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Yellows, Colors: How many dimensions?

In this paper, I will try to describe the space of colors, the space as seen by physicists, with many parameters and ideas, originating in physiological observations. First I will recall in the introduction why colors are located or described in a space with three primary colors, that is, with three dimensions. Then I will shortly describe the situation of color-blind people, who perceive colors in a two-dimensional space and we will see that their experience helps us understand why the 'space of colors' may be a more complicated issue than we think and why some painters often consider that, in the end, there may be four primary colors. I will finish by discussing the issue of gloss, and the importance, complexity and usefulness of it, in the way it gives more dimensions to color.

To begin, it is necessary to take into account the fact that the color of an object is a feeling, just a feeling, and not a property of the object in itself: even if we say 'a yellow submarine' or 'a red door', a color is just a feeling. The 'feeling' of this color depends first on the spectrum of the source. Indeed, the color recorded by a camera depends on the source, and films, for example, are designed on the basis of their expected exposure to sunlight or to tungsten lamplight, of the way they are lit. The colors depend on the spectrum re-emitted by the object and then on the physical properties of the object, for example, a lapis lazuli stone is blue, just because the physical state of the electrons in the stone are such that the electrons absorb the red and the green but re-emit the blue. Secondly, the feeling of color depends on the observer, it is a matter of perception, of physiology, as we will see below. Finally, there is space for interpretation, which is dependent on culture, psychology and language. As you know, in Russian, there are two words for blue, **синий** [see-niy] and **голубой** [gah-loo-boy], and in French, there is basically only one blue, we say that the sky is blue, and that the color of the shirt of the French soccer team is blue, even though the blue of the sky if completely different from that of the shirt. We have basically one word and do not often add precisions like *bleu clair*, *bleu ciel* or *bleu marine*. Meanwhile in German there is no clear translation for the word 'pink'.

1. Three-dimensional space

Let's begin with physiology. If we look at the picture of an eye made with a scanning electron microscope [Fig.1], we see the retina where light is focused at the back of the eye, and where the image is formed, and in the retina you have several types of sensitive elements, or light detectors. Now there are two types of light detectors: rods and cones, the former are very sensitive, but not to colors, while it is the cones which are sensitive to colors. We have three types of cones, blue, green and red, and this is basically the reason why we say that colors are within a three-dimensional space.

Fig.1 The retina: rods and cones

If we now look at a recent image of the retinas of five different persons [Fig.2], we can see those cones in color according to their varying absorption of the spectrum. We observe that, on the far right here, one person has many red cones, a few blue and a few green cones, while the person on the other side, on the far left, has many green cones, a few red and a few blue cones. This clearly confirms that we have different densities of cones, which means that the detected electrical signals which go to our brain are different from one person to the next. Of course, we have learned to name the colors from our personal perception even if each person's perception is different because of a different hardware in our retinas, but primarily we have learned together, in the same schools, in the same culture, how to name the colors. So that, in the end, although our perceptions are different, although their electronic signals in the retina and in the brain register differently, people belonging to a same culture give, most of the time, the same name to the color that they (think they) see.

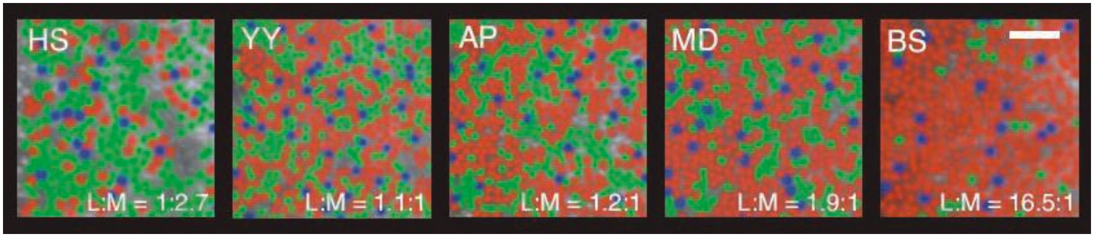

Fig.2 Variability of green, red or blue cones from one person to another (density, spectral response, …)

Here now are the different cones translated into the light spectrum [Fig.3]:

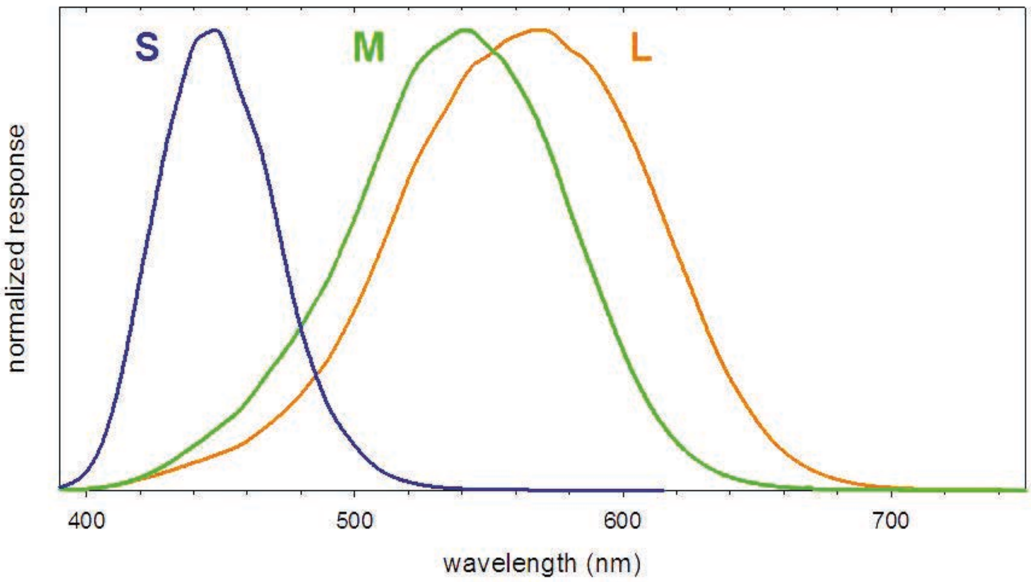

Fig.3

This has been the subject of intense experimental work, obtained by cross-experiments, from direct absorption measurements to photocurrent measurements, including in-vitro or in-vivo spectroscopic or electronic measurements. As we know, light can be described by an electro-magnetic wave, and the wavelengths of these waves, for the visible light, range from 400 to 700 nanometers, a nanometer being a fraction of a micron. The color blue corresponds roughly to wavelengths from 400 to 500 nanometers, and the curves [Fig.4] are the measurements of the photo-responses of the three different cones, with the rainbow's colors behind. The three types of cones are usually labeled with 's' (short wavelengths), 'm' (mid-wavelengths) and 'l' (long wavelengths). Here the mid-wavelengths—the green cone—and the long wavelengths—the red cone—are very close together, in terms of photo-responses. The only difference is that the green has a slightly higher response than the red cone, in the green, and the red goes a little bit further in the red, but the difference is small. All the curves shown here are the average results of many samples because, as we explained, from one person to another, these curves can vary slightly. So this is the 'typical' photo-response of an 'average' human observer. The interesting fact to notice is that the green and the red cones are very close together, they have almost the same photo-response.

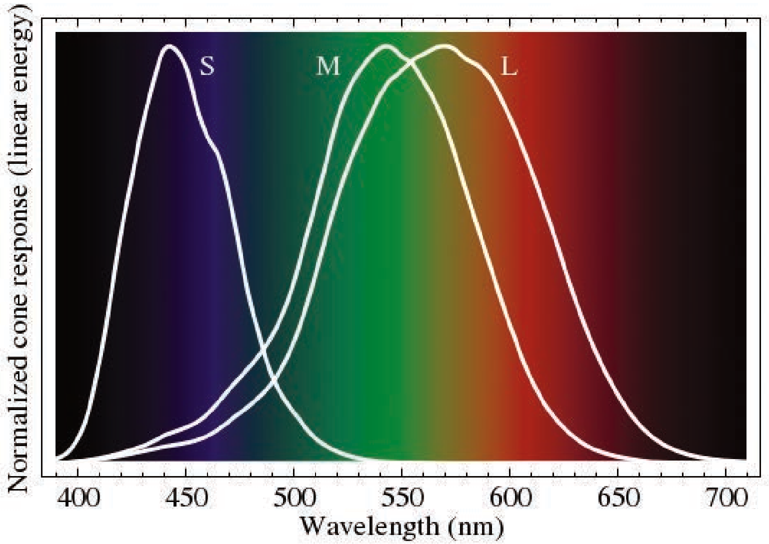

Fig.4

As a result, if you take several objects [Fig.5], here fruit, and observe the quantity of excitation, or stimulation, of the long wavelength cone (the red), and that of mid-wavelength (the green). We have just seen that the response spectra of the red and green cones are very similar, which means that, if an observer is looking at a green object, or at a red object, the excitation of the green cone and that of the red cone are very close. For example, here the dark green pepper and the red tomato have very close stimulations: they stimulate the ‘l’ cone and ‘m’ cone with very similar excitations. The same goes for the green apple and the orange, which are clearer, so the brightness is higher, but whose stimulations are almost the same. Of course, in the rainbow, yellow is just between red and green, and corresponds to a perfect balance between red and green excitation, right in the middle of the graph.

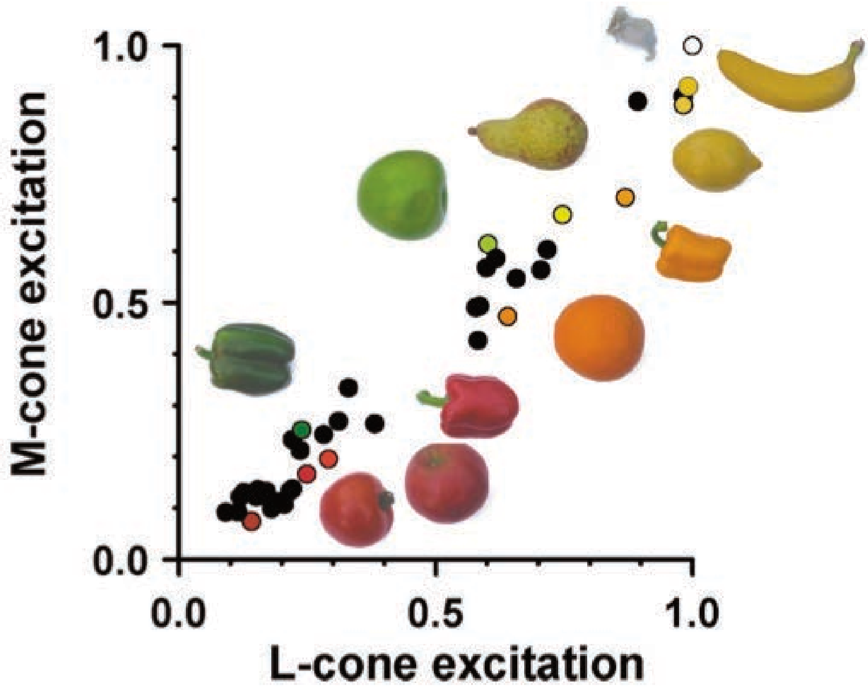

Fig.5 (Source: Gegenfurtner and Kiper, 2003)

So, how do we know that we have yellow, or green, or orange? The brain needs to calculate very accurately the ratio, the difference between the red cone excitation and the green cone excitation in order to recognize the colors. And where is this ratio done? In fact, it is not done in the brain; it is done in the retina itself [Fig.6]. The retina has a very complex neural network, which can calculate many sophisticated comparisons. For example, is a point darker or clearer than its neighbor? Is a point more green or red, or more blue? There is a compression of information in the retina before the transmission to the brain. There is a total of one hundred million rods and cones in the retina, but there are only one million fibers in the optical nerve, which carries the information into the brain. This means that the information has been compressed by a factor of one hundred before the transmission to the brain. And during this compression, ratios between green and red, or blue signals are calculated, and this constitutes the beginning of color vision, which takes place inside the retina, not in the brain.

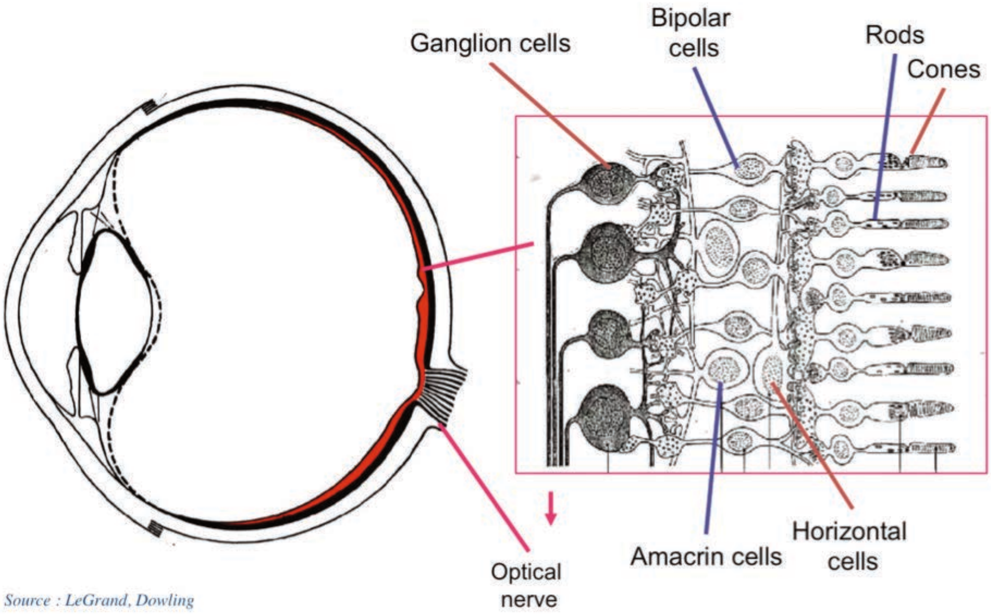

Fig.6**:** Retina and neural network

This is one of the reasons why we are sensitive to optical illusions. This one [Fig.7] is called ‘assimilation’:

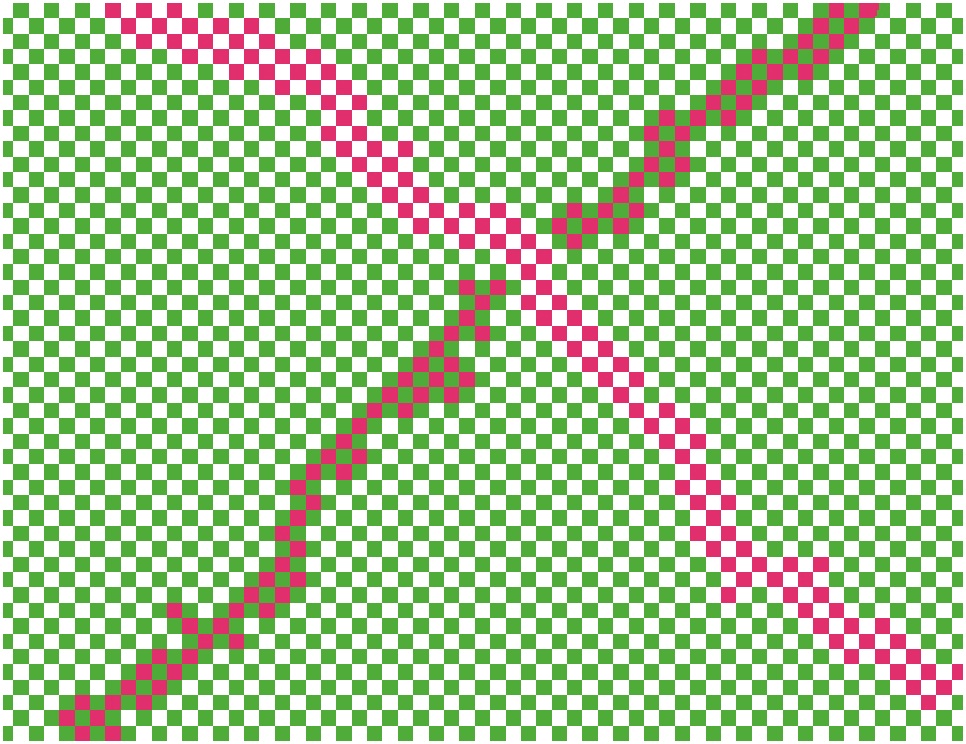

Fig.7

We think that one set of pink squares are darker than the other set of pink squares, when in fact they are the same color. The difference is that the first group are surrounded by white squares, and the second group by green squares. We calculate the balance between the different points in our retina and at the end of the calculation, the two colors appear as different. There are many different such effects, like successive contrasts or simultaneous contrasts, which were described by Michel-Eugène

Chevreul (1786-1889) in the nineteenth century[1], and this had a significant impact on the history of painting, as we know. Our brain cannot watch colors objectively since the colors are calculated in our retinas before the signal is transmitted to our brains, a point which confirms that color is indeed a subjective experience.[2]

Red, blue and green: three parameters, three cones, three dimensions, the colors appear to be in a three-dimensional space. In such a space, you need three coordinates to characterize the colors, and we can have several bases, several possibilities to describe a color. You can use the quantity of blue, of green and of red, which is, for example, the signals you set for your TV. You can also use yellow, cyan and magenta as a basis, or again hue, saturation and brightness, which can be taken in pairs. For instance, in French, when you come across a bright and saturated color (a buttercup, the red of a Ferrari, a laser ray), you call this *une couleur vive*. When you have a bright color which is not saturated at all (off-white or ivory, cream, the blue of the sky), you call that *une couleur pâle*, and in our colonial past our ancestors talked of *visages pâles* to refer to people with white skins. In the case of a dark and saturated color (the international Klein blue, Bordeaux, a pine tree, coffee, blood), we talk of a *couleur profonde*. And if the color is dark but not saturated (slate, taupe, black skin), we use the (rarer) phrase *couleur rabattue*.

In fact the saturation is the purity of the color: if there is only one wavelength with a color, you have a pure color, it is highly saturated; meanwhile white is not saturated at all, nor is grey. Brightness is the quantity of light, and a hue is a basic wavelength. Now three dimensions cannot be mapped on a piece of paper, because a piece of paper allows only a two-dimensional representation. Before we examine how this is commonly done, let's examine how the three-dimensional space can be illustrated [Fig.8]:

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1 See in particular *De la loi du contraste simultané des couleurs et de l'assortiment des objets colorés considéré d'après cette loi etc.* (1839) ; *Exposé d'un moyen de définir et de nommer les couleurs d'après une méthode précise et expérimentale* (1861) ; *Mémoire sur la vision des couleurs matérielles en mouvement de rotation, etc.* (1882). The phenomenon of assimilation is somewhat different from the simultaneous contrasts popularized by Chevreul, but the details of these phenomena have not yet been completely clarified and are sometimes still controversial.

2 Buffon (1707-1788) also worked on this phenomenon of successive contrasts of colors and shadows: 'lorsque [l'œil] est mal disposé ou fatigué, ou voit encore des couleurs, c'est ce genre de couleurs que j'ai cru devoir appeler *couleurs accidentelles*, pour les distinguer des couleurs naturelles' (*Introduction à l'histoire des minéraux*, in *Œuvres complètes de Buffon*, Paris, 1839, p. 638). We have all experienced it, when we look at a red square for thirty seconds, then at a white paper, and see a blue-green square.

Here we have four different colors: red, green, blue and yellow, four different hues. Saturation is increased from the left to the right, and brightness is increased from the bottom to the top of these different two-dimensional graphs. If you want to have all the space of colors, you have a three-dimensional atlas, here the Manson Atlas for colors [Fig.9], with several two-dimensional pieces for each hue to map the space of colors.

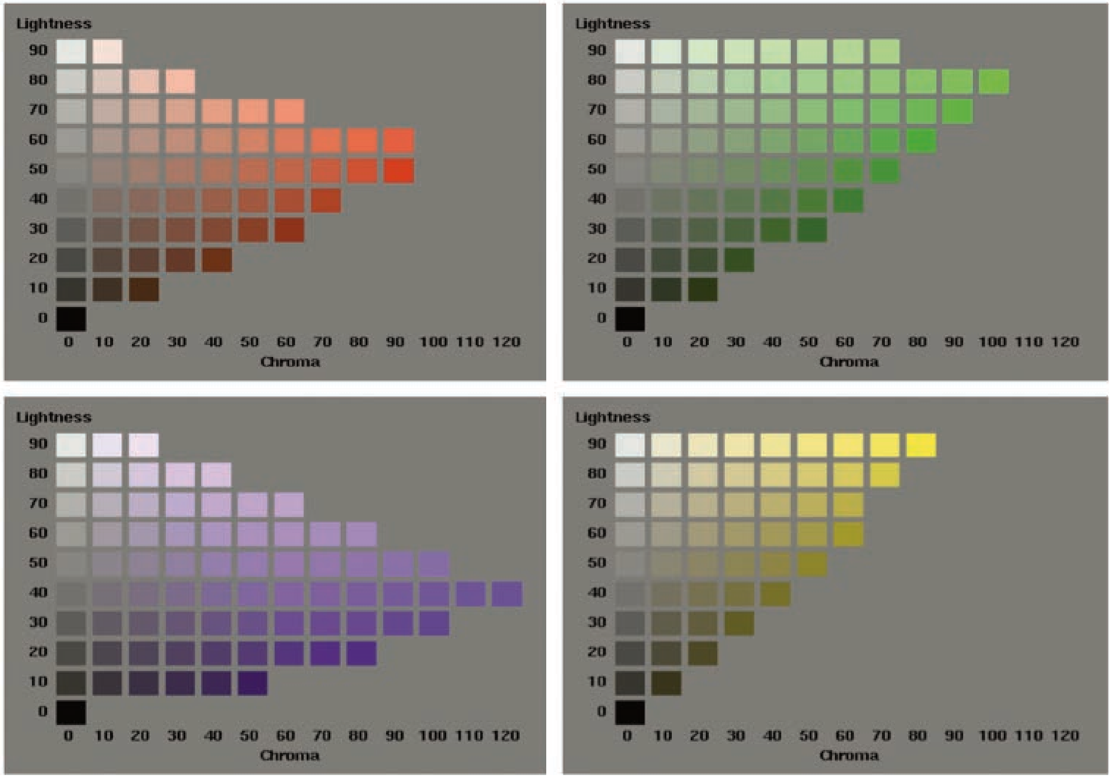


Fig.8: Hue, saturation, brightness

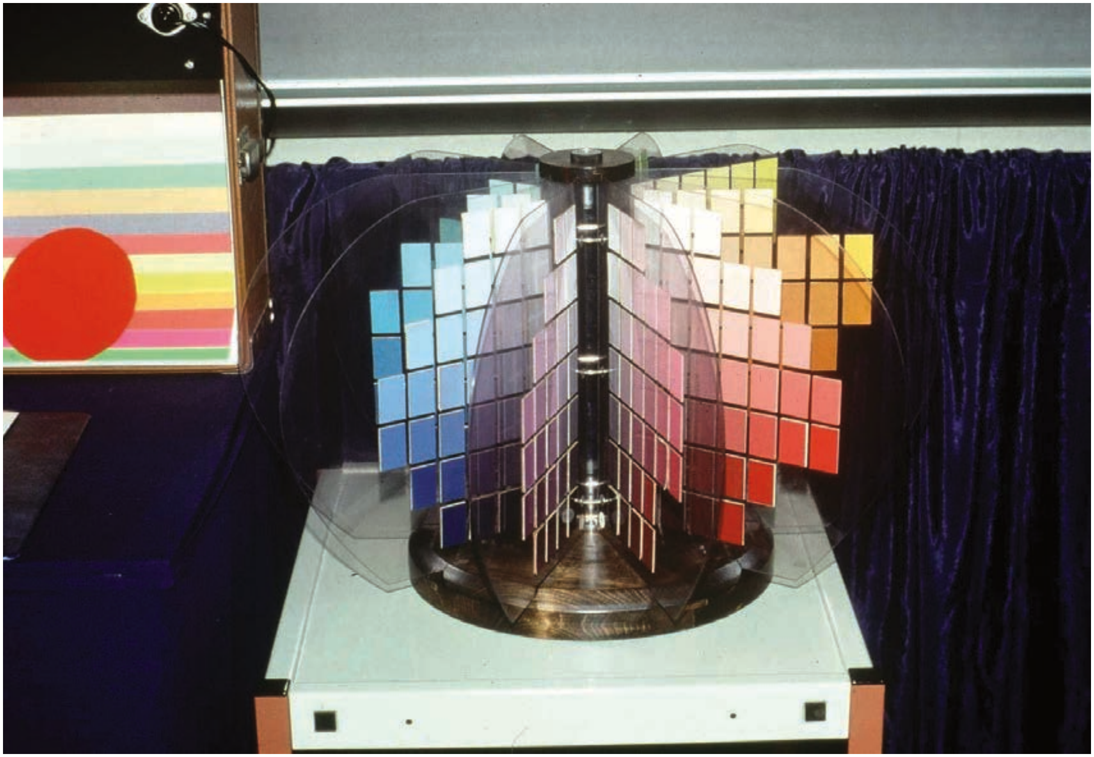


Fig.9 : The Manson Atlas for colors

Yet it is of course necessary to represent color in some two-dimensional space, but for this you need to forget one dimension. I will show you an example which is used everywhere by people working with color imagery, a chromaticity diagram [Fig.10], which basically skips over brightness. In this diagram, there is no black, no grey, no kaki, no brown, no coffee, no copper, no Prussian blue. Why does this chromaticity diagram have such a particular shape? Because it has been built in such a way that if you add two colors, if you do an additive mixing of two colors, then the new color you obtain through the mixing is in the middle between the two initial mixed colors. You have the pure colors at the periphery, and, for example, if you mix green and blue, the mix is a blue-green somewhere in the middle, if you do an additive mixing between yellow and blue you can create white light, and so on.

What is very interesting here is to talk about what is called the gamut [Fig.11], which is the space of colors that can be obtained by a TV screen.

The TV screen or the computer screen, as we know, has three phosphors, three primary colors: green, red and blue, which are clearly located in the chromaticity diagram. So if you mix blue and green, the colors are located on the line linking the two, and if you add red, you are located inside the triangle of lines. It means that all the colors that can be created on our TV screens are located in this triangle. Now as we can see, this triangle isvery small, which helps us understand why the screen can in fact only create a poor set of colors, if we compare it to the complete space of colors which it is possible to find in nature. We call this the gamut because 'gamma' is the lowest musical note (a G) in English, and 'ut' is the highest one (a C). So gamut designates the complete space of notes in music which can be produced by an instrument, and so the term is used here to show that this is the complete space of colors you can create with a TV screen. As we realize, there are many colors we will never be able to see on a TV screen or with any three-dimensional system of color representation. The gamut may be even more limited in the case of printers, which explains why, when we print

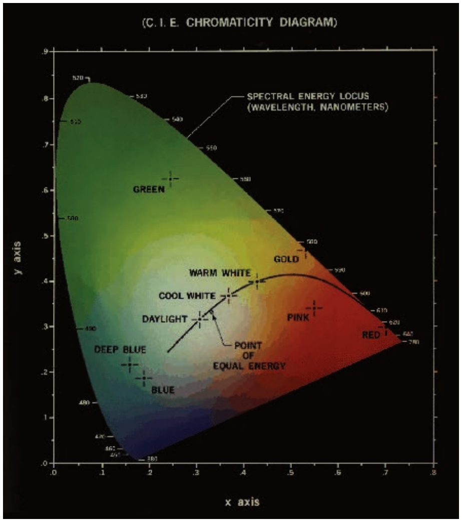


Fig.10 Chromaticity diagram

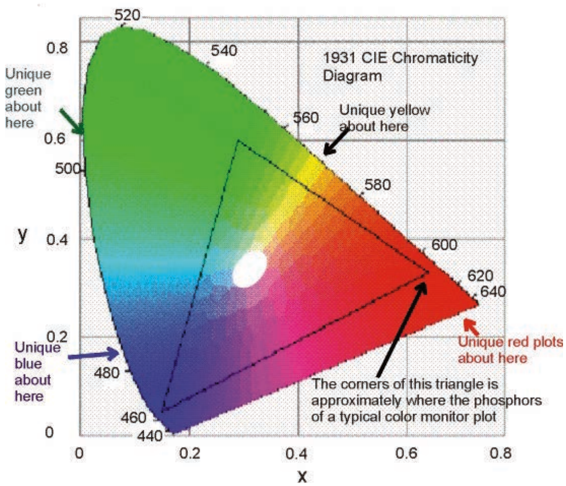


Fig.11 The gamut

something from our computer, we are sometimes disappointed by the quality of the printed colors when compared to those we see on our screen.

Similarly, when we go to museums, it is always interesting to compare the real colors of the works displayed and those of the representations we can find in books or on the Internet, because those representations have been made with a camera, a three-dimensional system of receptors, which, fundamentally, operate within a very limited gamut. Ironically, on the Internet, we can find many different representations of the chromaticity diagram [Fig.12], which do not look the same, because computers and printers are just not able to reproduce the colors.

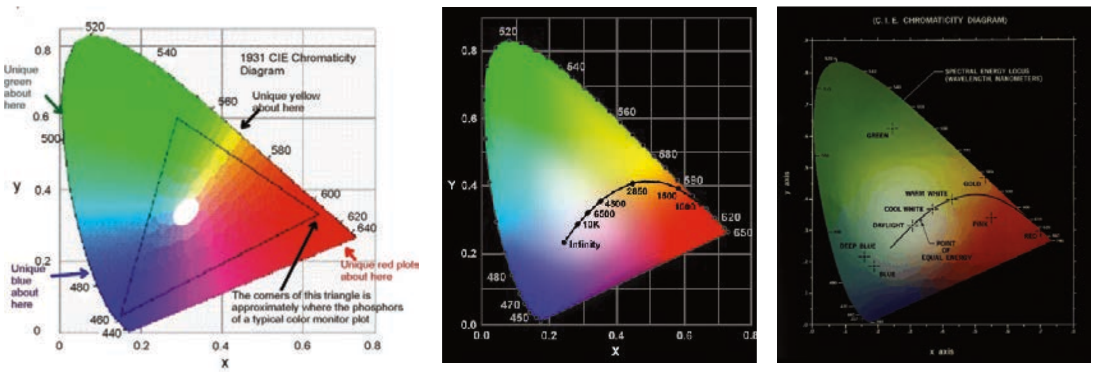


Fig.12

Here are examples of colors that just cannot be visualized on a screen:

- the buttercup [Fig.13], which is definitely ‘more yellow’ and brighter than its reproduction, it’s not this color, this is a really poor yellow;
- the purple of the gown [Fig.14] worn by a Professor of science at an Honoris Causa Doctorate ceremony;
- the various hues of blue and green in the sea [Fig.15], which have far more saturation than what any image of them can account for;
- the green ray of a laser pointer.

Fig.13

In the chromaticity diagram [Fig.16], those 'purer' colors are located outside the triangle of the gamut. We may therefore wonder why scientists chose to build such a small triangle, they could have chosen other points to obtain a larger triangle. The reason is that it was thought most important to concentrate on good representations of a certain number of 'common' colors, which were also deemed important for consumers (e.g. on TV, butter must look like butter, people's skin colors must look similar to those experienced in life).

Fig.14

Fig.15

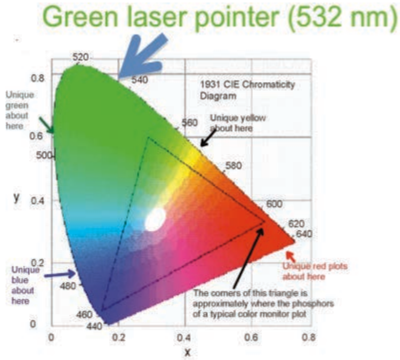


Fig.16

2. Of color-blindness

In French we call color-blind people *daltoniens*, in reference to the work of John Dalton (1766-1844), an English chemist who was color-blind himself, and who described and studied this problem. In fact, color-blind people happen to have only two cones [Fig.17]. Most of the time either the red or the green cone is missing.

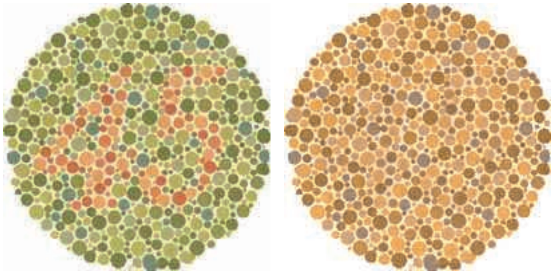


Fig.17

In this picture, a color-blind person cannot see the number 45 apparent in the left-hand-side picture, and sees what appears in the right-hand side picture. With her/his two cones, that person sees a projection of the space of colors in a poorer, or smaller, space of colors. The same happens of course with the chromaticity diagram [Fig.18].

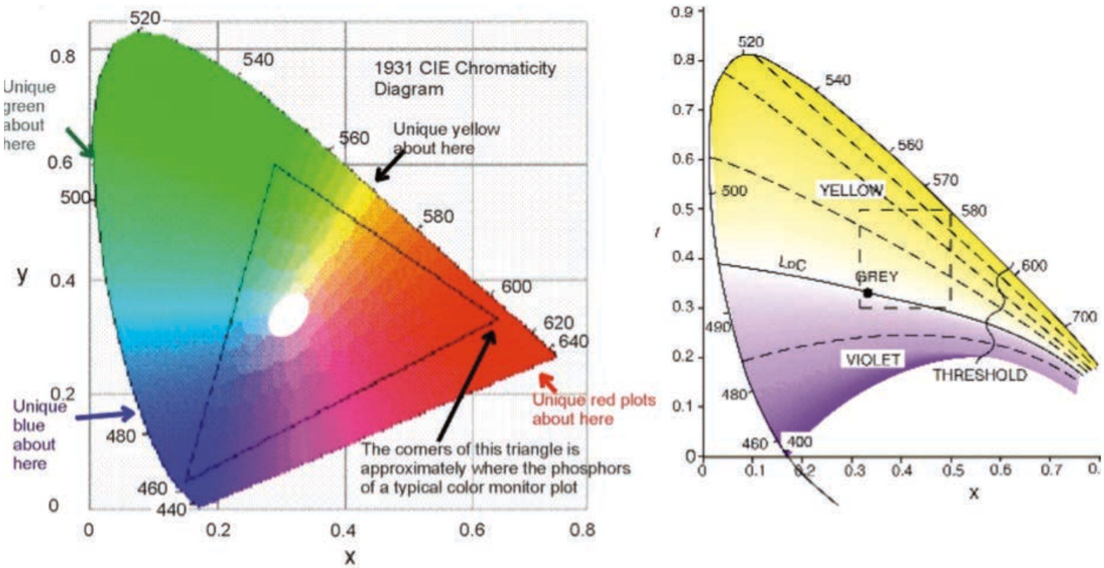
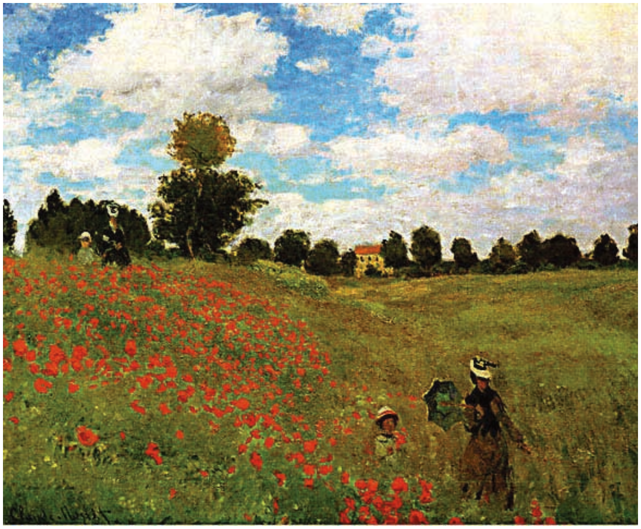


Fig.18



A very useful website, vischeck.com, allows you to calculate and visualize a picture you submit to them as seen by a colorblind person. Here is an example with a poppy field [Fig.19].

It is generally estimated that the proportion of color-blind people in the population is 8% male and 0.6% female. Why such a discrepancy? It is because the development of the green or the red cone depends on the presence of the right gene or the X chromosome. For men there is only one X chromosome, while there are two X chromosomes for women. So the probability for a woman to be colorblind is a square of the probability for a man (0.64% is a square of 8%). That is why we say that color blindness is given by women, but inflicted to men. Now this is interesting because we have seen that the red and green cones' spectral properties are very close to each other and thanks to the study of colorblind people, we understand that the genetic origins of the red and green cones are very close too.

Fig.19: http://www.vischeck.com/vischeck/vischeckImage.php

3. Yellow

At this stage in our story, we believe that there are typically three primary colors because we have three types of cones, except for color-blind people: blue, red and green. Yet, if you ask a painter[3], most of the time, he or she will say that there are typically four ‘primary’ or basic colors, outside black and white: red, green, blue and yellow, ‘primary’ in the sense of color composition, not in the sense of mixing. If we look at this picture [Fig.20], we will indeed agree on the presence of those four basic colors (even though, of course, there are far many more than this).

Anyone looking at orange can imagine it to be the result of some mixing between red and yellow, but no one looking at some red or blue will see it as the result of the mixing any other colors. The feeling some people have that green looks like yellow mixed with blue is probably related to childhood experience with boxes of paints. If you say to somebody, who is not aware of additive mixing, that blue and red give magenta, they will show no surprise. The same if you explain that blue and green give cyan, which is a kind of blue-green. But if you say that red + green gives yellow, it will seem surprising, because yellow does not seem to have any link, neither with red, nor with green, it’s a different color, it’s another color. So yellow is present in artists’ primary colors whereas it is not present in the three primary colors absorbed by the retina: red, blue and green.

Fig.20

3 Apart from the Ancient Greeks, of course, who did not have all the pigments, or painters like Mondrian or Yves Klein, who chose to paint without the green.

Color terms considered necessary (capitals) and desirable (lower-case letters), from Zollinger, *Color a multidisciplinary approach.*

German[30] (42)	French[30] (31)	English[30] (8)	Hebrew[32] (19)	Japanese[33] (55)
weiss	blanc	white	LAVAN	SHIRO
grau	gris	gray	afor	kai(-iro)
schwarz	noir	BLACK	SHAKHOR	KURO
GELB	JAUNE	YELLOW	TSAHOV	KI
	ocre			
orange	ORANGE	ORANGE	katom	daidai
beige	beige			
braun	BRUN	BROWN	khoom	cha(-iro)
	rouge carmin			
ROT	ROUGE	RED	ADOM	AKA
	rose	pink	varod	pink
	mauve	mauve		murasaki
		purple	tekhelet	
violett	VIOLET	violet	segol	
	indigo			
BLAU	BLEU	BLUE	KAKHOL	AO(I)
	turquoise			kon
GRÜN	VERT	GREEN	JAROK	MIDORI

Fig.21

This endows the color yellow with a particular role. If you look [Fig.21] at the colors or color terms considered necessary [capitalized] or desirable [low-case] in different languages, only four colors are always labeled as necessary—yellow, red, blue and green. It's another way, through language, of saying that these four colors, are the four most important colors for our understanding, our feeling of the space of colors.

This is an interesting problem because we realize that we have three cones in our retina, but four 'important' colors. The first thing to remember when we talk about yellow is that yellow is a complementary color of blue; that is why the association of yellow and blue is one of the most impressive contrasts, following the idea that complementary colors are reinforced when they are associated. One striking example of a colored masterpiece with such saturated colors is the mask of

Toutankhamon [Fig.22], which was made of gold and lapis lazuli[4]. Coming from another era and culture, another example can be found with this Tibetan mask [Fig.23].

Fig.22

Fig.23

Now the question is: why is yellow important? In fact, it becomes important, not at the detection level, but in the neural network. Again, we have to come back to the calculations made in the retina. Here is another picture, with the cones and the rods, showing all the calculations made in the neural network in the retina [Fig.24]:

4 Lapis lazuli is the stone from which was later extracted the ultra-marine color, the blue sometimes called 'Fra Angelico blue' (see his *Coronation of the Virgin*, in the Louvre Museum: http://www.louvre.fr/en/oeuvre-notices/coronation-virgin).
Another instance of the way yellow and blue have been associated as complementary colors can be seen in the comparison between the 1887 (www.vangoghgallery.com/catalog/image/0320/Self-Portrait.jpg) and 1889 (www.vangoghgallery.com/catalog/image/0627/Self-Portrait.jpg) portraits by Van Gogh in the Musée d'Orsay: the latter one has a cyan background therefore the hair has red hues, whereas in the former, with its bluer background, there is more yellow both in the hair and in the face.

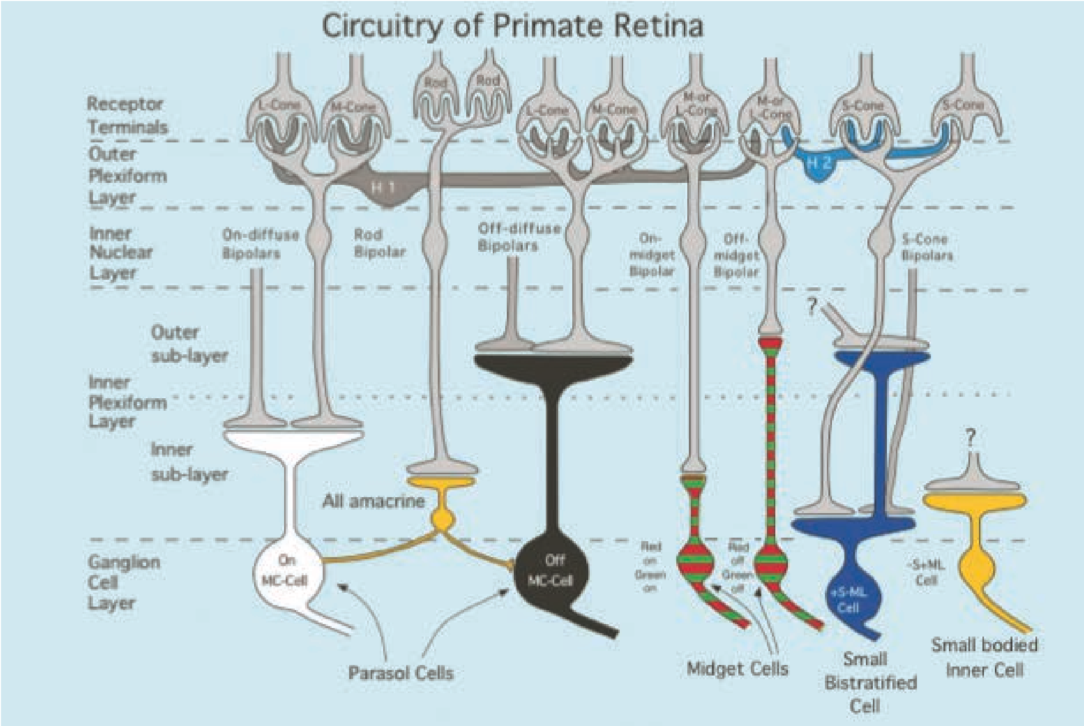


Fig.24 (Source Lee, 2005)

In fact, in the retina, mainly three parameters get calculated. The first one is the *luminance*, the total quantity of light, and in this case we make the sum of the three values of light detected by the three cones. Then, for color, there are two calculations that are made: the *blue/yellow ratio*, i.e. the difference of the short cone signals and the sum of the red plus green signal, and, finally, the *red/green ratio*, which is a recent evolution. Red and green photosensitivity present close spectra, since, as we have seen, red and green photospectra are close together, and originate from a recent bifurcation in what was before understood as a single physiological property. Before that (some 35 million years ago…), we had only two cones: the blue and the yellow (i.e. the red + green). The blue/ yellow ratio - which is calculated in the retina - is a memory of this old way of seeing colors.

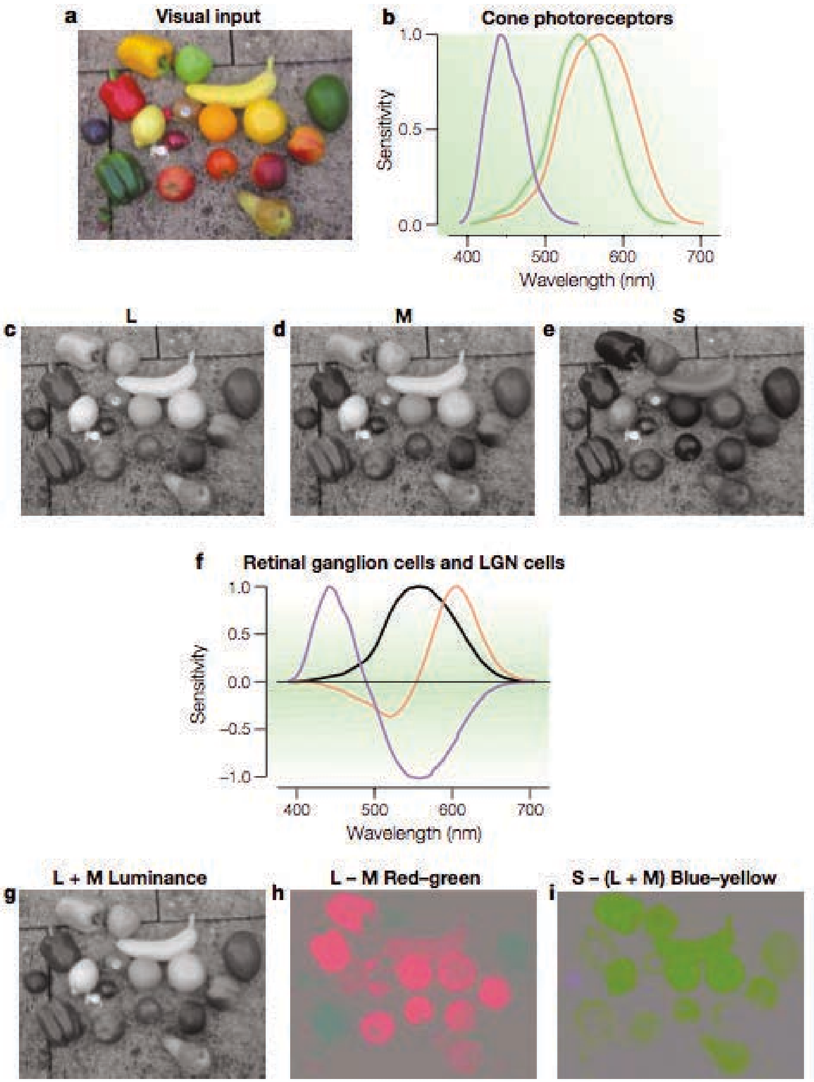


Fig.25 (Source: Gegenfurtner, *Nature Reviews* 2003

There are many different signs of this. The red and the green cones are very close together, which is a sign that it's a recent evolution, and red and green sensitivity are both encoded on the same chromosome, the X chromosome. To illustrate this, we have the very interesting example of New World monkeys. Male New World monkeys are all dichromats but some females are trichromats. These New World monkeys were separated from the Old World monkeys roughly 40 million years ago, and they may have migrated across the Atlantic Ocean on a raft of vegetation. After this separation, Old World monkeys in Africa evolved towards to trichromacy but the New World monkeys in South America did not develop this key completely since only some females became trichromats and these monkeys are, therefore, subject to a major gender inequality.

So, to summarize, if we have a visual input like this group of fruit [Fig.25], we see what the long-wave red cone registers, then the mid-wave green cone and then the short-wave blue cone (notice there is no blue in this image).

Then, there is a calculation and at the end of the process, what is transmitted to the brain, the signals which are carried through the optical nerve to the brain, are the luminance—the total quantity of light—, the red-green ratio and the blue-yellow ratio. There is an interesting result [Fig.26] showing the importance of these two ratios, which is the color-difference threshold as a function of wavelength (the number of wavelengths we can distinguish). We see that there are two points in the spectrum where the color-difference spectrum is very small, that is where you have the highest color distinction, when you meet the balance between red and green, and when you meet the balance between blue and yellow.

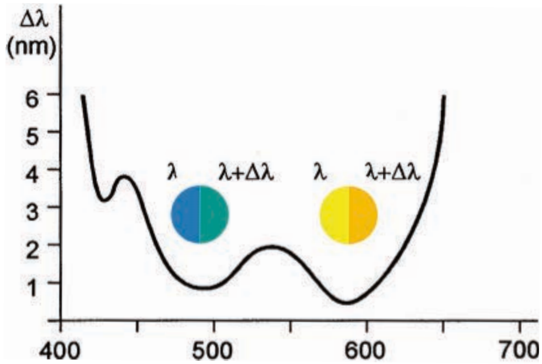


Fig.26 Color difference thresholds

4. Gloss

In the last part of this paper, I would like to focus on another, very important characteristic of an image, which is *gloss*, important in this context because it really opens more possibilities for yellows. If we return to the picture of the Toutankhamon mask [Fig.22], we realize that it is not merely a binary combination of yellow and blue.

We can see that there are very glossy points, which is due to the presence of gold and which we recognize as being different from a more ordinary yellow-painted piece of wood. It is also because of the gloss that we see it is a three-dimensional object, a face. Gloss is a key factor for the understanding of the characteristics of a material, and also of relief, of volume. For example, when you see a car [Fig.27] or a person [Fig.28], (see the earrings, the lips, the skin), when you are looking at chocolate [Fig.29] or a celadon porcelain from Korea [Fig.30][5].

Fig.27-30

Manufacturers of such products conduct frequent experiments in which they show pictures of different chocolates to people, and then ask them which one they deem is the best one, without testing it, just by seeing it, and there is a clear correlation between the gloss of the chocolate and the idea that it must be good chocolate.

5 See also the multi-layered paintings of the Flemish Renaissance, with their unique combination of color and gloss.

Gloss is constantly present in our everyday lives: are our teeth well brushed? Are our shoes well shined? Is our hair washed? Are we in a sweat? A bit weepy? With tears in our eyes? In all those questionings, color does not play any role, we only rely on gloss to get the answers. Gloss is not merely a secondary visual attribute, it is in fact a crucial factor in the analysis of a human being's vision. In contemporary art we all know the work of Pierre Soulages [http://www.pierre-soulages.com/], undoubtedly the master of gloss has chosen the 'no-color' option, and painted only in black, with an incredible array of gloss variations.

If we are presented with juxtaposed details of a series of black-coloured objects—a tyre, coal, a vinyl disk, the shirt of the New Zealand rugby team (the famous 'All Blacks'), the pelt of a panther, a Doc Martens shoe—it will take us just a second to identify which is which, and the only difference is that of gloss. The brain has learned to associate optical signals relevant to gloss perception and material identification, and it is very much part of our culture. In fact, it means that we have the capability to have access to a micro-roughness analysis of a surface through visual observation. Color originates from the spectrum of the light, texture from the variation of the surface of an object and gloss from the roughness of this surface, at a very small scale, below eye resolution.

When you have a very flat surface with reflection, you have a mirror. Light falls on it and the angle of the reflected light is the same, with the normal incidence, as the incoming light. This is called specular reflection. If you have an object which is not flat, but with a very important roughness at a very small scale (which you can't see)—e.g. a piece of paper or of cloth—you have diffuse reflection and light goes in all directions [Fig.31].

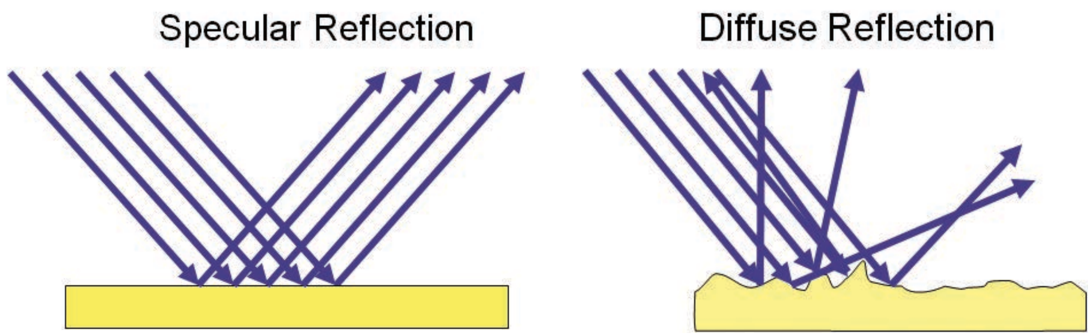


Fig.31 Reflection on a mirror and on a piece of cloth

In between, when you have an object with a roughness which is not completely equal to zero, i.e. which is not completely flat, then you begin to have gloss. In fact, there may be different cases: you can have a strong specular reflection, which causes the image to be quite distinct, but if the specular reflection is lower, that light is more spread around the specular reflection, then you have a contrast gloss, or a glint, or a sheen. This, of course, depends on the angle of incidence, you can find some materials which are glossy only at tangential angles of incidence.

This is well exemplified when we look at the same object through pictures taken with different wavelengths [Fig.32].

In the left picture we see that the table is not a mirror, but there is some gloss, a kind of fuzzy reflection. In fact, this picture is taken with visible light, at submicron wavelength, and we have an important diffuse reflection with a big gloss. The right-hand picture shows the same scene, but now seen with mid infrared light–ten micron wavelength, so the wavelength of light is ten times larger than with the other picture – and then the surface appears completely flat for

Fig.32

this wavelength. While in the top picture we had diffuse reflection and gloss, in the bottom one we have a perfect reflection, and this is a mirror. So the same surface can be a mirror for a given wavelength and a glossy plane for another.

To see gloss, to experience it, you have different possibilities [Fig.33].

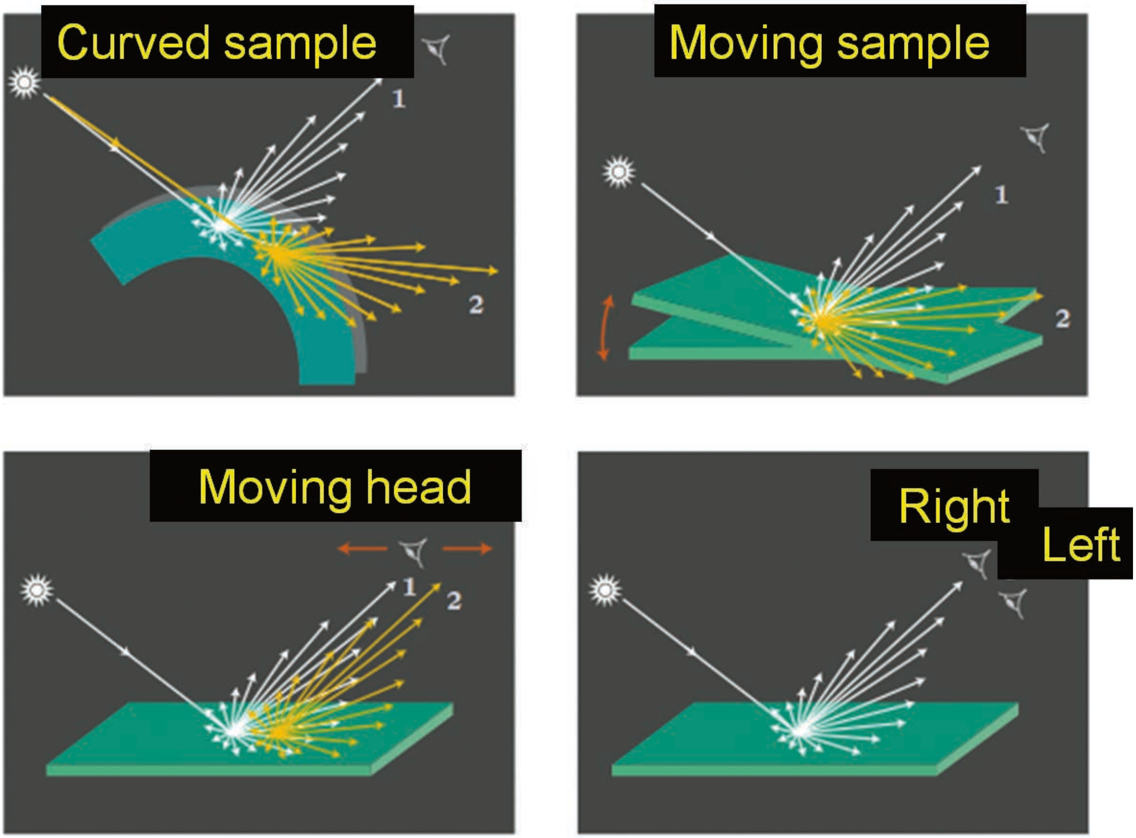


Fig.33 (Courtesy of Françoise Viennot, MNHN, Paris)

For instance you can curve the sample or the shape: when you are looking at somebody, the shape of the face moves, you can see the differences in gloss, and since you know the shape you can analyze the gloss. And if you know the gloss, you can analyze the face, so there is a dialogue between the two. If you want to be sure, you can move the sample, or you can move your own head, or you can use your two eyes separately, to see the different recordings by the right or the left eye, in order to add different angles of incidence. There are more complicated cases: butterflies and insects [Fig.34] have a very particular gloss because it depends very much on the angle of incidence, and these materials are of a very particular roughness, with a specific organization of the structures, and specific physical properties, angle properties which are very interesting to study and very particular. We don't know how to make this structure, how to fabricate it, only nature can do it, and researchers are looking for ways of designing this kind of material.

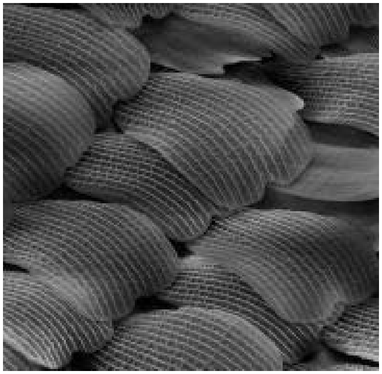




Fig.34 (Courtesy of Serge Berthier, Université Paris Diderot)

Here is a diagram of the intensity of reflection of light, for two different samples, depending on the angle of reflection [Fig.35].

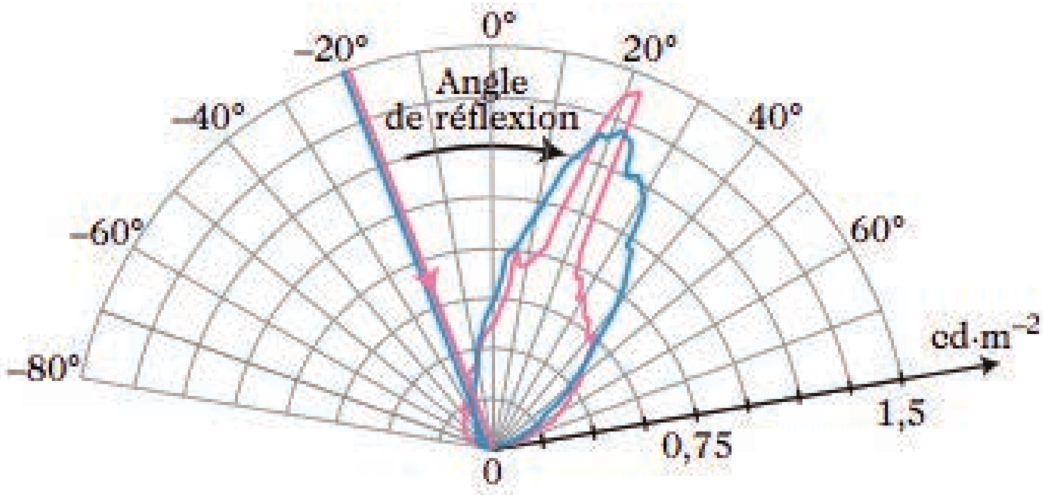


Fig.35 (Courtesy of Françoise Viennot, MNHN, Paris)

In pink, a rubber sample, and in blue, a coated paper with the same color, black. The two samples are black, and the only thing which is different is the curve of reflection for the rubber sample, it is more specular, more important here than for the coated paper, the focus of the reflection is more important. Our brain, the eye in your brain is able to analyze the difference between these two curves, to recognize, and to use this information to recognize the material. It is very impressive to see how the brain is able to analyze very complex parameters, such as the function of the angle of incidence. It is very important to understand how this is very much part of color, the topic of this collection of essays. Color depends on many parameters: the angle of incidence, the angle of reflection and the intensities.

That is why the title to my paper is ‘Yellows’, because if you include gloss in the calculation, in the analysis, there are indeed many yellows. Let’s try and summarize our findings. First, we have seen that colors are in a three-dimensional space, due to our three types of cones—red, blue and green. We have explained that, due to the intra-retinal neural network analysis, yellow has acquired a specific importance. Blue/yellow was a two-color system before the red/green ‘distinction’ appeared some 30 million years ago. We have also shown that the capacity of television or video-projection to reproduce colors is very poor. Finally, we have talked about gloss, which is extremely important in our apprehension of the world. What is surprising and what remains a question for us all is why the languages seem so poor in words to describe gloss. If we take the example of the six black objects examined above, we have no words to tell the different types of gloss between them. Why are there so very few words to account for a phenomenon that is so important in our incessant perception of nature?