Kurt Schläpfer

The Basics of Color Science

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Prof. Dr. Kurt Schläpfer

The Basics of Color Science

2nd Edition

Publisher:
Ugra Swisstesting AG

2026

Imprint

Publisher:
Ugra Swisstesting AG (Ugra)

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Distribution:
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Preface 2nd Edition

In honour of the author, Prof. Dr. Kurt Schläpfer, who sadly passed away in April 2019, we have slightly revised this brochure. Through this brochure, we aim to pay tribute to the author's life's work and continue his passionate dedication to the field of color theory. This second edition includes minor changes to the content and has only been slightly revised. In line with the author's intentions, the essential core of the brochure remains unchanged.

April 2025 *Mathias Schunke*

Preface 1st Edition

An author intending to provide the basic facts of color science is faced with the question how thoroughly this topic should be treated. Various condensed presentations can be found containing all major colorimetric calculations, but the necessary explanations are too abridged. In the author's view this is a wrong approach. Even a condensed treatment should be easily understandable by avoiding too much mathematics. Therefore this booklet contains only one colorimetric equation. Furthermore, the computation of color values from spectral values is omitted. Such a presentation should also attract non-technical readers.

As author I am most grateful to Erwin Widmer, the managing director of Ugra, who gave me free reign to write this booklet. Moreover, many thanks go to Harry and Patricia Keller for their editorial assistance of the English version. Finally I thank the staff of the company Visual Service AG for their collaboration.

February 2011 *Kurt Schläpfer*

1. Light as precondition for color vision

Color vision requires light, or more precisely, visible radiation. The so-called visible spectrum comprises the wavelengths from 380 nm to 780 nm. The wavelength band below 380 nm is called ultraviolet radiation. Above 780 nm is the region of the infrared radiation. All visible wavelengths together are perceived as white light. If the white light is split into smaller wavelength bands, the following colors result:

380–450 nm	violet to blue
450–500 nm	blue-green
500–550 nm	green
550–600 nm	green-yellow to yellow
600–650 nm	orange
650–780 nm	red

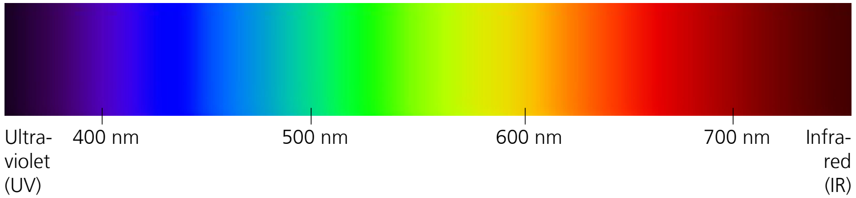


Fig. 1 Visible spectrum split into bands of different colors.

These colors can be seen in a rainbow. This happens when the sunlight shines through raindrops which split up the light into single wavelengths. The rainbow does not contain purple colors, because these colors only occur, if red and blue light are mixed.

There is no natural or artificial light source producing perfect white light. The most important light source is the sun whose radiation is perceived as slightly yellowish. This is because the shortest wavelengths representing the blue light are scattered in the atmosphere. As a result, the sky appears blue on a clear day. At sunset the sunlight becomes reddish, as it has to travel a longer way through the atmosphere thereby causing an additional scattering of the green and yellow portions of the visible spectrum.

An important criterion related to light and light sources is the illumination level, expressed in lux. The range of lux values extends over six orders of magnitude:

10,000 lux	full daylight
1,000 lux	store light
100 lux	dim light in living rooms
10 lux	well-lit street
1 lux	badly lit street
0.1 lux	full moon on a clear night
0.01 lux	moonless clear night

For perfect color vision the illumination should exceed 500 lux.

2. The human eye acting as camera

The eye is in many respects comparable to a camera. Where the camera has a film or an image sensor, the light-sensitive layer in the eye is the retina. It is equipped with so-called photoreceptors. Three types of receptors sensitive to blue, green and red light are responsible for color vision.

The entirety of colors the human eye can perceive is produced by different activation of these receptors. Yellow, for instance, is perceived, if the green and red receptors are nearly equally activated. Based on their physical appearance the color receptors are referred to as cones.

As proper operation of the color receptors requires a certain level of illumination, the human eye is equipped with a second type of photoreceptor which is not sensitive to color but has a light-sensitivity being about 100 times higher than the cones.

These receptors have the physical shape of *rods*. At illumination levels of less than 0.1 lux, only the rods but not the cones are active, meaning that color vision is not possible at such a low illumination. You may realize this, if you try to recognize the color of a car on a badly lit car park.

Or as the saying goes: "All cats are gray by night." Above 500 lux the rods become inactive, so that perfect color vision is possible.

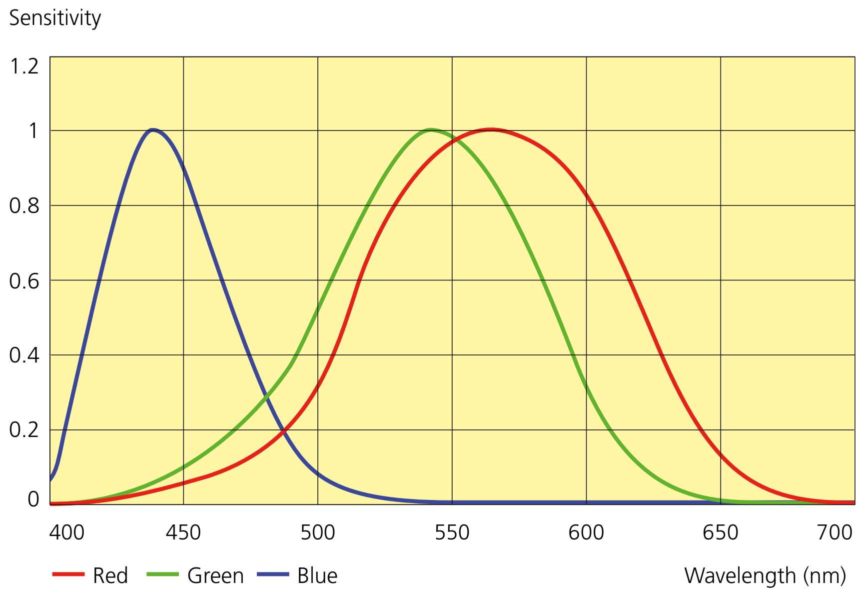


Fig. 2 Spectral sensitivity of the three different color receptors of the human eye.

3. Color vision deficiencies

Not all people have identical color vision. The reason is that one or several color receptors can be defective. In the past, the various types of color deficiency have been thoroughly investigated. The most frequent category of color deficiencies is the red-green color vision defect. In this case, the spectral sensitivity of the green receptor is shifted closer to the red receptor making the red-green discrimination impossible.

Fig. 3 A red-green color picture as viewed with normal color vision and with the red-green color vision defect.

Another kind of color vision deficiency occurs when one of the three color receptors is missing. This leads to the inability to perceive blue, green or red colors. Moreover, it is possible that two color receptors are missing. This defines three further cases of defective color vision. Finally, there are very few persons, namely one in 20,000 of the population, who are missing all three color receptors. This is known as total color blindness. Color deficiency can be detected in different ways. Very popular are the so-called Ishihara Charts.

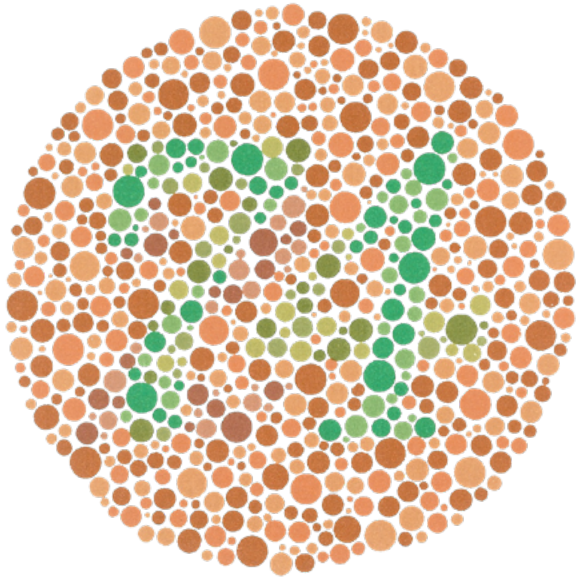


Fig. 4
Ishihara Chart for testing the red-green color vision defect: Viewers with normal color vision read the numeral 74, while viewers with a defective color vision may read it as 21.

Men are more frequently affected by color vision defects than women, because the genes controlling the function of the color receptors are carried on the X chromosome. Men only possess one X chromosome (and in addition a Y chromosome), while women have two X chromosomes both of which would need to be defective, which is less likely. The most common form of color vision deficiency, i. e. the red-green color vision defect, is found 15 times more often among men, the frequency being one in 20 for men and one in 300 for women.

4. Classification and description of colors

If a person is given a random collection of color samples and asked to classify them, it is likely that the first step will be to sort them according to their hues. One would probably start with clearly discernible hues such as red, yellow, green and blue. These groups could then be subdivided in red-yellow, yellow-green, green-blue and blue-red. A closer look at these eight hue steps, i. e. yellow – yellow-green – green – green-blue – blue – blue red – red – yellow-red, shows that, if yellow is added, they form a closed chain permitting to arrange them on a circle. The organizing principle is then to give the four principal hues opposite positions on the circle and to arrange the other hues in such a way that a smooth transition from one to the other principal hue results. This arrangement of hues is called a *color circle.* To identify a particular hue on the circle, it is basically possible to use a denotation in words, but a more scientific approach is a numerical characterization by dividing the circle in angular degrees and relating each hue to a so-called *hue angle.* The color circle is typically subdivided in 360 degrees, with the following hue angles attributed to the four principle colors:

- Red 0° (identical with 360°)
- Yellow 90°
- Green 180°
- Blue 270°

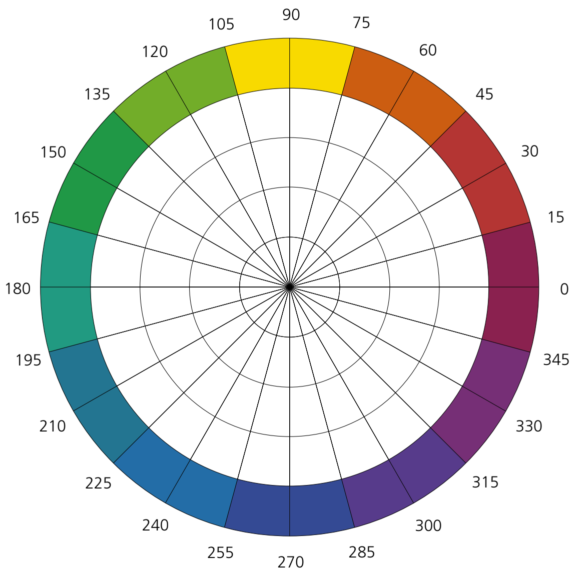


Fig. 5 Color circle subdivided into 360 degrees.

Having classified the colors according to hue, the next step is to distinguish color samples having the same hue. An obvious approach is a classification into darker and lighter samples, which leads to the criterion of *lightness.* Among the samples with the same lightness one would further find some being more colorful or saturated than others. This third criterion is called *chroma.* (The term chroma correlates approximately with the attributes of saturation and colorfulness.) Colors having the same hue can be arranged in a two-dimensional diagram using the attributes of lightness and chroma as coordinates (see Fig. 6).

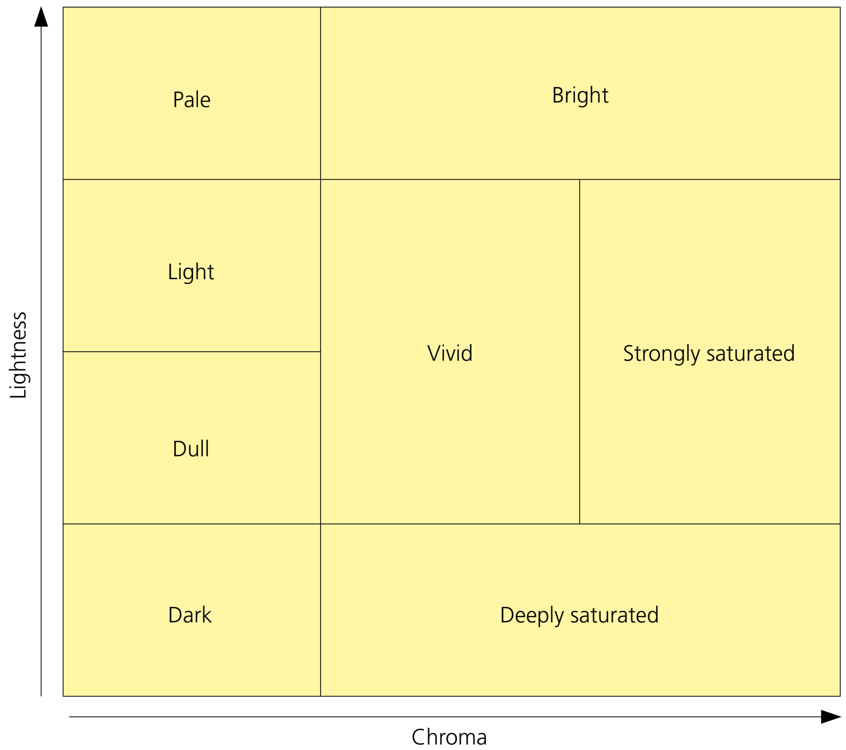


Fig. 6 Names for different combinations of lightness and chroma.

Certain combinations of lightness and chroma for a given hue can also be denoted by color terms. For instance, a dark red is a brown and a dark yellow is olive. To describe intermediate tones on the lightness and chroma scale as accurately as possible, a numerical characterization is again possible, usually using a scale between 0 and 100. If the possible color samples for a given hue are arranged in steps of 15 units for both lightness and chroma, a color chart results. Fig. 7 shows an example for an orange color having a hue angle 50°.

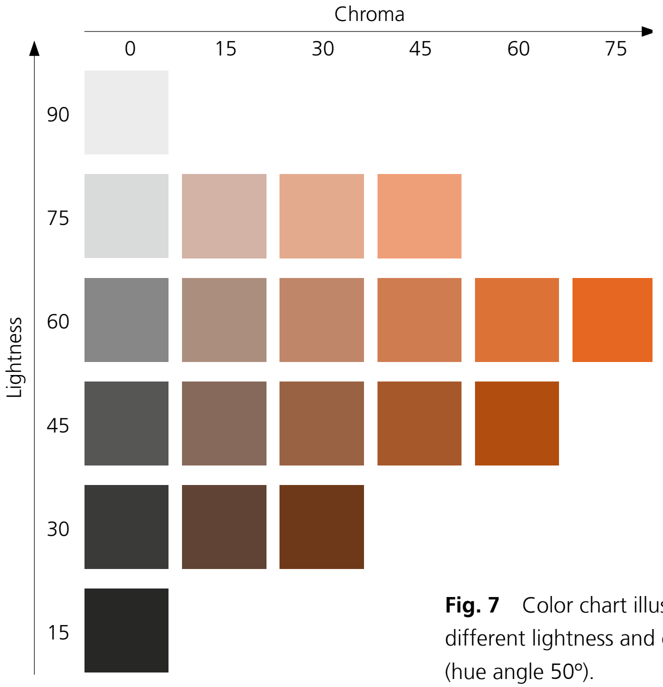


Fig. 7 Color chart illustrating steps of different lightness and chroma for orange (hue angle 50°).

An important principle of such color charts is that the color samples are visually equally spaced, meaning that the perceived color difference between any sample and its neighbour is the same. It is important to note that lightness values of 0 and 100 are theoretical limits not existing in the real world. Even a lightness value of 15 is a very dark black, but for instance possible as car paint. White surfaces may attain values of 95 or 98 at the highest. Many white papers used for magazine printing have lightness values not higher than 90. Equally, the highest chroma values are less than 100 for most hues. Generally, yellow colors attain higher chroma values than green and blue colors, which are slightly above 60.
To summarize, a color description requires three attributes, meaning that colors are mapped into a three-dimensional space which is referred to as *color space.*

Let us return to the classification of colors: If different "observers" perform this task, the resulting classifications are not identical. For instance, the yellow assigned to a hue angle of 90° might be more reddish or more greenish, depending on the individual judgment of the viewer. The same differences may occur when the principal hues green, blue and red are defined. Therefore, if a given color has to be described in terms of hue, lightness and chroma, it is of vital importance that a unique color classification is applied for all users. As a consequence, a standardized color space is needed. It is the merit of the *Comité International de l'Eclairage* (abbreviated CIE), the international body responsible for recommendations for photometry and colorimetry, to have created such a standard color space. Prior to discussing this, it is necessary to learn how colors are measured.

5. Measuring colors

As mentioned earlier, the human eye is equipped with three color receptors and color perception is the result from their different activation. Suppose that you want to reinvent the principles of color measurement, you would probably construct a kind of digital camera being capable of imitating the function of the human eye and their color receptors. This camera would then produce three signals describing the blue, the green and the red portion of the measured color. With this design you are already close to the concept how color measuring instruments are working today.

Before color measuring instruments could be built, it was necessary to identify the spectral sensitivities of the three color receptors of the human eye. These sensitivity curves cannot be simply measured in the human eye. The only way to determine them are color matching tests carried out with a sufficient number of test persons. We will not go into the details how such color matching tests are performed. The results are sensitivity values for the blue, green and red receptor at each wavelength. As not all observers chosen for such a test have exactly the same color perception, although they all have normal color vision, it was necessary to define average values. Already in 1931, a set of such sensitivity values has been standardized by the CIE. In this way, the so-called *Standard Colorimetric Observer* has been defined. This specification is still the basis for all devices that measure color. Therefore, the instrument measures colors as they are recorded by the virtual CIE standard observer rather than as they are perceived by an individual person.

However, it must be added that the virtual standard colorimetric observer matches the average observer having normal color vision.

Important principle in colorimetry: When discussing color values, it is not important how the involved persons perceive the colors. The accepted colors are the ones measured with a color measuring instrument based on the CIE Standard Colorimetric Observer.

The CIE standard curves defined above are specified in such a way that white light produces three signals yielding a sum of 100. The curves are therefore different from the curves shown in Fig. 2. To avoid any confusion, the CIE has denoted the red signal with X, the green with Y and the blue with Z. Hence, a color measuring instrument measures primarily the three values XYZ. In principle, any color can be completely described by these three values. Although the XYZ values are somewhat abstract, they have a certain significance (see Appendix).

6. The CIELAB color space

The CIELAB color space was created with the aim to transform the somewhat abstract XYZ values into the perceptual values of hue, chroma and lightness. Such a transformation also takes place when the cone signals are transmitted from the human eye to the brain where they are converted into a color sensation. Since these signals cannot be directly measured, other methods to find this transformation must be chosen. For this task, the starting point are color samples being equally spaced as shown in Fig. 7. In this chart the perceived difference between the color samples is equal in both the horizontal and the vertical direction. It is of vital importance that the color matching tests to create such equidistant arrangements are carefully conducted with observers having a normal color vision. A somewhat easier task is to create an equidistant arrangement of gray patches. In this case, the connection with the XYZ values is simpler, as the Y value, according to the definition of the CIE, does not only represent the green cone signal but also the lightness of a color. (The explanation for the connection between the green cone signal and the lightness of a color would exceed the scope of this booklet. Details can be found in the relevant textbooks.) Once a visually equidistant scale of grey patches has been realized, the task is to find a mathematical relationship between the visually perceived gray values and the measured Y values.

At the time when no digital calculators were available, the solution was seen in a straightforward formula thereby accepting compromises in the correlation between visually judged and measured gray values. Later on, this correlation could be improved by applying more sophisticated formulas. When the CIELAB color space was defined in 1976, one formula known at that time has been adopted for the definition of the lightness scale. The lightness value in the CIELAB color space is denoted by L*. The relationship between L* and Y is mathematically defined by a cube root equation which will not be discussed here in detail. Some numerical examples may suffice to illustrate this relationship (see Tab. 1).

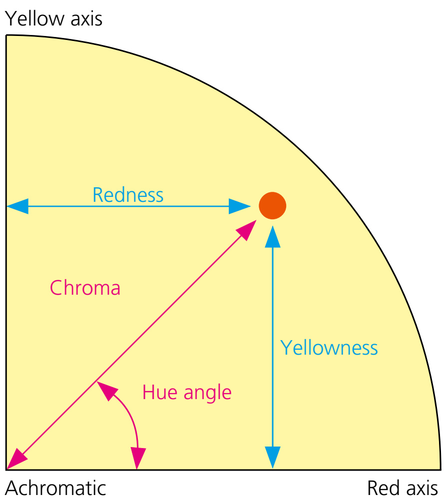
Y	0	10	20	40	60	80	100
L*	0	37.8	51.8	69.5	81.8	91.7	100

Tab. 1 Relationship between the CIE value Y and the CIELAB lightness value L*

The next issue being of interest is the transformation of the XYZ values into the values of hue angle and chroma. As these are so-called polar coordinates, they have first to be converted into coordinates based on a horizontal and a vertical axis (Cartesian coordinate system). Applied to the color circle, the horizontal axis extends from the principal color Green (angle 180°) to the principal color Red (angle 0°) and is referred to as red-green axis. Vertically, the so-called yellow-blue axis goes from the hue angle of 90° (Yellow) to 270° (Blue). The connection between the rectangular and the polar coordinates can be illustrated by an orange color as example: On the color circle, orange is located between the principal colors Red and Yellow, being on the red side of the red-green axis and on the yellow side of the yellow-blue axis. This color could be therefore alternatively described by its red portion (redness) on the horizontal axis and by its yellow potion (yellowness) on the vertical axis (see Fig. 8).

On the CIELAB color circle, the horizontal axis is denoted by a*, the vertical axis by b*. For the calculation of a*b* values from XYZ, again a mathematical transformation must be found being able to produce visually equidistant values. Similar as with the conversion from Y to L*, a successful solution depends on both the quality of the used color samples and the chosen mathematical approach.

Fig. 8 Connection between the polar coordinates (hue angle and chroma) and the rectangular coordinates (redness and yellowness) using an orange color as example



Over the course of time, many attempts have been made to develop transformations leading to visually equidistant values. In 1976, the CIE has adopted a set of conversion formulas having the widest acceptance at that time.

The CIELAB color space is schematically depicted in Fig. 9. The vertical axis represents the lightness scale going from white to black. The color circle with the red-green axis a* and the yellow-blue axis b* is shown as horizontal plane.

Figure 10 shows the CIELAB color circle in an idealized form. In reality, chroma values of 100 are not possible for all hues, because the corresponding colors do not exist. Moreover, the maximum chroma values depend on the lightness values. Yellow colors reach their highest chroma values at high lightness levels, while for violet colors high chroma values are only possible at low lightness levels.

Fig. 9 Schematic view of the CIELAB color space

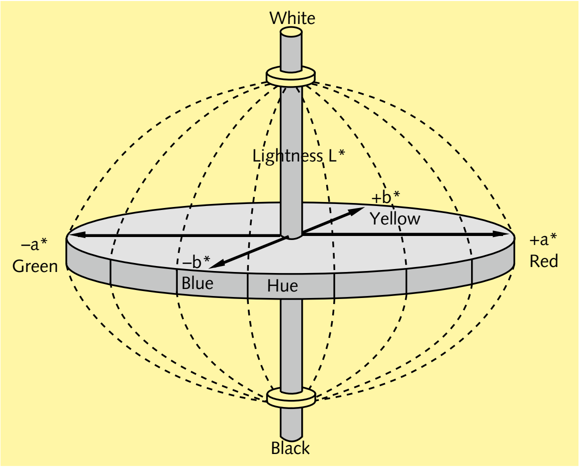
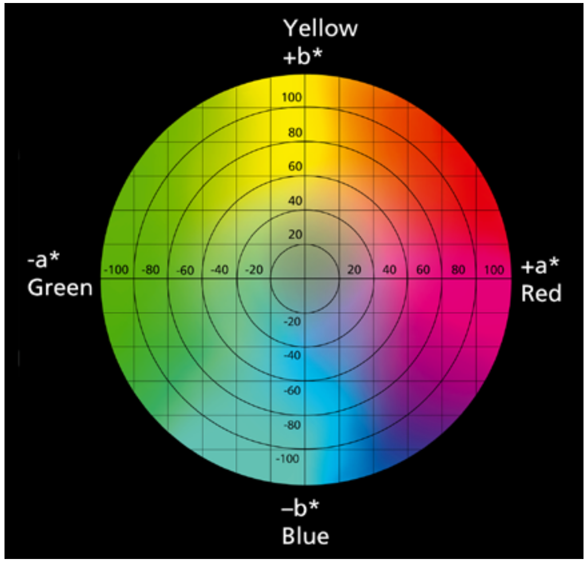


Fig. 10 Mapping of the colors in the CIELAB color circle



It should be pointed out again that the CIELAB color space has been created more than 40 years ago. From a present-day perspective the perceived visual uniformity of this color space has some deficiencies. Its advantage, however, is the worldwide acceptance and the fact that its coordinates are displayed by virtually all color measuring instruments.

7. Effect of light on the perceived color

The following case frequently occurs: A woman is buying brown gloves that should match the color of a brown dress. Under the store light the two colors match perfectly. As soon as she compares the gloves and the dress in the daylight outside of the store, the colors look clearly different. This phenomenon is called *metamerism.* It describes the situation that a pair of colors which match under one set of viewing conditions do not match, if the viewing conditions are changed. Strong metameric color differences appear for instance, if objects are viewed in the yellow light of a sodium vapor lamp. In contrast to daylight the sodium vapor light does not even enable to distinguish between blond and gray hairs or between gold or silver jewelry.

As said earlier, no perfect white light exists. What we perceive as white light is always slightly colored. As an example let's look at an incandescent lamp: Its light has a deficiency of blue wavelengths and appears hence yellowish. As a consequence, blue objects are seen with too much contrast. Vice versa, if objects are viewed in the light of the sunless blue sky (the daylight coming in a north-facing window), yellow-reddish colors have too much contrast, particularly the so-called skin tones. Therefore, the light used for color matching must have balanced amounts of yellow and blue wavelengths. An almost neutral light is the noon daylight on a cloudy day. However, this light is not constant in its spectral composition nor is it available at all times. It was the task of the lighting industry to provide light sources simulating the daylight. In this context, it was necessary to specify the color shade of a light source. Basically, this is possible by describing the wavelength spectrum, but it is unpractical to compare light sources on the basis of such diagrams. It was again the CIE which created a numerical specification for light sources. It is called *color temperature.*

What has color to do with a temperature? This connection becomes evident, if we heat a piece of coal. It can be seen that the color of the coal is changing first to dark red, than to yellowish and eventually to almost white. It is obvious that the temperature of the coal determines the color of the emitted light. As it is possible to measure both, a relationship can be derived between the temperature and the corresponding color. There are numerous other materials than coal that produce visible radiation when heated, for instance the metal filament of an incandescent lamp. Therefore, the relationship between the temperature and the color of the emitted light has been standardized without reference to a particular material. This temperature is referred to as color temperature. The color temperature scale starts with yellow being typical for a candle and goes to white light and further to the bluish colored daylight (see table 2). The temperature is specified in Kelvin (without a degree symbol) and begins at –273 °Celsius (the absolute zero temperature).

As colors look different depending on the chosen illumination, it is important that the light source being used for color matching is standardized. There are different options: If it is of interest to know how colors appear under a light bulb at home, one has to agree on this particular light for color matching. But more frequently one is interested to compare colors under daylight. It is again the merit of the CIE to have standardized the average daylight with overcast sky under the name of *standard illuminant D65*. (D stands for daylight and 65 for a color temperature of 6500 K.) As can be seen from table 2, the standard light D65 is slightly bluish. This is acceptable, because it is a typical light in the Northern hemisphere. For further applications, the CIE has standardized additional illuminants, for instance the daylight with clear sky under the name of *standard illuminant D50.* This slightly yellowish light became the standard illuminant in the graphic arts industry, because color slides used for reproduction have a color balance optimized for viewing in the yellowish light of projector lamps.

Conditions for viewing of prints and proofs in the graphic arts industry according to ISO 3664:2009:

Light: standard illuminant D50
Illumination level: (2000 ± 500) lx
Surrounding area: matt medium gray

Color temperature	Light source	Color of light
1500 K	candle	yellow
2200 K	light bulb 40 W	yellowish
2800 K	light bulb 100 W	yellowish
3400 K	studio lamp	yellowish
4100 K	moonlight	yellowish
5000 K	noon daylight with clear sky	slightly yellowish
5500 K		white
6500 K	noon daylight with overcast sky	slightly bluish
7500 K	north sky daylight	bluish

Tab. 2 Color temperature scale with some typical examples

Based on what has been said above, a white surface should appear yellowish under an incandescent lamp and bluish under the blue sky. But this is not the case, for the human eye is able to perceive a near-white light as perfect white. This phenomenon is called *chromatic adaptation.* Example: A monitor display viewed in a dimmed room appears white. In an illuminated room, the human eye becomes adapted to the room light and the monitor display appears yellowish or gray.

8. Effect of the surround on the perceived color

Figure 11 is often taken as an example of an optical illusion: The green circles have – when isolated observed – exactly the same color, but when viewed with different adjacent colors, they look different. In this context, the adjacent or surrounding area of an observed color element is called *surround.* What is regarded as optical illusion is a perceptional interaction in the brain between the observed color and its surround. This effect is referred to as *simultaneous contrast.* Another example for the simultaneous contrast can be observed with gray patches: If the surround is dark, the same gray tones appear to be lighter than if the surround is bright (Fig. 12).

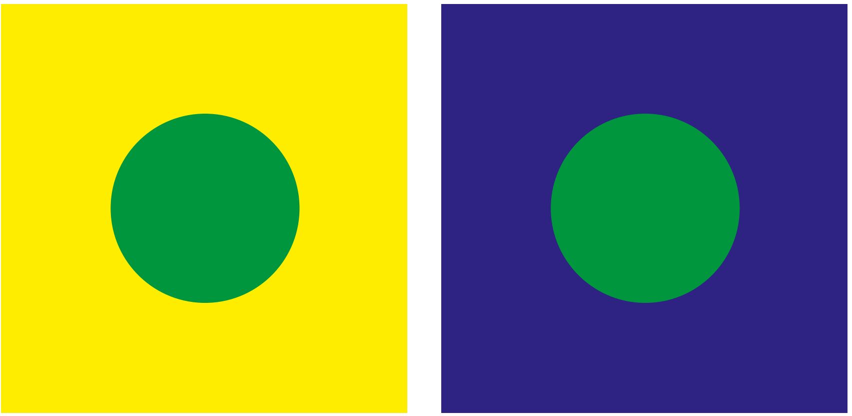


Fig. 11 Effect of the surround on the appearance of colors: The color of the two green circles is identical, but the color appears to be different depending on the surround.

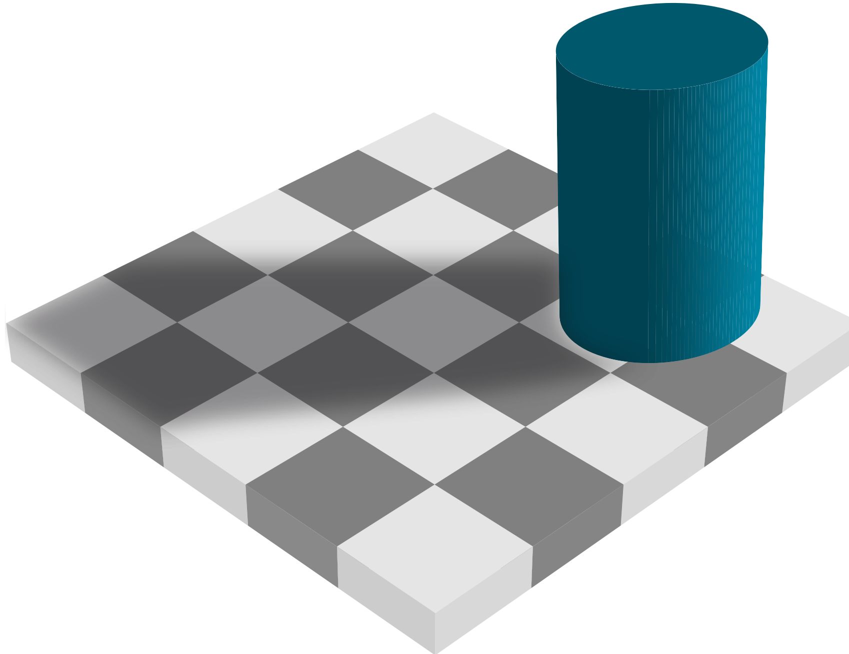


Fig. 12 Effect of the surround on the appearance of gray tones: The white squares in the shadow of the cylinder have the same gray value as the dark squares outside the shadow.

The surround also affects the perception of color differences. When two light gray tones are viewed in a bright surround, their difference appears to be smaller than in a dark surround. Vice versa this applies to dark grey tones. For this reason, the surround used for color matching, for instance the surface on which color samples or images are placed, should be a medium gray. The simultaneous contrast is most intense, if the observed color and the surrounding color are complementary to each other. *Complementary colors* are pairs of colors being diametrically opposite on the color circle. For each hue angle the complementary color can be found by adding or subtracting 180°. Simultaneous contrast effects based on complementary colors are often used in advertisements: Green vegetables against a red background or meat against a green background appear more saturated and make the food looking "tastier" than against a neutral background.

9. Color measuring instruments

As already said, each color measuring instrument records primarily the three values XYZ corresponding to the sensitivity curves of the CIE Standard Observer. It is possible to display these values or to convert them into the CIELAB coordinates which are lightness, hue angle and chroma or – instead of hue angle and chroma – the coordinates on the red-green axis and on the yellow-blue axis. Examples of these values are given in table 3 for a popular color in Switzerland, i.e. the red of the national flag. This red is standardized as PANTONE 485 (see chapter 14). Please note that the CIELAB coordinates are denoted with very specific alphabetic characters. It is also important to note that the CIELAB coordinates are based on a particular illuminant, in this case on standard illuminant D65.
Even if a person looking at Tab. 3 does not know that a red color is described, its appearance can easily be recognized from the values: The hue angle of 38 indicates a red color containing yellow. The chroma value is relatively high meaning that the color is very saturated. It is therefore a vivid red of medium lightness.

CIE tristimulus value for the red receptor	X	27.87
CIE tristimulus value for the green receptor	Y	16.47
CIE tristimulus value for the blue receptor	Z	3.52
CIELAB lightness	L*	47.58
Value on the CIELAB red-green axis	a*	58.12
Value on the CIELAB yellow-blue axis	b*	45.93
CIELAB hue angle	h_{ab}	38.3
CIELAB chroma	C^*_{ab}	74.08

Tab. 3 CIE tristimulus values and CIELAB coordinates for the standardized red color of the Swiss flag specified for standard illuminant D65.

Today, almost all color measuring instruments are so-called spectrophotometers recording in a first step the spectral distribution of the color to be measured. The result is a diagram showing for every wavelength the percentage of reflected light. As example, the spectral distribution curve of the red color of the Swiss flag is shown in Fig. 13. These spectral values are the starting point for the calculation of the CIE values XYZ and the CIELAB coordinates. It is not in the scope of this brochure to describe this calculation in further detail.

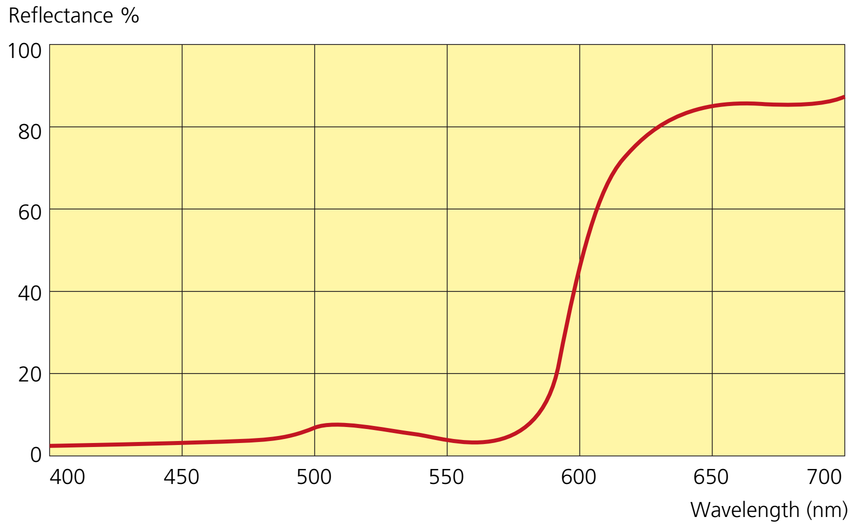


Fig. 13 Reflection values as a function of the wavelength, plotted for the red color of the Swiss flag.

A color measuring instrument should allow selecting different illuminants, predominantly the CIE Standard Illuminants D65 and D50. An important criterion when measuring colors is the measurement geometry, i.e. how the specimen is illuminated and "viewed" by the detector. It seems natural to apply a geometry which is also used for visual color matching where, typically, the eye is positioned vertically above the specimen and the incident light falls in from an oblique angle. If this geometry is standardized, the specimen is illuminated at an angle of 45° and the detector is placed at 0°. This geometry is referred to as 45/0. The CIE recommends this geometry for measurements on smooth surfaces such as paper or plastic. If the surface has a distinct structure such as a rough-textured fabric, this geometry is not meaningful, because light scattering effects on the uneven surface lead to inconsistent results depending on the sample orientation under the detector. In this case the specimen has to be illuminated diffusely. This geometry is called d/0 (d = diffuse).

A further criterion when measuring colors is the aperture size of the detector determining the minimal necessary diameter of the specimen. If the sample size is large enough, aperture sizes of more than 5 mm are recommended, because in this case the result is less influenced by the structure or unevenness of the sample surface. However, where small color samples are typical, as in the graphic arts industry, an aperture size of 3 mm is more beneficial.

Many substrates such as magazine papers on which colors are applied are very thin and therefore slightly transparent. In this case, the surface under the colored material can influence the result. Equally, if the substrate is colored (or printed) on both sides, the back side can shine through and affect the measurement. To suppress this influence, a black backing can be used. However, in case of non-transparent substrates a white backing material is recommended.

When color measurement data are reported, they should be accompanied by the following information:
– the applied illuminant,
– the measuring geometry of the instrument,
– whether white or black backing is used.

For many color measuring tasks it is advantageous to utilize a wireless handheld instrument that allows to position the measuring head on surfaces of any size. For the use in laboratories, however, a tabletop instrument having power supply with cable is better suited.

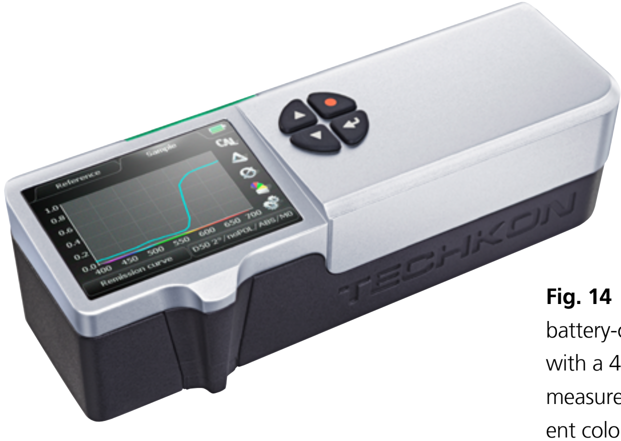


Fig. 14 Example of a portable and battery-operated spectrophotometer with a 45/0 geometry. It allows the measurement of color values in different color spaces and under different illuminants. Weight: 495 gram.

10. Determining color differences

The assessment of color differences is probably the most important application of color measurements. Frequently a given color specification or color specimen has to be reproduced in a given production process and it has to be determined whether the deviations from the original color are within a defined tolerance range. In such a situation the assessment of color differences has clearly an economic significance. In this context, it should be stressed again that it is not important how the involved persons perceive the color differences. Using a color measuring instrument removes any subjective ambiguities.

If the CIELAB coordinates L*, a* and b* are given for a pair of colors, the color difference can be, first of all, described by the differences of the three coordinates. The pair of colors can be regarded as two points in a three-dimensional space and their distance is then described by the differences in the height, in the width and in the length. This distance can also be expressed by a single number, i.e. by the length of the straight line joining the two points. This formula can be found in any geometry textbook.

If this formula is applied to the CIELAB coordinates, the following expression results:

$$\triangle E^*_{ab} = \sqrt{\triangle L^{*2} + \triangle a^{*2} + \triangle b^{*2}}$$

The symbol △ stands for difference. The result is called color distance or color difference denoted by $\triangle E^*$. To make clear that this color difference refers to the CIELAB color space, the exact denotation is $\triangle E^*_{ab}$. Measured color differences can be assessed according to the scale given in Tab. 4.

Color difference $\triangle E^*_{ab}$	Meaning of the color difference
below 0.2	not visible
0.2 – 1.0	very small
1.0 – 3.0	small
3.0 – 6.0	medium
6.0 – 12.0	large
above 12.0	very large

Tab. 4 Connection between the measured and the perceived color difference

If instead of the rectangular coordinates a* and b* the polar coordinates hue angle and chroma are given, the calculation of the color difference is not as simple. Therefore, the starting point for calculating color differences should always be the coordinates a* and b* (in addition to L*). The color difference can also be computed by the color measuring instrument, if the values of the reference color are entered.

When a customer and a supplier have to reach an agreement upon the color differences being acceptable in a production process, the customer tries to enforce the lowest possible tolerances. The supplier, on the other hand, tends to argue that his production process does not allow going below a certain tolerance limit. In most cases the production process does determine the tolerances. But the customer can insist that the production process should be optimized to result in the lowest possible variability. This may include that the supplier needs to obtain a quality certificate. One method to define color tolerances based on process deviations is to determine the color difference inside of which 90% of all measured samples are located.

On the other hand, color tolerances can also be based on the criterion whether or not a certain color deviation is visually acceptable. The human eye perceives color differences very sensitively, if directly adjacent colors have to be assessed, as for instance on wallpaper. In such a case a difference of $\triangle E^*_{ab} = 2$ can already be unacceptable, meaning that the production process has to comply with this tolerance. On the other hand, deviations in the sky blue of a postcard edition can still be acceptable with a $\triangle E^*_{ab} = 7$, even if the production process would permit lower tolerances.

11. How many colors do exist?

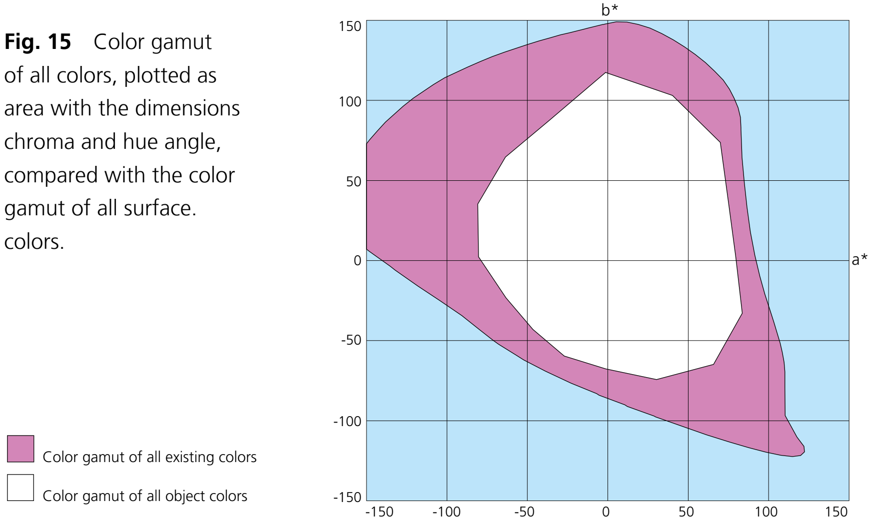
Many answers can be found to this question most of which being very rough estimations. Strictly speaking, the question is how many different colors can the human eye distinguish? The starting point for determining all visible colors are the spectral colors. All visible colors are composed of spectral colors. If the spectral colors are mixed in all possible combinations, the maximum chroma values can be computed for each hue angle and each lightness value. From this, the volume of all visible colors can be calculated in the CIELAB color space. This volume is called *color gamut*. To obtain the number of all distinguishable colors, a color difference has to be defined for which two colors are just discernible. Based on this value and the volume in the CIELAB color space, it can be calculated that the *number of all distinguishable colors amounts to 2,325 million.*

The entirety of all visible colors can be divided in two groups, those originating from visible radiation and those created by using colorants. The second group is far more important in everyday life and is referred to as *surface colors or object colors.* All colors applied to materials such as paper, textiles, plastic or metal are object colors. Only the colors appearing on a monitor are generated by radiation. With radiation far more colors can be produced than with colorants. This can be explained by the fact that the highest chroma values can be achieved by monochromatic or near-monochromatic light (narrow spectral bands) which can only be generated with radiation.

When talking about the number of distinguishable colors, most people mean primarily the number of surface colors. This color gamut cannot be computed; rather all available pigments and dyes must be tested on different surfaces to find the highest possible chroma values. This leads again to a volume in the CIELAB color space from which it can be calculated that *the number of all surface colors amounts to 1,141 million.*

As the vertices of the color gamut need three coordinates for its description, they are hard to visualize on paper. It is much more practical to use only two dimensions, e.g. chroma and hue angle, and plot them as area. For many color applications, the interesting information is primarily the chroma value attainable at a particular hue angle rather than the lightness level. A presentation of the color gamut as geometric area shows that the object colors cover only 54% of the area of all visible colors. There is no hue angle at which the object colors attain the maximum possible chroma value, the highest value being 80% for red colors.

Fig. 15 Color gamut of all colors, plotted as area with the dimensions chroma and hue angle, compared with the color gamut of all surface. colors.



	Calculated as volume	Calculated as area (omitting lightness)
Total of all colors	2,324,900	45,910
Total of surface colors	1,140,800	24,980

Tab. 5 Entirety of all visible colors and of all surface colors calculated by the author for the CIELAB color space under standard illuminant D50.

12. Color rendering on paper

Colors rendered on paper are always a mixture of a few base colors. For watercolor paintings 12 to 18 base colors are commonly used. However, it has been recognized early that only three base colors – in this context called *primary colors* – are sufficient to create a very large number of other colors. A typical reproduction process working with three primary colors is color photography. The names of the primaries are here *cyan, magenta and yellow.* A photographic print consists basically of three superimposed transparent images each colored with one of the three primary colors. The principle how the color mixture process works can be shown with colored filters. As an example, if white light is sent through a magenta filter and a yellow filter, each filter subtracts corresponding wavelengths. The light which has not been absorbed by the filters has in this case the color red. The process that light is subtracted by the filters is called *subtractive color mixing.*

With three given filters it is possible to create four additional colors:
- Red from cyan and yellow,
- blue-violet from cyan and magenta,
- green from cyan and yellow,
- black from cyan, magenta and yellow.

By varying the color strength of the filters any desired variation of these seven colors can be created.

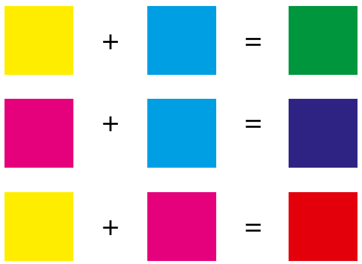


Fig. 16 Laws of subtractive color mixing

The same kind of color mixing takes place, when pigments or colored liquids are mixed. The three primary colors cyan, magenta and yellow are also used in other reproduction processes such as offset printing, electrophotography or inkjet printing.

As offset printing is an important reproduction process, it is worthwhile to describe it in more detail: In addition to cyan (C), magenta (M) and yellow (Y) a forth primary color, i.e. black (K), is used for printing. This leads to the so-called *CMYK color space.* The purpose of black is to enhance the contrast in dark colors and to stabilize the gray tones. The so-called gray balance is an important criterion in color reproduction, because the human eye responds very sensitively to deviations in gray tones. This is of particular importance in fashion advertisements where color casts in gray textile tones are not tolerated. In principle, the black ink alone would suffice to render black or gray in a color image. This, however, is undesirable for various reasons. A common technique is to moderately reduce the amount of cyan, magenta and yellow when printing gray tones. This is referred to as *undercolor removal.*

Today, offset printing is to a large extent an internationally standardized process based on the ISO Standard 12647-2. In order to obtain a standardized image reproduction, a number of parameters must be specified the most important being the following:
- The color coordinates of the four primary colors as inks: This determines the color gamut. In addition, as the ink films should be transparent, their transparency is specified.
- The properties of the printing paper: This includes the color coordinates and the characteristics of the paper surface. To cover all major applications of the offset process, five different paper qualities are specified.
- The gradation of the printed image: For this, target values are given to describe the gradation curve.

It has been said that the three primaries cyan, magenta and yellow permit to render a large number of other colors. This raises the question of the limits of this three-color process. The standardized primary colors of the offset printing process permit to calculate the color gamut as volume or as area. As can be seen from Fig. 17, the offset printing process enables to render more than half of all object colors on coated papers. While the primaries cyan and magenta have saturations coming close to the limits of the object colors, the orange and violet tones show clear limitations in their attainable chroma values.

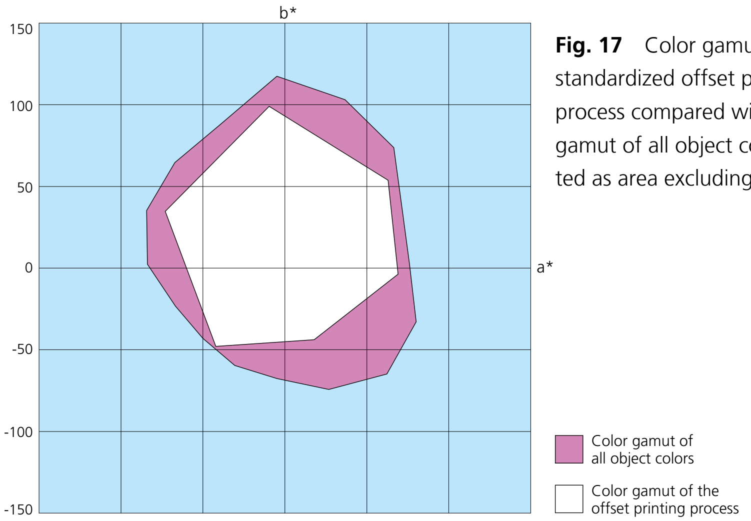


Fig. 17 Color gamut of the standardized offset printing process compared with the gamut of all object colors, plotted as area excluding lightness.

There have been many attempts to expand the color gamut of offset printing by various methods. As the saturation of the current primary colors is already quite high, the choice of primaries with other color coordinates offers no benefit. The only option to substantially expand the color gamut is the application of additional primary colors. If, for instance, a red, a green and a blue are used as additional primary colors, they can be chosen to have a higher saturation than prints obtained from superimposing cyan, magenta and yellow. In this way, three-quarters of the color gamut of all object colors can be rendered. However, this advantage comes at the cost of a much higher production effort, because seven colors (6 chromatic colors plus black) have to be printed rather than only four colors.

13. Color rendering on a monitor

As already mentioned, the colors on a monitor display are generated by mixing colored lights. Again three primary colors are used: a red, a green and a blue. The mixing principle is very simple: When red, green and blue light are projected together on a screen, the resulting color is white. The process that colored lights are added is called *additive color mixing.*

With red, green and blue light of a given intensity it is possible to create four additional colors:
- Magenta from red and blue,
- yellow from green and red,
- cyan from green and blue,
- white from red, green and blue.

By varying the intensity of the three lights any desired variation of these seven colors can be created.

The three primaries red (R), green (G) and blue (B) define the so-called RGB color space encompassing all colors that can be rendered on a monitor. As most PC monitors and almost all TV screens have a similar color gamut, a standard RGB color space (abbreviated sRGB) has been defined.

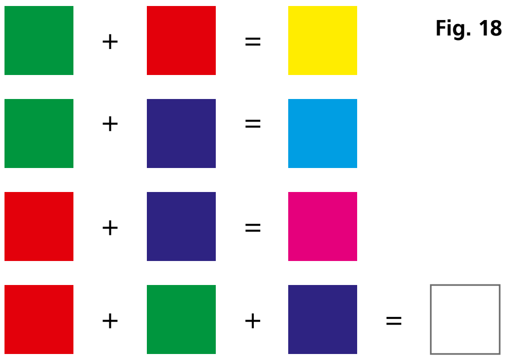


Fig. 18 Laws of additive color mixing

Keeping in mind that colored lights permit to create more colors than pigments or dyes, it is not surprising that the sRGB color space has a clearly larger gamut than the offset printing process. This is particularly true for violet, purple, blue and green which can be rendered on a monitor with a much higher saturation. Only in case of some green-blue and yellow tones the offset printing process permits to attain higher chroma values than a monitor display.

As we have seen, creating colors on paper and on a monitor involves two completely different technologies. This especially refers to the kind of color mixing, to the difference of the primary colors and to the conditions how images are viewed. In daily life, however, these two worlds do touch each other when the same image is rendered on paper and on a monitor and it is expected that the two images look the same. In order to achieve a match between a printed image and an image displayed on a monitor, the parameters how images are rendered and viewed on monitors and on paper must be adjusted accordingly. Since the color gamuts cannot be matched, at least the white displayed on the monitor, the gradation of the displayed image (the so-called gamma value) and the viewing conditions have to be adapted. As the gradation of a monitor image is influenced by the room light, the ambient brightness has to be specified as well. For this purpose the ISO Standard 12646 has been established. With the help of special software tools it is possible to make sure that a monitor image matches the printed image. The application of these tools is called *color management.* While color management is utilized almost everywhere in the graphic arts industry, the private PC user is still faced with the problem that his monitor images look different from images printed with a laser or an inkjet printer.

14. Collections of standard colors and color order systems

If a particular color needs to be specified for a production process, it seems natural to use numerical values. But a color can also be specified in the form of a physical color sample. This offers the advantage that the specified and the reproduced color can be measured with the same instrument. It is a fact that different color measuring instruments deviate in their results, often to an extent corresponding to half of the production tolerance. As a numerical specification is based on another instrument than the instrument being used in the production control, it is more beneficial to avoid a numerical specification and to use a single instrument instead. That is the reason why collections of standard colors are available for many applications, for instance in the textile, automobile, construction and graphic arts industry.

In Europe, the RAL Color Collection is widely used in many industries. There are 213 standard colors with matt or gloss finish. The "corporate color" of many companies is defined by a *RAL specification*, for instance the Lufthansa Blue (RAL 5022), or the Swiss Post Yellow (RAL 1004). RAL standards are mainly used where colors have to be applied to different materials such as paper, metal, plastic or textile.
A worldwide known color collection is the *PANTONE System*. From the numerous PANTONE products the best known is a series of 1,341 standard colors arranged in a fan format, available on both coated (C) and uncoated (U) paper. An example of a PANTONE specification is the red of the Swiss flag (PANTONE 485).

A color collection specifically designed for the graphic arts industry is the *HKS Color System* comprising 3,520 standard colors. The collection is arranged in a fan format and available on gloss-coated and uncoated paper. A limited selection of colors is also available on newsprint and on paper for continuous printing. With this concept, allowance is made for the fact that colors appear different when printed in a high polish folder, in a magazine, in a newspaper or on a form.

Often you want to describe a color without utilizing a color measuring instrument. In this case, instead of a color collection a system is required offering a perceptually equidistant spacing of the colors. This is referred to as a *color order system.*

The probably best-known system is the *Munsell Book of Color*. It is widely used in North America, but also known worldwide because of its educational value. In this system the colors are arranged according to the criteria lightness, hue and chroma. As the color patches cannot be produced in multi-color printing, their production is very elaborate. Currently (2023) a Munsell Book of Colors containing 1,568 color samples with gloss finish costs 1,450 Euro. In principle, it is possible to use a color patch from the Munsell Book as specification for a production process. This, however, implies that the customer or the manufacturer is familiar with this system what is often not the case in small and medium companies. A color order system based on the CIELAB color space is the *RAL Design System* (not to be confused with the RAL Color Collection). Similar as the Munsell Color Book it is a color atlas. Its 1,625 color samples are spaced at a distance of 10 CIELAB units representing all possible combinations of hue, chroma and lightness.

15. Color names

When colors have to be described in daily life, they are characterised by an appropriate name such as tomato red, lemon yellow or grass green rather than by using a color chart or a numerical specification. Such color names are not very accurate but can be easily attributed to a color sample in a color atlas. However, in some fields such as in the fashion industry less self-explanatory color names are often used, for instance buff, castor or pansy. Moreover, different color names are sometimes used to describe the same color making the color communication more complicated. As an example, the following pairs of color names refer to the same colors: turquoise and teal, cardinal red and geranium red, sapphire blue and midnight blue or daffodil and cadmium yellow.

It has been said in chapter 11 that the human eye is able to distinguish 1.1 million surface colors. This statement is true if the colors are directly adjacent and if the illumination is at least 2000 lux. For isolated colors and lower illumination levels the number of distinguishable surface colors is much lower amounting only to 125,000. However, this number is still too large to attribute an own name to every color. For a comprehensible systematic color description it is often sufficient to use the attributes introduced in Fig. 6:

pale	dark	strong
light	bright	deeply saturated
dull	vivid	

Together with the twelve most important hue names (Fig. 19) many colors occurring in daily life can be described in an easy to understand way. Some examples are listed in Tab. 6. It is important to note that bright colors can only occur with yellow tones, while deeply saturated colors are solely possible with red-violet tones. Strong colors are limited to orange, yellow and green shades.

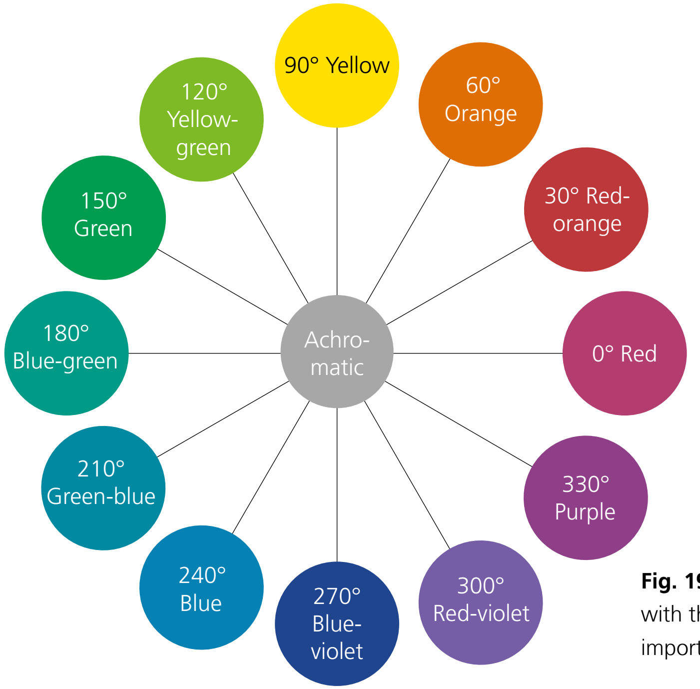


Fig. 19 Color circle with the twelve most important hue names

Color name	Description	Color name	Description
Ruby	vivid red-orange	Olive	dull yellow-green
Crimson	strong red-orange	Jade	vivid green
Maroon	dark red-orange	Turquoise	vivid blue-green
Brown	dark orange	Alice blue	pale blue-violet
Khaki	dull yellow	Indigo	dull blue-violet
Beige	light yellow	Lavender	vivid red-violet
Ivory	pale yellow	Cobalt blue	deeply saturated red-violet
Gold	vivid yellow	Lilac	light purple
Canary	bright yellow	Pink	light red

Tab. 6 Easily comprehensible description of selected color names.

Appendix: The XYZ color space

As has been said in chapter 5, every color measuring instrument is designed to simulate the function of the human eye. For this purpose, the sensitivity curves of the CIE Standard Observer are programmed. The result of a measurement is an X value for the red portion of the measured color, a Y value for the green portion and a Z value for the blue portion. The XYZ values appear somewhat abstract. If we look at the values of the red of the Swiss flag (see Tab. 3):

X = 27.87   Y = 16.47   Z = 3.52

The Z value is the smallest value and seems to indicate that the blue portion of the color is insignificant. X as highest value signifies that the red portion must be substantial. The Y value which also describes the lightness suggests a dark color. It goes without saying that this description is not very illustrative. But similar to the CIELAB color space, it is possible to suppress the lightness value. The remaining two coordinates which are obtained by a conversion describe the hue and chroma of a color and can also be plotted as area. These coordinates are denoted with the lower case characters x and y. If the entirety of all colors is plotted in an x-y diagram, the result is an area similar to a triangle which is called the *CIE color triangle* (see Fig. 20). This color triangle is used since 1931 when the CIE Standard Observer was defined. Color values can be easily plotted in this triangle, however, color differences are difficult to recognize, because the colors are not equally spaced. This can be seen in Fig. 20 where the green and red colors occupy a larger area than the blue colors. In an equidistant presentation all colors should cover approximately the same areas. Therefore, the CIE triangle is not suited to map color gamuts, although it is often used for this purpose. Yet, as no generally accepted equidistant color space has existed before 1976, the CIE triangle has always played a central role. For many people it is often the only one method to map colors they know.

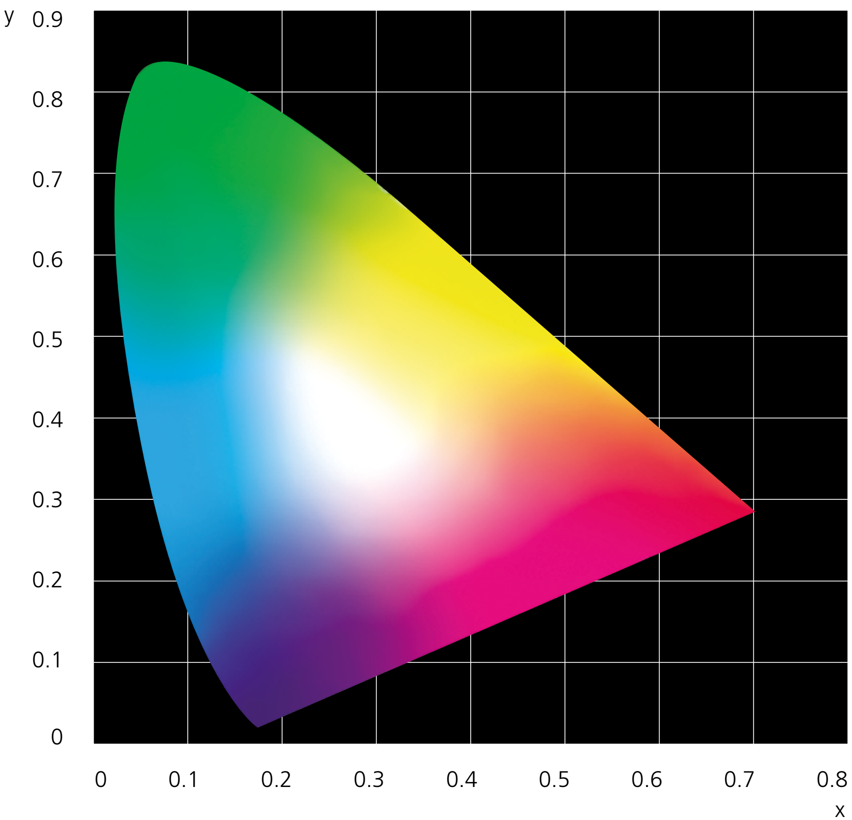


Fig. 20 CIE color triangle

About the author

The author of this brochure, Prof. Dr. Kurt Schläpfer († 2019), worked in various functions at the Swiss Laboratories for Materials Science and Research (Empa) in St.Gallen, lastly as deputy director. He managed the reproduction/printing technology department for 20 years. He was also a lecturer at the University of St.Gallen for 18 years, teaching mainly communication technology.
Prof. Schläpfer was Chairman of the International Association of Research Organisations for the Printing, Information and Communication Industries (IARIGAI) for six years. His area of expertise was colour science and its application in the graphic arts industry. He is the author of over 200 publications on printing and reproduction technology. Prof. Schläpfer passed away in 2019, but he will always be remembered.

Datacolor TECHKON – Integrated Color Communication and Management for Print & Packaging

Datacolor TECHKON delivers end-to-end color communication and management capabilities tailored for the complex demands of print and packaging, addressing every stage of the workflow — from brand specification to pressroom (production) execution.

Holistic Approach to Color Accuracy

At its core, the solution is designed to ensure **color consistency and predictability across global supply chains**. Brands and converters face increasing pressure to maintain exact color standards while reducing materials and time waste and improving sustainability. Datacolor TECHKON tackles these challenges through:

- **Comprehensive Quality Control:** centralized color quality management, enabling real-time monitoring, job reporting, and compliance with industry ISO standards and standardization methodologies like G7 and PSO/PSD.
- **Closed-Loop Process Control:** Inline spectrophotometers and scanning systems automate color adjustments during production, minimizing make-ready times and reducing costly reprints.
- **Cloud-Based Connectivity:** allows remote access, global color monitoring, and data analysis, supporting multi-site operations and brand oversight.

Workflow Integration Across the Value Chain

The solution spans **prepress, inkroom, and pressroom environments**, ensuring seamless communication between stakeholders:

- **Prepress:** ICC profiling and plate inspection tools guarantee accurate color reproduction from the start.
- **Inkroom:** Advanced formulation engines optimize ink recipes, reducing material waste and accelerating turnaround.
- **Pressroom:** High-speed scanning and inline measurement systems deliver real-time feedback, enabling operators to maintain color targets efficiently.

This interoperability is critical for packaging converters managing diverse substrates, print processes (flexo, offset, gravure), and global brand requirements.

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- **Speed to Market:** Faster make-ready and standardized workflows shorten production cycles.
- **Sustainability:** By minimizing ink and substrate waste, the solution supports environmental goals and corporate responsibility initiatives.

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Further information

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