma and lightness decrease, the "yellow" sensation weakens and then disappears. It is no longer possible to describe the color in relation to yellow, except intellectually (by studying color vision). In this case the color appears as a brown or ochre that seems to **lean either toward red or green**. This red/green balance signals indirectly the relationship of the color to the saturated affinity hues:

If the color appears to contain **more red than green**, then it is at a hue angle below 60° (see diagram, above right), and would *if made brighter* shift toward a red (orange or scarlet) color.

red > **green**
→
orange or scarlet

If the color appears **more green than red**, then it is located somewhere at a hue angle above 60°, and would *if made brighter* shift toward a yellow or greenish yellow color.

red medium yellow or green

If the color appears **neither red nor green**, then it is at a hue angle of about 60° and would shift toward a deep yellow or light orange if made brighter.

red = **green**
→
deep yellow

"Made brighter" means **brightened by lightness contrast**, that is, at a higher lightness and higher chroma. The effect of lightness contrast is to **increase lightness** proportionately more in greenish (yellowish) unsaturated colors, but to **increase chroma** proportionately more in reddish unsaturated colors. This is because a pure red orange is much darker valued, and also more intense, than a pure yellow.

The perceptual quality of brown as a red/green mixture is the same as that of green as a blue/yellow mixture. Greens appear either cool (bluish) or warm (yellowish), and similarly browns, ochres, umbers and siennas can appear either cool (greenish) or warm (reddish). The difference is that a balanced green and blue mixture appears as a dull green, but a balanced red and green mixture appears as a brown or umber.

painting warm & cool

In this section I emphasize the key points argued in this long and somewhat speculative page, and offer some guidance on manipulating the warm/cool contrast in painting.

I don't provide a separate discussion for manipulating colors in digital or video media, because these are created by light projection systems and additive light mixtures, not illuminated surface colors and subtractive pigment mixtures.

What is the origin of warm/cool contrast? The perceptual importance of the warm/cool contrast probably arises in the capability of the human visual system to adjust to changes in the color and intensity of natural illumination under different phases of daylight. In response to these illumination changes, color vision changes both its relative sensitivity to light (chromatic adaptation) and its relative judgment of colors (color constancy) to maintain a consistent appearance in surface colors.

A heightened awareness of the warm/cool contrast in painting technique probably dates from the representation of diurnal and climatic changes of light in late 17th century landscape paintings, and was explicitly extended in artistic practice during the 18th century.

What are these changes in natural light? Natural daylight changes in two ways: brightness and chromaticity (color). Under clear skies, brightness ranges from a high around noon to a low just after sunset. The chromaticity changes, as defined by the correlated color temperature, range from a greenish white at noon to an intense scarlet at sunset (for direct sunlight), or from a cerulean or greenish blue at noon to a deep yellow at sunset (for sunlight and skylight combined).

Light intensity also has specific warm/cool effects as it interacts with different kinds of materials. In general, as the intensity (illuminance) of light on or through materials increases, the apparent color of the materials shifts toward yellow: blues become blue green, greens become yellow green, oranges become yellow, reds become orange; violets shift either toward red or toward blue, depending on the hue balance. The effects of reflected, filtered or shadowed light change in the opposite direction, from yellow to red or green blue to blue. (For example: layers of translucent yellow material redden as they become thicker, greenish pools darken to blue green as waters get deeper, etc.)

What are the warmest (coolest) hues? There is no such thing as a "warmest" or "coolest" hue in colorimetry. Two traditions have developed in representational painting. Emphasizing the *chromaticity* changes across natural daylight phases suggests a warm/cool contrast anchored on **red orange**. This makes the warmest hue a paint such as pyrrole scarlet (PR255) or pyrrole orange (PO73); the coolest hue is a greenish blue such as phthalocyanine cyan (PB17) or phthalocyanine turquoise (PB16).

Emphasizing the *intensity* changes in natural light suggests a warm/cool contrast anchored on **deep yellow**. This makes the warmest hue a paint such as hansa yellow deep (PY65) or quinacridone gold (PO49); the coolest hue is a (dark) blue violet such as ultramarine blue (PB29) or cobalt blue (PB28).

Are there objective criteria for a warm/cool judgment? Yes. All warm surface colors have three reflectance attributes: (1) a sharp transition or "cliff" in reflectance located between the "cyan" to "yellow" wavelengths; (2) maximum reflectance from this cliff to the "red" end of the spectrum; (3) little or no reflectance from the cliff to the "violet" end of the spectrum. This locates warm colors in the hues from light yellow to deep red.

The "cool" hues are defined in nearly complementary terms: (1) a "cliff" profile located between the "cyan" to "yellow" wavelengths, (2) maximum reflectance from this cliff to the "blue" region of the spectrum, and (3) little or no reflectance from the cliff to the "red" end of the spectrum. The "violet" wavelengths must be excluded from the judgment, as these stimulate the **a**+ opponent function (appear to contain some "red" light). This locates cool colors in the hues from bluish green to deep blue.

Is every color either warm or cool? No. I feel that greens and purples are in themselves neither warm nor cool, because they do not conform to *all three* of the three criteria just listed for a warm or a cool color, and because they are not salient in the orange to blue transitions of .

However, any color can be *relatively* warmer or cooler in relation to any other color, depending on which color is closer to the arbitrarily chosen warmest (or coolest) color around the hue circle. These judgments must be made in context with the other colors in the image or scene, including the scene illumination, and not as abstract comparisons between color wheel locations.

Are warm colors advancing or arousing? No. The illusion of relative depth or a specific mood effect are not consistent attributes of warm or cool hues. Colors typically "advance" or come forward in an image because they are (1) light valued and/or (2) highly saturated. These confusions developed because warm pigments as a group are lighter valued and more saturated than cool pigments.

Mood effects depend on combinations of both lightness and chroma: strongly saturated hues at medium lightness are usually "arousing" or "vibrant"; highly saturated hues at high lightness are usually "cheerful"; low saturation hues at high lightness are typically "restful"; and low saturation hues at low lightness are "somber" or "subdued". These effects are mostly independent of hue, but are strongly dependent on the image, usage or scene context. (Audrey Hepburn is not somber and subdued in those slim black pants!)

What are the unsaturated color zones? These are relatively dark (nonreflecting), low chroma colors perceived as categorically different from light valued and high chroma colors of the same hue. They only occur among "warm" hues, and include maroon (dark red), brown (dark orange), ochre (dull deep yellow), raw umber (dark deep yellow) and green gold (dull or dark light yellow).

What causes the unsaturated color zones? In warm surface colors, color appearance is strongly affected by the lightness contrast (http://www.handprint.com/HP/WCL/color3.html#whitepurity) between a color area and surrounding surfaces.

This seems to be a compensation for the lack of **S** cone response (similar to tritanopia) to long wavelength light. Because there is no third cone sensitivity across the "yellow" or "red" wavelengths, the surface color chromaticity (the ratio between **L** and **M** outputs) is not significantly altered by increased luminance (**L**+**M** outputs), coupling chromaticity and lightness perception in yellow to red surface colors.

However, because of the remarkable consistency of the "warm cliff" reflectance profile in all yellow to red material colors, the visual system is able to compensate for this deficiency. It compares a color's lightness (**L**+**M**) to the lightness expected for a of the same hue, which represents the physical limit for a "pure" color of the same hue (**LM**). If the contrast lightness is near this maximum for a given **LM** balance, perception signals this fact by adding a distinct "yellow" color sensation to the color appearance.

A warm color can only exceed this optimal contrast ratio through the addition of short wavelength reflectance, which both increases the color lightness (**L**+**M** response), which preserves the yellow sensation but mixes it with a chromaticity shift toward white or green (separate **S** response). (In other words, **L**+**M** and **S** really do make green!)

When the color's lightness falls substantially below the lightness expected of a maximally saturated color of the same hue, the yellow sensation disappears and the color can only be characterized tritanopically, as a balance between red and green sensations. These yellowless mixtures of red and green create the unsaturated color zones.

Saturated blue reds (such as the quinacridones) that reflect some "blue" wavelengths make a dark violet when mixed with black paint or illuminated by a broadband blue or near UV light, while a "spectrum" red given the same treatment turns deep brown or black. Browns and ochres do not appear in surface colors illuminated by a broadband orange or red light source, because this provides no **S** stimulating "green" or "blue" light and therefore no ambiguity in the "warm" part of the spectrum. Brown, ochre or green gold colors appear in any darkened color where the reflectance almost entirely stimulates the **L** and **M** cones and the **S** contribution is small enough (in relation to quantity of **S** stimulation in the light) to be ambiguous.

Does the apparent warm/cool contrast depend on the illumination?
Absolutely. Brilliant, balanced natural light occurs under a high sun and a clear sky. All hues are rendered perfectly, and both the colorfulness contrasts (http://www.handprint.com/HP/WCL/color3.html#colorvchroma) and lightness contrasts (http://www.handprint.com/HP/WCL/color3.html#brightvlight) are optimal. All directly illuminated surface colors appear in their unbiased local color and can be painted in that way.

In daylight shadows are tinted with a desaturated red blue (such as indanthrone blue, PB60 (http://www.handprint.com/HP/WCL/waterb.html#PB60) or a grayed cobalt blue, PB28 (http://www.handprint.com/HP/WCL/waterb.html#PB28)), not a purple. A general yellowing of color or a slightly increased saturation from orange to yellow green and a decreased saturation from magenta through cyan can be used for expressive emphasis or to show variations in illuminance intensity produced by the angle of surfaces to the light source ("brighter" illuminance = yellower or, for warm hues, more saturated color).

Dim light either means greatly reduced illuminance or filtered (chromatically altered) light. If the light is dim, the chromatic balance among colors, measured in the spectral composition of the reflected light, is roughly the same. However, it produces very different than bright light of the same chromaticity. Dim light seems softer, more intimate and pleasant if it has a "warm" chromaticity, but seems cold, gloomy and depressing if it has a "cool" chromaticity. In either case the average value may be darker, but values always contract toward the average value (extreme lights and darks disappear, with the larger shift toward gray occurring in the dark values).

If the light is filtered, the color depends on the tinting layer that produces the filtering. Overcast clouds produce a darkening that is approximately the same chromaticity as unfiltered daylight, or slightly bluer. In painting this is commonly represented as a shift toward blue, with a loss of colorfulness (graying) and contrast in all colors, but especially warm colors (which shift toward green).

Near sunset, short or "blue" wavelengths are strongly filtered from sunlight by atmospheric dust and smoke, causing the "blue" component in all colors to darken and the "red" component to appear unnaturally bright. This causes greens to shift toward yellow and the dull yellow or red of tree bark and wood to appear unnaturally red.

Night light is is viewed under scotopic vision, which means colors are principally symbolic rather than imitative. Even so, the typical representation of night relies on a near monochrome palette of blues or blue greens, with yellow accents contributed by isolated artificial lights and the near surfaces they illuminate.

How do I make a color warmer or cooler? The answer depends on whether your axis of reference is the illumination or the hue circle. If you want to make a color warmer within a certain kind of illumination (that is, the light in any representational landscape or portrait), then the "warmest" color is typically shifted from red orange toward the color of the illumination. Greenish light makes oranges and yellow warmest, because reds are dulled almost to blacks; orange light makes oranges warmest, and dulls magentas and yellow greens.

If the axis of reference is in terms of the hue circle (as would be used in nonrepresentational color design, for example), then "warmest" color depends on all the colors in the image. However, given the way our visual system is structured and the range of available pigments, a red orange located at a CIELAB hue angle of about 40 or darkened, whitened or dull paints of similar hue, such as burnt sienna, burnt umber, convenience "naples yellow" paints, or quinacridone orange are good standards of comparison.

When you "cool" a warm color in paint mixtures, it is important to use a blue that contains no red reflectance (http://www.handprint.com/HP/WCL/IMG/RC/blue.html) and no green hue. In paints, only indanthrone blue (PB60 (http://www.handprint.com/HP/WCL/waterb.html#PB60)), phthao blue (PB15 (http://www.handprint.com/HP/WCL/waterb.html#PB15) or iron blue (PB27 (http://www.handprint.com/HP/WCL/waterb.html#PB27)) meet these two criteria. All paints compounded with ultramarine blue or cobalt blue contain some "red" reflectance and give the mixture a purple tint. At the same time, paradoxical shifts can result if you use a saturated "blue" red (http://www.handprint.com/HP/WCL/IMG/RC/red.html) that contains some "violet" reflectance. This paints will shift toward purple, rather than gray, when mixed with a blue paint.

In most representational works, the coolest hue is the visual complement to the color of the illumination. As landscape light declines toward sunset, for example, the color of the sky becomes more greenish, appearing cerulean just before sunset.

For representational modeling, the most versatile shadow colors are iron blue

(PB27 (http://www.handprint.com/HP/WCL/waterb.html#PB27)) and indanthrone blue (PB60 (http://www.handprint.com/HP/WCL/waterb.html#PB60)). Both are remarkably versatile and effective shadow colors; iron blue is appropriate for shadow tints under "red" or late afternoon light or weak incandescent lamps, while indanthrone blue is best for shadows under intense incandescent or natural daylight. For more expressive or coloristic effects, almost any paint from perylene maroon to phthalocyanine green can be effective.

How do I mix any specific color to make it warmer or cooler? Again, this depends on whether you want to model the effects of natural light or create an abstract color design, and which specific color you intend to shift.

All warm hues are made warmer if they are darkened, dulled or mixed with any paint that does not contain "green" or "blue" reflectance, which can raise the **S** cone response. Oranges or yellows make a brown color similar to burnt sienna or yellow ochre if mixed with purple, which warms them, but these mixtures characteristically shift toward red rather than yellow when lightened. The saturated "blue" reds (http://www.handprint.com/HP/WCL/IMG/RC/red.html) (which include all quinacridones and many naphthols, perylenes and pyrroles) shift toward blue when diluted or mixed with white paint, sometimes by as much as 20° hue angle.

Warm hues are made cooler if they are neutralized by any green or blue paint, which shifts them toward gray without proportionately darkening the color.

Blues are warmed by mixture with any magenta, red or orange paint, up to the point where they become purple. Blues are generally cooled by mixture with yellow, but greens are warmed by it. Greens are cooled by mixture with purples or blues.

How do I decide if a color is relatively warmer or cooler than another?

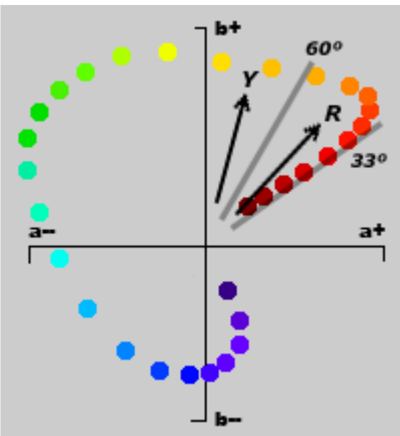
There are three possible definitions of "warmer": (1) contains more yellow; (2) contains more scarlet (red); (3) is closer to gray.

If you want to convey luminance, then yellow mixtures and yellow bias in reflectance curves is the key; you need to know how to increase or decrease those in any color by paint mixtures and how to harmonize the yellow content of paints in a total painting.

if you want to convey dryness, lack of moisture, heat, intensity, then the same is true, only now your focus is on red (any scarlet or red with no blue reflectance cadmium red deep is ok, quinacridone red is not).

N E X T : color wheels (http://www.handprint.com/HP/WCL/color13.html)

(http://www.handprint.com/HP/WCL/wcolor.html)



involute of "warm" hues in CIECAM

handprint.com (http://www.handprint.com/HP/WCL/color12.html)