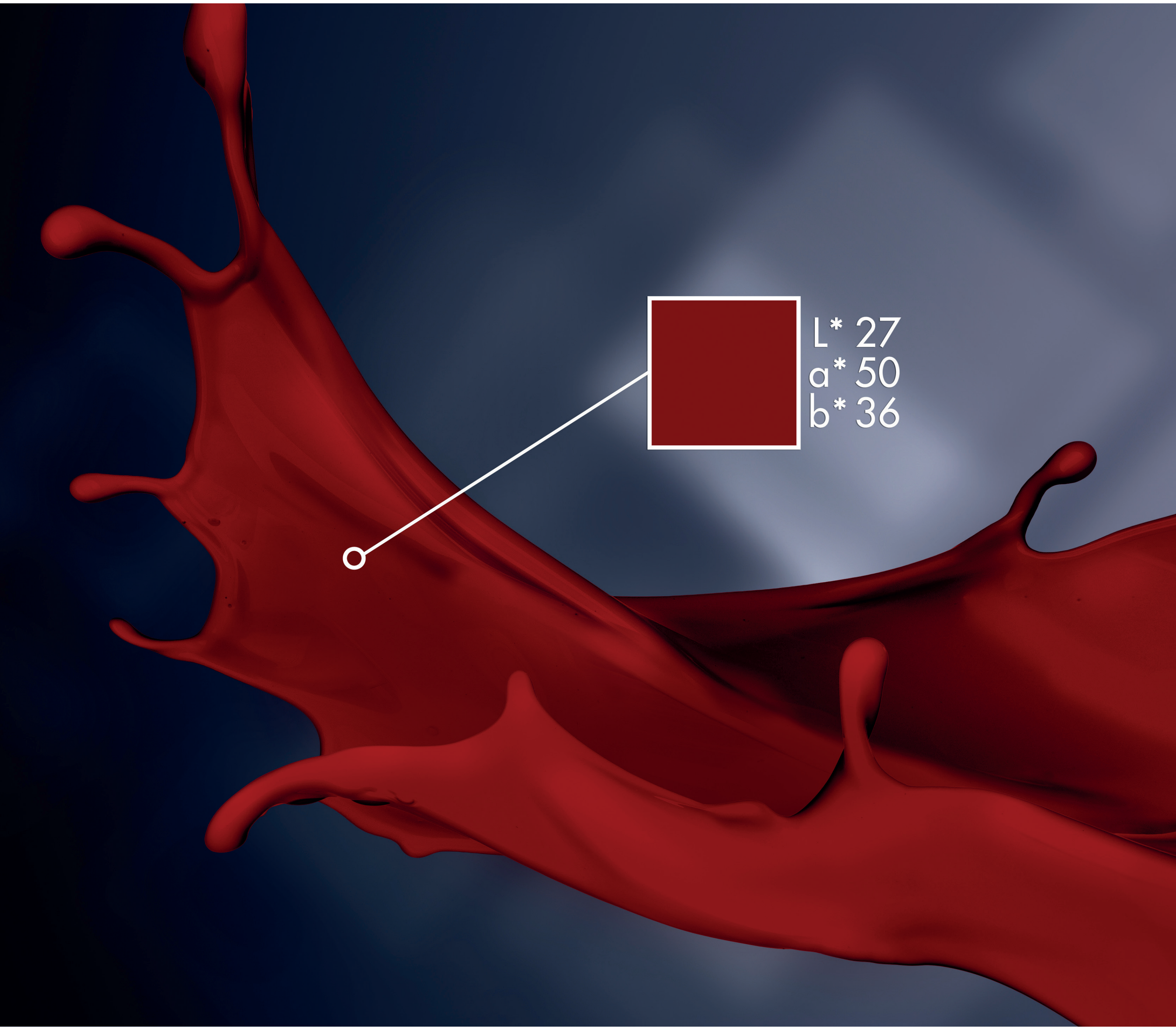
BOOK FOUR OF COLOR MANAGEMENT



Color distances, metamerism and practical color equations

datacolor

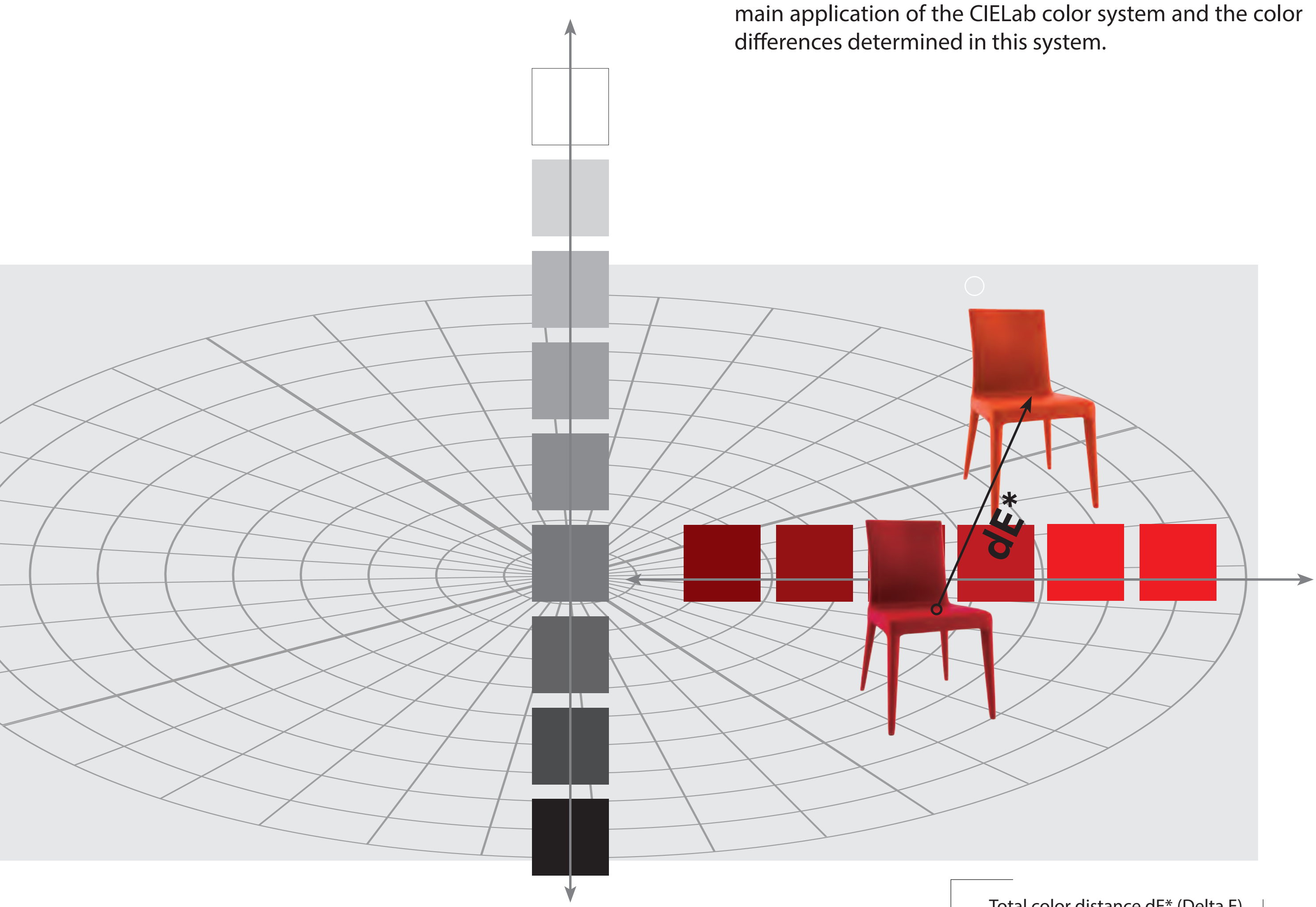
Chapter 11

Color distances and acceptability of colors

Introduction

Most industries require that their products demonstrate color consistency from one batch to another. For example, if you are painting a room and you run out of paint, you expect that there will be no visible difference between the two batches used. There are also products for which color consistency is required across a variety of materials. Your automobile contains parts of the same color, such as plastic arm rests, carpeting, cloth interiors, etc. that are made from different materials and processes. Often these components may display small color differences when located side-by-side, but if the differences are small you find them visually acceptable. In either case, when the color is grossly inconsistent, you will probably reject the product as defective.

In practice, it is generally impossible to reproduce the color of a product 100% exactly; as in the example below, the t-shirt could exhibit minimal color differences in different places, even if we cannot perceive any differences visually. Using colorimetry, such color differences can be measured and recorded. Color measurement and the evaluation of color differences help the manufacturer greatly in adhering to the specifications agreed between customer and supplier. In order to determine the difference between the colors of two samples, the color coordinates of the standard and of the reconstruction are entered in a color space; the distance of these two color points from each other shows the color difference between the samples. The distance between two points is calculated with a relationship based on its spatial projection onto each of the three main variables of the color system. This is the main application of the CIELab color system and the color differences determined in this system.



Total color distance dE* (Delta E) between two red samples

Color differences in the CIELab color space

The color distance between two colors is specified as dE (alternative notation: Delta E, ΔE). It can be calculated by a formula that was developed in 1976. Thus, the CIELab color space allows the color deviations to be represented using two procedures as follows:

- With perpendicularly plotted coordinates L*, a* and b*, the formula is as follows:

$$dE^* = \sqrt{dL^{*2} + da^{*2} + db^{*2}}$$

where

  - dL* represents the deviation of the lightness on the L* axis
  - da* represents the red-green deviation on the a* axis
  - db* represents the yellow-blue deviation on the b* axis

- With cylindrically plotted coordinates L*, C* and h, the formula is as follows:

$$dE^* = \sqrt{dL^{*2} + dC^{*2} + dH^{*2}}$$

where

  - dL* represents the deviation of the lightness on the L* axis
  - dC* represents the deviation of the colorfulness or chroma on the radius C*
  - dH (in degrees) represents the deviation of the hue angle on h

Standard (S_0)

Sample (E_1)

L^*_0 = 52.15	dL^* = +3.40	L^*_1 = 55.55
a^*_0 = +51.72	da^* = +2.60	a^*_1 = +54.32
b^*_0 = +19.29	db^* = +1.80	b^*_1 = +21.09

$$dE^* = \sqrt{dL^{*2} + da^{*2} + db^{*2}}$$

$$dE^* = \sqrt{3.40^2 + 2.60^2 + 1.80^2} = 4.64$$

By D65 / 10°

CIELab color space. Color distances in L* a* b*

Standard (S_0)

Sample (E_1)

L^*_0 = 52.15	dL^* = +3.40	L^*_1 = 55.55
C^*_0 = 55.20	dC^* = +3.06	C^*_1 = 58.26
h_0 = 20.45°	$\left\{ \begin{array}{l} dh = 0.77° \\ dH^* = 0.78 \end{array} \right\}$	h_1 = 21.22°

$$dE^* = \sqrt{dL^{*2} + dC^{*2} + dH^{*2}}$$

$$dE^* = \sqrt{3.40^2 + 3.06^2 + 0.78^2} = 4.64$$

By D65 / 10°

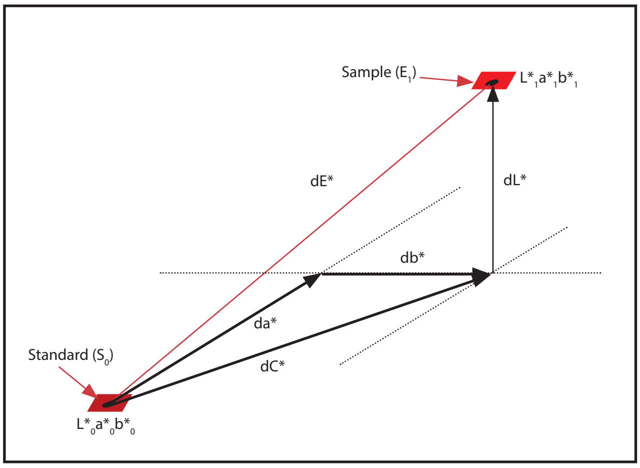
CIELab color space. Color distances in L* a* b*

Since the equation for the distance calculation (for the parameter dh) can be expressed only in units of length, the distance of the hue angle dh (actually expressed in °) is converted into a unit of length. This hue distance is specified with dH*, in conjunction with the radius of the color circle C*, which represents the chroma.

Color deviations and color tolerances in the CIELab color space L* a* b*

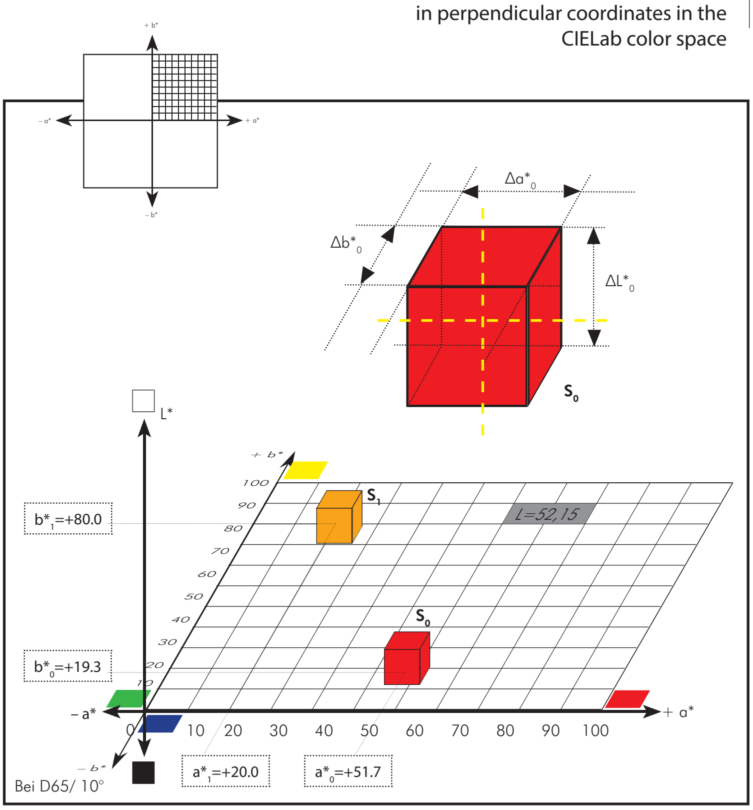
The description of a color deviation via perpendicularly plotted coordinates L*, a* and b*, in terms of the physics of perception, follows opponent color theory:

- Red/green deviation: projection of the distance onto the a* axis
- Yellow/blue deviation: projection of the distance onto the b* axis



Color deviations dL* da* db* expressed in perpendicular coordinates

Tolerances dL* da* db* expressed in perpendicular coordinates in the CIELab color space



dE* total color distance

dL* difference in lightness (− = darker; + = lighter)

da* green color difference ⬄ red (− = greener; + = redder)

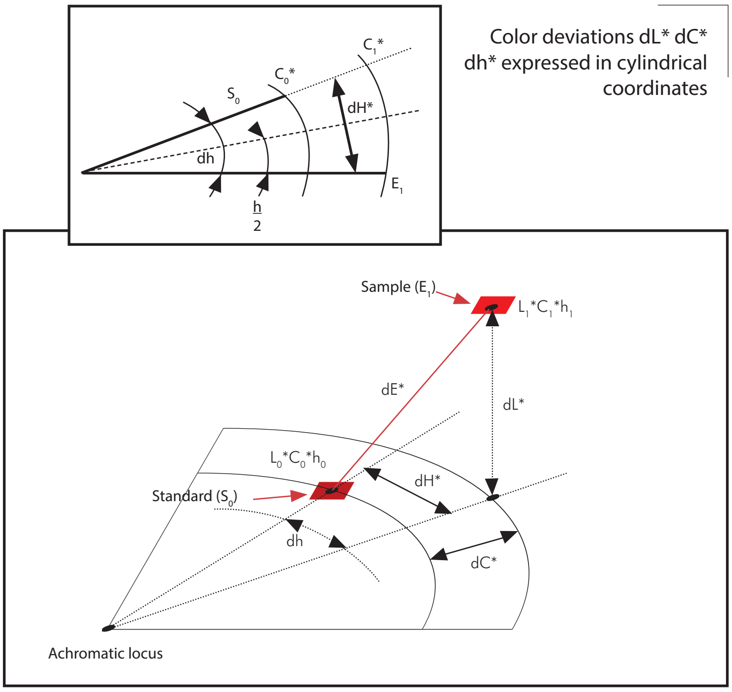
db* yellow color difference ⬄ blue (− = bluer; + = yellower)

Color deviations and color tolerances in the CIELab color space L* C* h

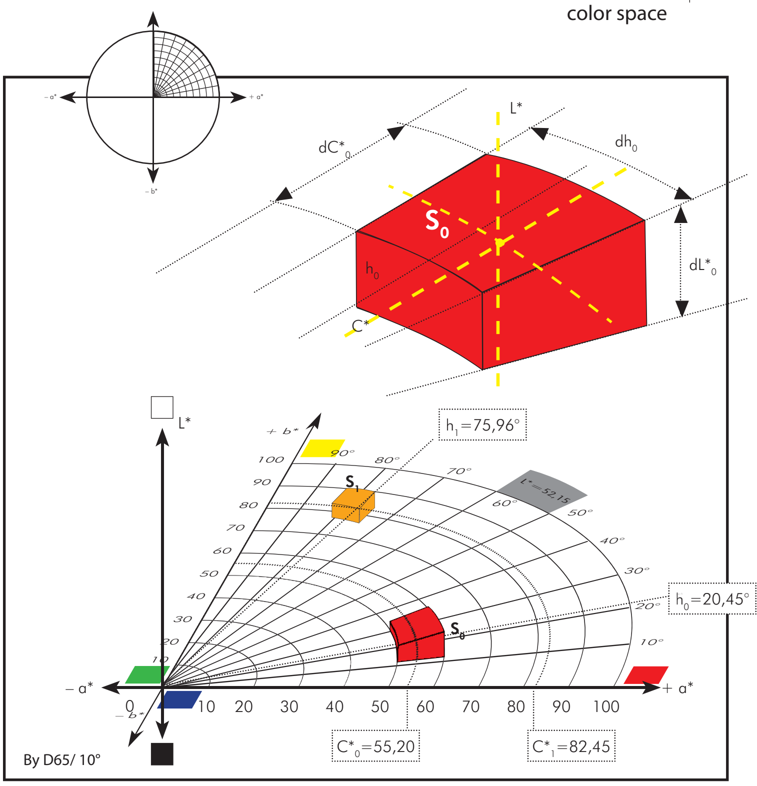
In contrast to the theoretical L*a*b* system, colors in the actual perception space do not behave linearly with each other. The human eye does not perceive color distances (green, red, yellow, blue) to the same extent as differences in colorfulness (chroma) and lightness. Generally, a person will first perceive distances in color shade, then in colorfulness, and finally in lightness. A color distance of e.g. dE = 1 is an acceptable color difference for brilliant yellow or green shades, but for achromatic grey colors, in contrast, dE = 1 represents a different color that is not acceptable.

The same mathematical difference of 1, therefore, does not correspond with our visual impression. The CIELab color space L* C* h provides an alternative in the "achromatic" area. Determination of the color deviation via cylindrically plotted coordinates L*, C* and h in the CIELab color space allows the description of color and color distances just as we see them. The total color difference (dE*) is split into the lightness difference (dL*), the chroma difference (dC*) and the hue difference (dH*).

Color deviations dL* dC* dh* expressed in cylindrical coordinates



Tolerances dL* dC* h expressed in cylindrical coordinates in the CIELab color space



The formula is then as follows:

$$dE^* = \sqrt{(dL^*)^2 + (dC^*)^2 + (dH^*)^2}$$

L* Lightness axis

dL* = Lightness difference: value and interpretation are identical with the description in the L*a*b* system

C* Chroma (colorfulness)

dC* = Difference in colorfulness: represents the difference in the distances from each color point to the lightness axis.

$dC^* = C^*_1 - C^*_0$
where C^*_0 = chroma of the standard
and C^*_1 = chroma of the sample

- if dC* is positive, the sample has a higher chromaticity than the standard
- if dC* is negative, the sample has a lower chromaticity than the standard

H° color shade (angle)

dh = hue angle difference: represents the difference in angle (in degrees) between the vector courses associated with the two colors (standard and sample). The angle difference dh is converted into a distance of length dH* using the following transformation:

$$dH^* = 2\sqrt{C^*_0\, C^*_1} \cdot \sin\left(\frac{dh}{2}\right)$$

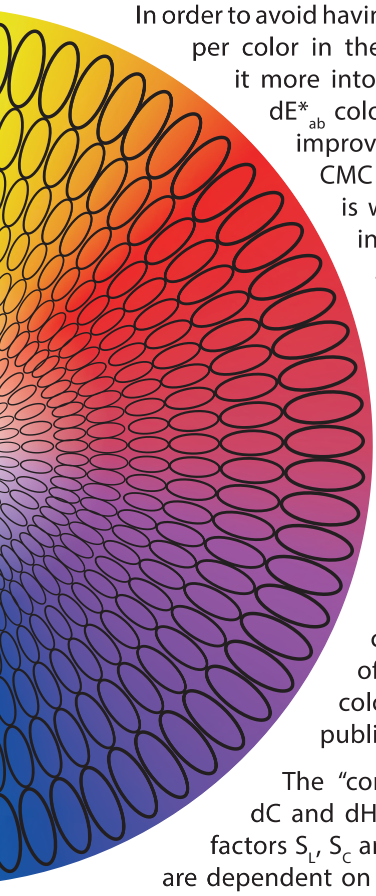
Breaking down the total color difference dE* into dL*, dC* and dH* like this puts it on a level with describing color deviations using visual evaluation in natural classification. As it is simpler and more practical, this is the most frequently applied method.

Color specialists very often use dL*, da* and db* as the form to express the color deviations, if C* ≤ 5 and the color distance is evaluated according to L*C*H* > 5. If C* ≤ 5, then the coordinates L*a*b* must be used for evaluation. If the value C* > 5, then the coordinates L*C*H* must be used for the evaluation.

CMC compliance system

The color distance formulae in the CIELab color spaces L*a*b* and L*C*h have the advantage of being relatively simple and practical in their application.

A disadvantage is that the CIELab color system is not visually of uniform scale. The calculated color distances do not correspond to the perceived or sensed color distances for all colors. In practise, this means that for the achromatic colors, the human eye can distinguish the slightest differences in color shade. Accordingly, the lowest possible dE^*_{ab} numerical value had to be determined here. The more brilliant the color shades being evaluated, that is, the higher the C values, the further out are the colors in the CIELab system, and the lower the sensitivity with which the human eye reacts to the color distances. Here, among others, a numerically higher dE^*_{ab} difference is not recognised by the eye. The eye is also better at evaluating differences in the color shade than differences in lightness or chroma (brilliance).



In order to avoid having to determine color tolerances per color in the CIELab system, and to bring it more into line with the human eye, the dE^*_{ab} color distance formula was further improved. This brought about the CMC formula, for example, which is widespread today in the textile industry.

The CMC formula comes from Great Britain, where continuous research has been carried out since 1970. It was tested based on tens of thousands of visual evaluations and finally standardised by the UK standards body, the British Standards Institution. The original name, JPC70, was later changed to CMC (for color Measurement Committee of the Society of Dyers and colorists). The CMC formula was published in 1984.

The "components" of dE, namely dL, dC and dH, are weighted with correction factors S_L, S_C and S_h, which themselves in turn are dependent on the lightness, colorfulness and hue. S_L, S_C and S_h are essentially hyperbolic functions, ensuring that dL and dC increase as the colors become darker and more achromatic (greyer). dH also decreases as the chroma increases. A correction is also made depending on the situation of the color circle.

The CMC color distance formula is as follows:

$$dE_{CMC} = \sqrt{\left(\frac{dL^*}{l\,S_L}\right)^2 + \left(\frac{dC^*}{c\,S_C}\right)^2 + \left(\frac{dH^*}{S_H}\right)^2}$$

- l lightness factor
- c chroma factor
- S_L function of L
- S_C function of C
- S_H function of H and C

- Valid for S_L:
  If $L^* < 16$ $S_L = 0.511$

  If $L^* \geq 16$ $S_L = \dfrac{0.040975L^*}{1 + 0.01765L^*}$

  This correction improves the evaluation of dL values by almost 200% in the case of very dark colors!

- Valid for S_C:

  $$S_C = \frac{0.0638C^*}{1 + 0.0131C^*} + 0.638$$

  With the parameter SC, dC values close to the achromatic axis are weighted approx. 60% more highly. For brilliant colors (high chroma values), CMC decreases existing DC values.

- Valid for S_H:

  $$S_H = (FT + 1 - F)\,S_C$$

  where $F = \sqrt{\dfrac{C^{*4}}{C^{*4} + 1900}}$

  And $T = 0.36 + |0.4 \cos(35 + h)|$

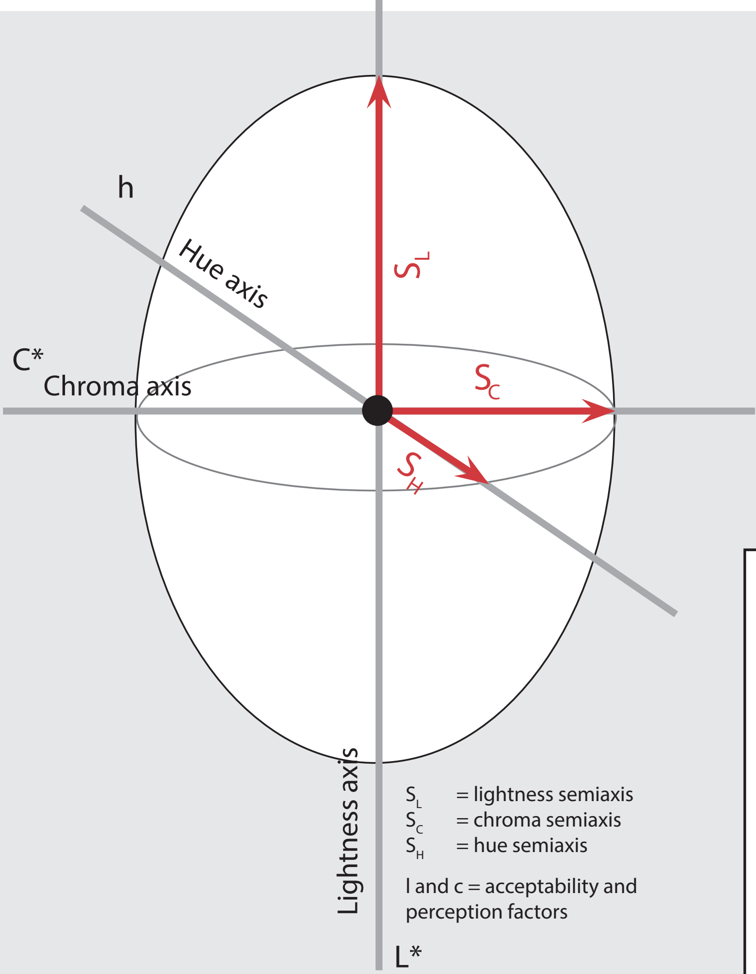
  unless $164° < h < 345°$

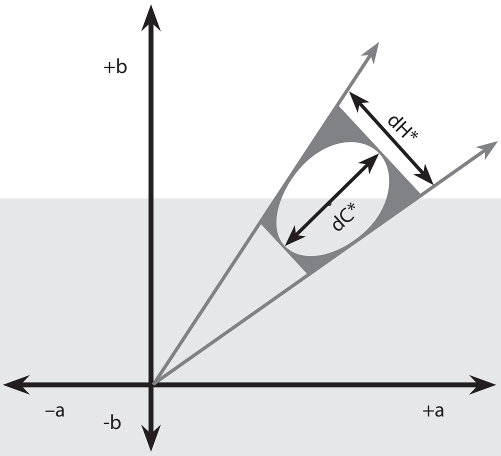
  Or $T = 0.56 + |0.2 \cos(168 + h)|$

  Note: | represents an absolute value

Due to the influence of SC, given dH values close to the achromatic axis are weighted more highly, but not as highly as with SC alone, due to the influence of the factor f. According to the CMC formula, dH increases in the orange area and in the violet area, and decreases in the green to blue area and in the purple to red area.

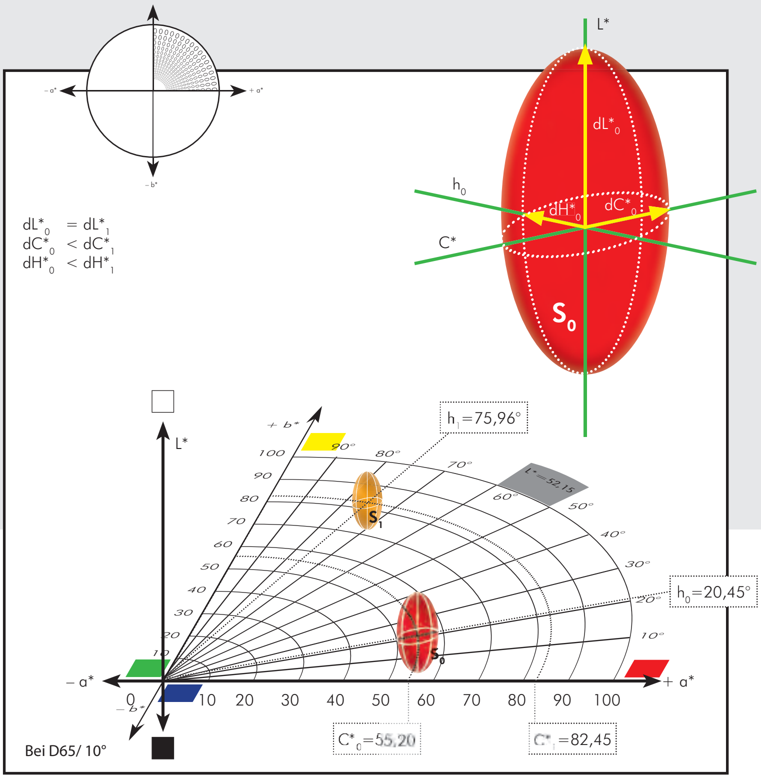
The principle of
CMC acceptability





$$dE_{CMC} = \sqrt{\left(\frac{dL^*}{l\,S_L}\right)^2 + \left(\frac{dC^*}{c\,S_C}\right)^2 + \left(\frac{dH^*}{S_H}\right)^2}$$

CMC – tolerance = ellipsoid



CMC acceptability tolerances in
the CIELab color space

The CMC color distance formula is based on approximately 2,000 textile samples that were matched under D65 illumination and measured using the CIE64 10° standard observer function.

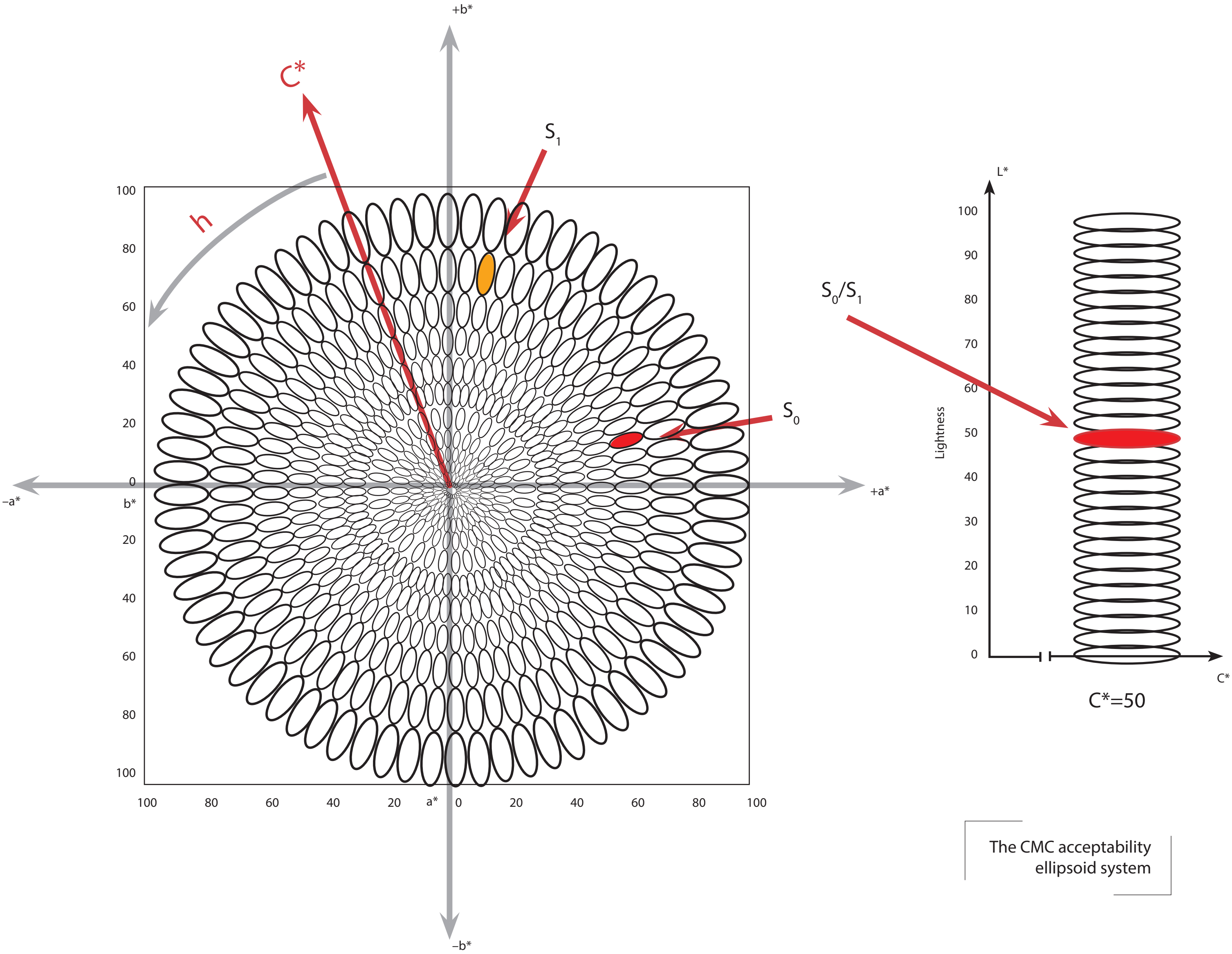
The correction parameters (S_L – S_C – S_H) have therefore been empirically evaluated and are available in formulae that allow prior calculation. Furthermore, the two additional factors l ("lightness") and c ("chroma") can influence the results depending on how a problem – especially the acceptability of a deviation – is positioned.

The correction parameters l and c can be changed by the user. They are both equal to 1. This corresponds to the most common case when evaluating the perceptibility of color deviations. In order to evaluate the acceptability, the values l and c can be increased or decreased. For example, the CMC combination (2,1) is used in the textile industry, where l = 2 and c = 1. Here, l = 2 means that only half of the lightness distance goes into the calculation for the total color distance.

The lightness difference (dL*) is changed only via the lightness. It increases for lower lightness values and decreases for higher lightness values.

The differences in colorfulness (dC*) are changed only via the colorfulness. They are generally smaller compared with the CIELab system, with the exception of low values of colorfulness, smaller than 6.

The hue deviations (dH*) are changed only via the hue angle and the colorfulness. It can be seen, especially for orange shades, that the color deviations become larger in relation to the green shades, and that the effect of the color deviations with reference to the CIELab system reduces considerably if colors are relatively saturated.



The CMC acceptability ellipsoid system

The effects of these correction parameters can be seen in the above graphic. The visually determined differences of the same magnitude are specified as ellipses for the area a*/b* for a constant lightness. The differences within an ellipse are perceived by the human eye as equal. The right-hand side of the graphic shows the acceptability ellipses on the L* axis (for a constant colorfulness C* = 50, but a variable lightness L* of 0 -100).

The graphic makes one thing clear: The CMC formula does not provide a uniform representation system or form a color space, but it enables the calculation of color deviations and acceptability based on an empirical valuation of any color point in the CIELab color space.

In the context of improving the acceptability formulae and the color distances, the CIE developed the color distance formulae CIE94 and CIE2000.

The CIE94 color distance formula

In 1994, the CIE published the CIE94 color distance formula. It is based on a similar approach to the CMC formula, but provides three correction parameters (kL, kC and kH) that can be optimised according to the application area. Observation conditions have also been added to the formula, which serve as a basis for the presentation and observation of the samples.

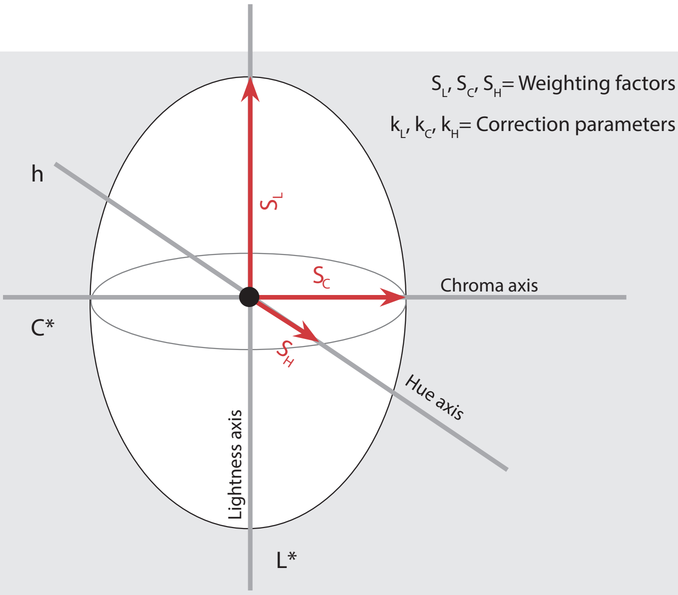
The CIE94 color distance formula is as follows:

$$dE_{94} = \sqrt{\left(\frac{L^*_2 - L^*_1}{k_L S_L}\right)^2 + \left(\frac{C^*_2 - C^*_1}{k_C S_C}\right)^2 + \left(\frac{dH^*_{ab}}{k_H S_H}\right)^2}$$

$$L^*_2 - L^*_1 = dL^*$$

The total color distance dE^*_{94} between 2 color samples represents the distance in the CIE76 color space (CIELab) that has been weighted and adjusted by the user. Under specified reference conditions, the formula takes into account the components of these color distances, such as the differences in lightness (dL*), the difference in colorfulness (dC*), and the hue difference (dH*).

The factors SL, SC and SH represent the respective weighting factors for the differences in lightness, colorfulness and hue. They are calculated and weighted as follows:



$$dE_{94} = \sqrt{\left(\frac{L^*_2 - L^*_1}{k_L S_L}\right)^2 + \left(\frac{C^*_2 - C^*_1}{k_C S_C}\right)^2 + \left(\frac{dH^*_{ab}}{k_H S_H}\right)^2}$$

CIE94 Color distance formula

The factors kL, kC and kH are correction parameters that are linked with the observation conditions of the samples. The reference conditions are determined experimentally as typical conditions for the observation of control colors.

$S_L = 1$
$S_C = 1{+}0.045\ C^*$
$S_H = 1{+}0.0015\ C^*$

The reference conditions:

- Illumination – light source: the light source simulates the D65 standard illuminant type, which is the equivalent of daylight
- Illumination of the sample with a light intensity of approximately 1000 lux
- Environment: uniform observation background of a neutral grey color and lightness L* = 50
- The surfaces to be observed (samples) must fulfil the following conditions as far as possible:
  - Observation field and distance must be illuminated so that the field of vision is greater than the centrally fixed field of vision of 4°
  - The samples must be arranged next to one other; they cannot be separated and must be in direct contact so that the separating line is not apparent, as far as possible.
  - The structure, texture and color must be as uniform as possible.

Note:

The correction factors k_L, k_C and k_H are still valuated very badly for special prerequisites. The correction factors k_L, k_C and k_H are equal to 1 for the reference conditions. In the textile industry, the following factors are generally used: $k_L = 2$ and $k_C = k_H = 1$.

The CIE color distance formula must be expressed in the form of dE^*_{94} and written using the abbreviation CIE94. The correction parameters k_L, k_C and k_H do not have to equal 1. In this event, they must follow the abbreviation dE^*_{94}. An example from the textile industry: for the factors $k_L = 2$ and $k_C = k_H = 1$, the notation is then CIE94 (2:1:1) with the symbol dE^*_{94} (2:1:1).

Tolerance diagram CIE94

CIE2000 – the current CIE color distance formula

Even though it was an improvement on the CMC formula, CIE94 achieved little or no acceptance in the industry. Therefore, it was refined using new data sets and replaced by the new formula CIE2000. The CIE2000 color distance formula is the formula that currently best matches visual perception. It contains not only weighting functions for lightness, colorfulness and hue, but also mixing terms. These terms take into account additional dependency of the colorfulness on the hue.

The CIE2000 color distance formula is as follows:

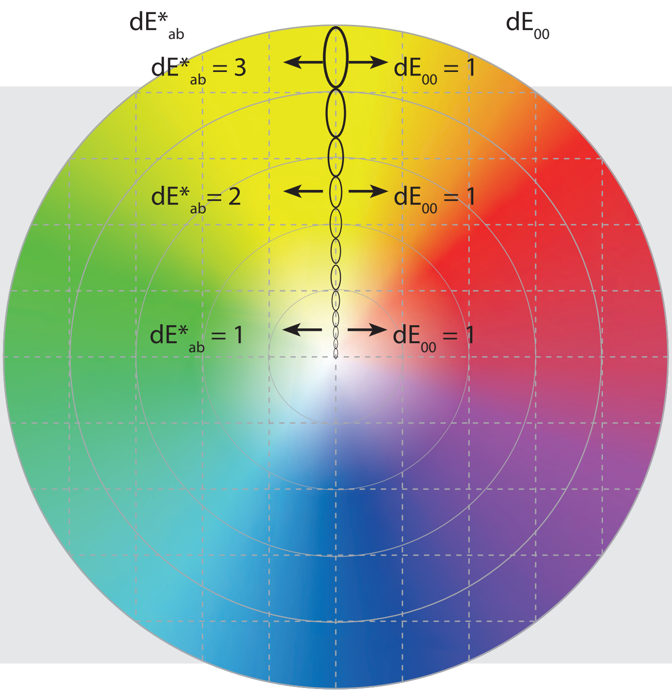
$$dE_{00} = \sqrt{\left(\frac{dL^*}{k_L S_L}\right)^2 + \left(\frac{dC^*}{k_C S_C}\right)^2 + \left(\frac{dH^*}{k_H S_H}\right)^2 + R_T\left(\frac{dC^*}{k_C S_C}\right)\left(\frac{dH^*}{k_H S_H}\right)}$$

The last term in the equation is also referred to as a rotation term. This introduces an additional weighting dependent on the “rotating” hue, and should correct particularly bad cases of lack of equivalence between visually perceived and calculated color distances in the blue color range.

All of the color distance formulae described up until now can be represented by means of the above equation. Thus, for CIE94 and CMC, $S_L = 1$. The rotation term does not exist for the color distance formulae CMC and CIE94, so therefore it is zero (R_T=0).

CIE2000 gets very close to the goal of obtaining an equivalent color distance for all shades of color.

Comparison between dE^*_{ab} and dE_{00}



Assessment of CMC, CIE94 and CIE2000 in summary

All of the corrections to the original CIELab dE formula represent a significant improvement to color difference evaluation. However, as long as no DIN or ISO standards exist, no corrected dE formulae will gain acceptance in practice. Therefore, the technical standards committee for color in the DIN (especially working committee 4), in parallel with the development of the CIE (CIE2000), had the idea of transforming the entire color space to make the scale more uniform instead of modifying the color distance formulae themselves. The result was a new color coordinate system, which subsequently defined a color space that had a uniform chromaticity scale for small color distances. As color distances can now be calculated as vector length from the differences of the color coordinates (here L_{99}, a_{99} and b_{99}), this is referred to as a “Euclidean color space”. The relevant formula was introduced in 1999 as the DIN 99 formula.

Relative color differences – comparison of differently calculated color distances

		L^*	a^*	b^*	C^*_{ab}	dE^*_{ab}	dE_{94}	dE_{00}	dE_{99}
Cyan (C)	1	54	-37	-50	62.2	6.00	3.54	2.29	2.16
	2	52	-41	-46	61.6				
Magenta (M)	1	47	75	-6	75.2	6.00	2.94	2.66	2.54
	2	45	79	-2	79.0				
Yellow(Y)	1	88	-6	95	95.2	6.00	2.77	2.69	2.54
	2	86	-10	91	91.5				
Black	1	18	0	-1	1.0	6.00	5.78	6.28	4.76
	2	16	4	-5	6.4				
C+M	1	26	22	-45	50.1	6.00	3.73	4.56	3.97
	2	24	26	-41	48.5				
C+Y	1	49	-65	30	71.6	6.00	3.26	2.97	2.83
	2	47	-69	26	73.7				
M+Y	1	48	65	45	79.1	6.00	3.23	3.48	2.59
	2	46	69	41	80.3				
Paper	1	93	0	-3	3.0	6.00	5.45	6.13	4.09
	2	91	4	-7	8.1				

Source: Schläpfer, K.: Farbmetrik in der grafischen Industrie (colorimetry in the graphics industry), 3rd edition, St. Gallen, Switzerland; UGRA, 2002

The DIN 99 color space

The basis for the DIN 99 color space is the CIELab color space with its coordinates L*, a*, b*.

The transformation from CIELab to DIN 99 took place in two parts: A transformation of lightness to the new DIN 99 lightness L_{99}, and a transformation of colorfulness or chroma.

After the transformations, the values such as chroma (C_{99}), hue angle (h_{99}) and color distance (dE_{99}) can then be calculated.

The DIN 99 formula is designed for small to medium color distances. Its application is recommended for small color distances up to 5 dE $CIEL_{ab}$ such as those dealt with in quality assurance and recipe calculation.

Calculation

Lightness transformation

The lightness L* is transformed to the DIN 99 lightness L_{99} :

$$L_{99} = \left(\frac{1}{k_E}\right) \cdot (105.51 \cdot \ln(1+0.0158 \cdot L^*))$$

This transformation is to better reproduce the distinguishability of darker shades of color. The transformation resembles a power function with an exponent of 0.75. The area for the dark shades of color is expanded and the area for the light shades is compressed. Medium lightness values are shifted upwards on the lightness axis.

The variable k_E describes the influence of changed observation conditions.

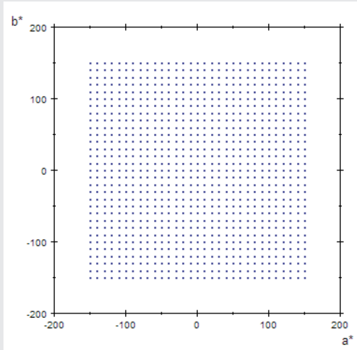
Under reference conditions, k_E =1.

Colorfulness transformation

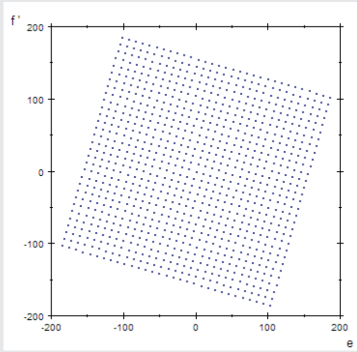
The transformation of the colorfulness coordinates takes place in three steps:

- The colorfulness axis is rotated by 16°
- The yellow/blue axis is multiplied by the factor 0.7, and is therefore compressed
- The colorfulness (chroma) values are logarithmically compressed radially around the L_{99} axis

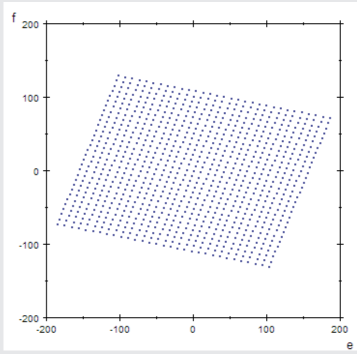
Unlike in the CIE94 and CIE2000 formulae, it is not necessary to determine the hue angle in order to calculate the color distance.



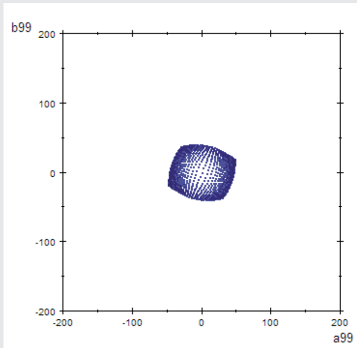
Starting situation: a*/b* plane. The points in these and the following illustrations represent each set of a*/b* coordinates going from -150 to 150 in steps of ten



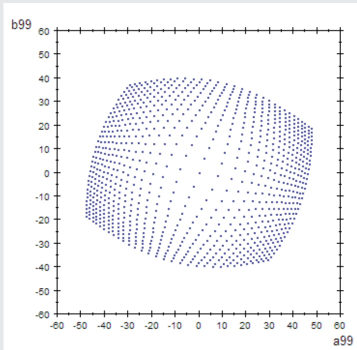
Step 1: rotation of the a*/b* plane by 16°



Step 2: compression of the f axis



Step 3: radial compression of the e/f plane



Enlarged view of the a_{99}/b_{99} plane

The individual calculations are as follows:

a^* and b^* are transformed to:

Redness values (red/green axis)

$$e = (a^* \cdot \cos(16°) + b^* \cdot \sin(16°))$$

Yellowness value f (yellow/blue axis)

$$f = 0{,}7 \cdot (-a^* \cdot \sin(16°) + b^* \cdot \cos(16°))$$

From this, the chroma value G (colorfulness) is then calculated:

$$G = \sqrt{(e^2 + f^2)}$$

With the compression factor

$$k = \frac{\ln(1 + 0.045 \cdot G)}{(k_{CH} \cdot k_E \cdot 0.045)}$$

this results in the

hue values

$$a_{99} = k \cdot \frac{e}{G}$$

$$b_{99} = k \cdot \frac{f}{G}$$

In the case that $a^* = b^* = 0$, also $e = f = G = 0$, then $a_{99} = b_{99} = 0$.

An advantage compared to the other correction methods is that with the transformed a_{99} and b_{99}, you can now proceed exactly as you do in CIELab, to now calculate, for example, a C_{99} (corrected colorfulness/chroma) or a H_{99} (corrected hue difference).

Accordingly, the formulae are then as follows:

$$dH_{99} = \frac{(a_{99\,B} \cdot b_{99\,P}) - (a_{99\,P} \cdot b_{99\,B})}{\sqrt{0{,}5 \cdot ((C_{99B} \cdot C_{99P}) + (a_{99B} \cdot a_{99P}) + (b_{99B} \cdot b_{99P}))}}$$

or

$$dE_{99} = \sqrt{(dL_{99})^2 + (da_{99})^2 + (db_{99})^2}$$

where

$$dE_{99} = \sqrt{(dL_{99})^2 + (dC_{99})^2 + (dH_{99})^2}$$

$$C_{99} = \sqrt{(a_{99})^2 + (b_{99})^2}$$

In the DIN 99 system, dC and dH are calculated exactly as in CIELab. The index B stands for the reference or comparison sample, and P stands for the sample.

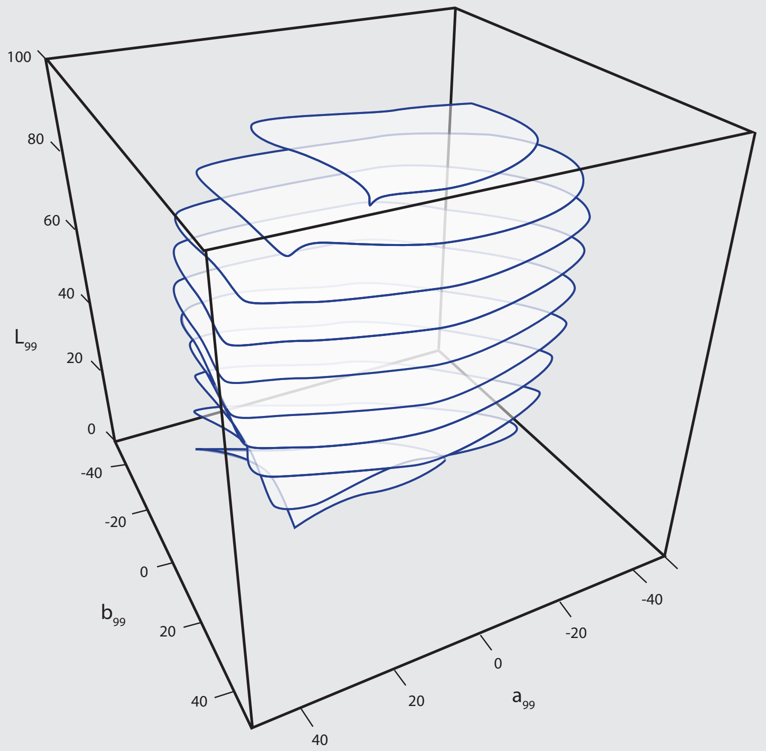
Quality and further development

The DIN 99 color space is very close to the CIE94 color distance formula and has similar qualitative characteristics, also comparable with CMC(l:c). A great advantage as opposed to CIE94 is the permutability of the sample and comparison sample in the calculation, making the transformation completely and easily reversible.

The difference from CIELab is that, with regard to the calculations, the equivalence with perceived color distances has been improved. The DIN 99 formula is handled the same way as the CIELab formula.

The modification of the lightness axis and the higher weighting of the colors close to the achromatic axis by the compression of extremely saturated colors considerably improve the uniformity of perceived color distances.

The evaluation categories of lightness axis and hue axis (yellow/blue and red/green) have not changed in comparison with CIELab. The calculation of the color distance as a simple Euclidean distance is a great advantage compared with CMC(l:c), CIE94 and CIE2000, for which the calculation is very complicated.

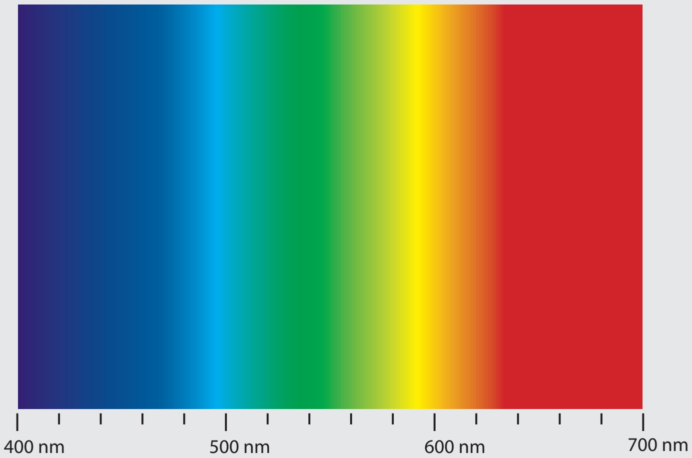


DIN 99 optimal color solid – standard illuminant D65

Example of a modern color space:

DIN 99 optimal color solid in cross-sectional view. Sectional planes for lightness L_{99}=5 to 95 in steps of ten. a_{99} represents the yellow/blue direction, b_{99} the red/green direction. Distortions come about because the connection of the colors with lightnesses is a factor in present-day color spaces. The area of this color solid is created via spectra. The area represents the entirety of all optimal colors (colors with the highest chroma and brilliance). The volume of the color solid represents all of the colors that are theoretically possible.

VISIBLE SPECTRUM



Conclusion and outlook for the future

Instrumental color measurement is an essential aid to quality assurance in industry. It complements visual color matching and allows the introduction of numerical values as tolerances. Cooperative work between suppliers and customers is thus put on a reproducible basis, with both sides using technical measurement. It is important, however, that the colorimetric assessments match the visual assessment as far as possible.

The color spaces developed over the years now come very close to visual color perception, but also display weaknesses, as the color distance perceived visually in many cases does not correspond with the parameter for the measured color distance, dE*.

Further work is constantly being carried out on the development of a completely uniform color space, on a formula for color distance, and on simple acceptability that is representative of visual perception. Research in recent years on the neurophysiology of vision and psychology of perception, together with statistical research, is also leading to improved efficiency of acceptability formulae and making their automatic usage ever more reliable. It can therefore be said in good conscience that with perfect command and expert handling of the current mathematical model calculations in the area of the objective automatic control of colors and color distances, color measurement can today be applied accurately to guarantee high quality of the colored products.

Metamerism

Metamerism is a characteristic of a pair of samples. Two samples match when viewed by a specific observer under a specific lamp. However, when either the lamp or observer changes, the colors no longer appear to match. The choice of colorants in the recipe influences the degree of metamerism between the samples. Computer color matching systems include settings to select the least metameric formula available to match a color. The formula selected may be the best match to the color under a variety of lighting and viewing conditions, and you may not be able to visually detect the metamerism between the samples when you change either condition.

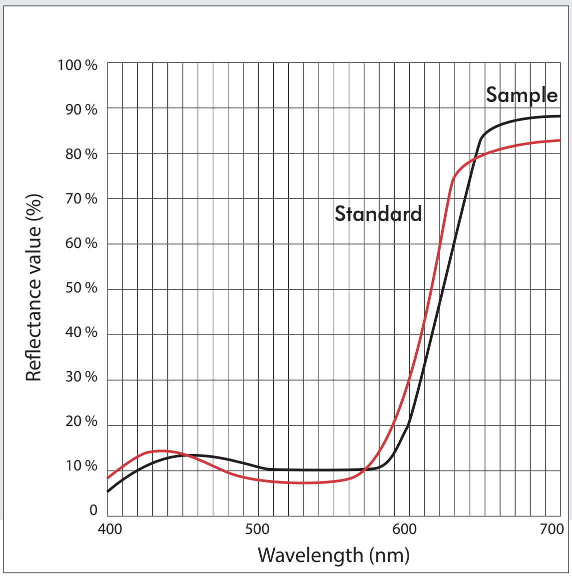
When you use the same ingredients in the original sample to match a color, you can match the spectral curve of the object, wavelength by wavelength. However, this is not necessary to reproduce a color. In commercial applications, it is standard practice to match the colorimetric description of a particular color. You find a formula that matches the tristimulus values of a color for a specific lighting and viewing condition. To do this you do not have to have the exact colorants used to make the target color. You may find several different recipes to match the color. However, keep in mind that changing the lighting or viewing conditions, changes the colorimetric description of the color. When you match the tristimulus values, if you change either condition the colors may no longer match.

Metamerism

Standard specifications (X-Y-Z)
for the 10° -normal observer

	Illuminant type D65 (Daylight)		Illuminant type A (Artificial light)	
	Standard STD.N	SampleNo.2 ECH2.N	Standard STD.N	SampleNo.2 ECH2.N
X	$X_{\varnothing D} = 31.28$	$X_{2D} = 31.28$	$X_{\varnothing A} = 47.88$	$X_{2A} = 52.66$
Y	$Y_{\varnothing D} = 20.28$	$Y_{2D} = 20.28$	$Y_{\varnothing A} = 27.57$	$Y_{2A} = 31.41$
Z	$Z_{\varnothing D} = 12.71$	$Z_{2D} = 12.71$	$Z_{\varnothing A} = 4.04$	$Z_{2A} = 4.42$

Color-matching functions



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