Colour perception and measurement

the calculation of colour coordinates within the CIELab system

1 Introduction

Everyday we see all sorts of coloured objects. The observation of colour is important for survival, and that is why men can distinguish colour well. We all know that an apple showing brown spots or even blue-green structures on its surface may not taste well anymore. Green stained meat-products are not only unattractive, but may cause sickness also. A pale faced child will be examined to determine whether it is ill or not. So, colour perception supports us in surviving. But colour is more. We can enjoy the colours of a bouquet of flowers. Emotions can be touched by observing the colours of a painting. With the colours of their clothing people can show whether they obey fashion. So, colour also fulfils an important role in our social life.
This chapter aims to explain how colour can be determined objectively, only colour formed by diffuse reflection from not glossy surfaces is considered.

Colour observation by diffuse reflection is uncommon, generally also some gloss is observed. Obviously we correct the colours observed for gloss. The car shown in figure 1 is considered as entirely painted red with one colour shade, but, as the enlarged squares in the photograph show, the colour observed differs from spot to spot.

Figure 1. Despite gloss, causing different colours observed, we consider the car as entirely painted red with one colour shade.

Beside gloss from the surface also other reflections may contribute to the arise of colour. Cars e.g. can be varnished with metallic paints and pearl paints. If we observe cars finished with such paints we also are able to consider them as entirely painted with one colour shade as well. Later on we will see that yellow and blue are complementary colours. Yet there exist pearl paints which exhibit both these colours, as shown by figure 2. The colours produced by these varnishes can not be measured and calculated by the method treated in this chapter.

Figure 2. A car painted with pearl varnish. The different combinations of direction of light incident and direction of observation with respect to the metal surface can result to observation of complementary colours, like blue and yellow in this case.

2 Colour perception

Colour perception expresses experience of colour. The colour perceived from an object depends on several elements: the light source, the colour properties of the object observed and the colour sensitivity of the observer. Furthermore the perception is influenced by the colours present in the environment of the object.

2.1 The light source

White light is a mixture of light of all colours. This light can be separated into different colours, which can be seen in nature when a rainbow appears.

Figure 3. A doubled rainbow, the white sunlight is decomposed into different colours. The inner rainbow is red on the outside and violet on the inner side. The outer rainbow is coloured in the opposite way.

The white daylight is separated in different colours by small raindrops, and reflected in the direction of our eyes.

If we hold a piece of white paper under a yellow lamp we will observe the paper as yellow. After putting the same paper under a blue lamp we will observe it as blue. So, the colour perceived depends on the colour of the light source.

Figure 4. The photographs presented above are taken using different coloured light sources.
1: white, 2: red, 3: orange, 4: yellow, 5: green, 6: blue.

Figure 4 shows photographs of two cardboard boxes illuminated by different coloured lamps. Strikingly is the observation that photo's 2 and 3 seem not to contain any blue anymore. Photograph 4 shows that the colour of the 'hair' and the 'face' on the right box are equal under yellow illumination, but photo 1 shows their colours are different if white light is used. This effect is called metamerism: essentially different colours seem to be equal due to the combination of light source and properties of the observer. So, the colour of the illuminating light source influences the colour that we observe. These photographs were made under extreme conditions, but if we want to measure and quantify colour exactly we have to account for the light source used.

Light can be considered as radiation with a special wavelength. Like waves on the sea, we can measure the distance between two summits of the waves, this distance is called wavelength. Water waves will show wavelengths up to several tens of meters.

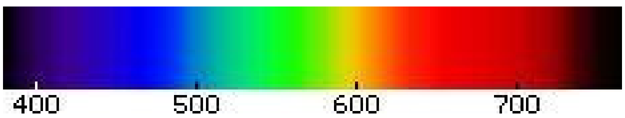

Figure 5. The spectrum of light. *NB. Due to the properties of your screen and/or the printer, and their adjustments the colours shown will differ form their real spectral colours, this figure is just an illustration.*

Light also has a wavelength, but this wavelength is much shorter, we express it in nanometer, abbreviated as nm (one nanometer eqauls one millionth of a millimeter, so,
1 nm = 0.000 001 mm, or 10^{-9} m). Visible light measures wavelengths of 480 - 780 nm.

The relation between wavelength and colour is indicated in figure 5. Light with a wavelength between 380 and 500 is observed as violet to blue, around 550 nm is green, wavelengths longer than 620 nm are seen as red.
This wavelength to colour relation can not simply be reversed. Blue light does not always contain only light with wavelengths shorter than 500 nm. It can also contain the entire visible spectrum from 380 - 780 nm, but the intensities of the 'blue' wavelengths will be relatively higher than the intensities of the other wavelengths.

White light can be composed from very different spectra. A spectrum is a graph showing the intensity as a function of the wavelength. Figure 6 shows some examples of spectra form light sources that we will perceive as 'white'. The curve 'D_{65}' shows the spectrum of a standard light source as defined by the CIE (Commission Internationale d'Eclairage), and corresponds to *daylight*: a clear northern sky without direct sunlight. The curve 'Planilux' shows the spectrum of a light box used to judge X-ray photographs (made on film). The blue curve represents the spectrum of a white LED.
Because our colour perception adapts to the light sources used, we are inable to judge the colour of light sources adequately. The big differences between D_{65} on one hand and the Planilux and the white LED on the other in the red part of the spectra are not visible because our eyes are relatively insensitive for wavelengths longer than 700 nm.

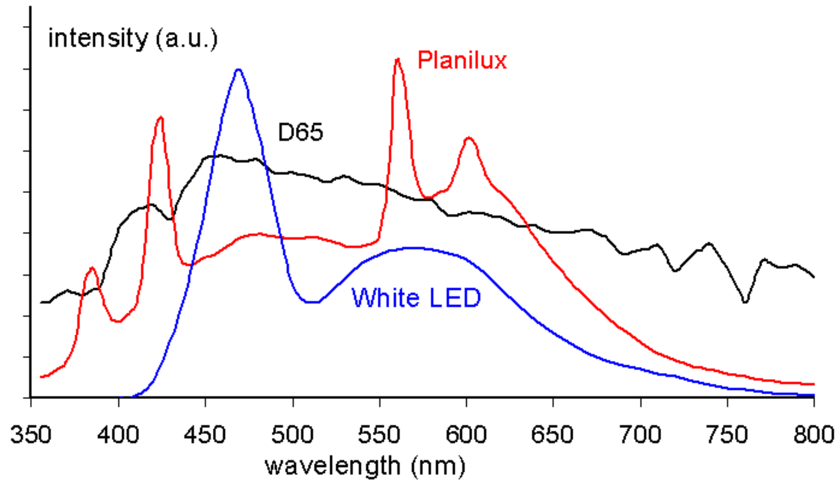

Figure 6. Examples of spectra of white light sources. D65: standard daylight, Planilux: a light box for judgement of X-ray photographs, and a white LED.

2.2 Spectral reflection

Light incident on an object can be reflected. White objects reflect all wavelengths. In general a part of the light will be absorbed. A green object e.g. absorbs red light mainly, resulting in reflection of yellow, green and blue light, which are observed as green. If an object absorbs all wavelengths shorter than 600 nm we will observe it as red. Black objects absorb the entire visible spectrum.

2.2 The eyes and the brains

Our eyes contain only four types of light sensitive cells: rod cells and three types of cone cells. The rods are sensitive for all colours, so, they can not distinguish between colours. The rods are used for vision in the dark. The cones are colour selective, three types are present: sensitive for red, green or blue light. The sensitivity of these cells varies with the wavelength of the light observed. If a specified ratio of signals is generated by the red and the green sensitive cells, the light will be seen as yellow. Combination of the signals and the sensitivities of the three types of cone cells results in the ability to see all colours possible. The signal processing, resulting in the observation of colour is performed in the brain. We have to be aware that *wavelength* is a *physical property*, whereas colour is just a human interpretation of light. The construction of our eyes and our brain enables us to observe different spectra as different colours. We made only agreements on what we call 'red', 'yellow' and 'blue', but the colours are not physically present.

3 The measurement of the colour of objects

In order to quantify colour in an accurate objective way the CIE-Lab system was developed. The calculations below only consider colours formed by light reflection.

Within the CIE-Lab system colour is represented as a point in a three dimensional space, with coördinates L*, a* en b*. De L*-axis represents the lightness: L* = 0: black; L* = 100: white; a* = -60: green, a* = +60: red; b* = -60: blue; b* = +60: yellow. De set of all colours possible is not cubic, for something that is white (L* = 100) can not be green (a* = -60) at the same time, so there is a determined connection between the maximal and minimal values on the three axes.

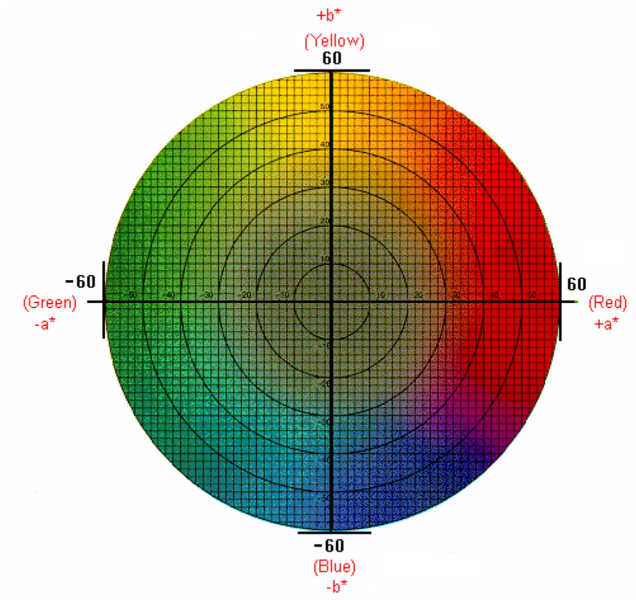

Figure 7. Colous shown in the a*b*-crossection of the CIE-Lab-system.

Because the colour of an object depends on the illumination, colour measurement should always be performed using a reference: a white standard under the same illuminating conditions. This white standard reflects only the spectrum of the light source used, so that we are able to correct for the illumination. The colour coordinates in the CIE-Lab system are mostly determined under D_{65} illumination. The reflection spectrum measured with the white standard $L_W(\lambda)$ is ideally equal to the spectrum of the light source. The reflection spectrum measured from the coloured object is $L_S(\lambda)$, both spectra are expressed in the unit W/m^2sr.

The colour coordinate under D_{65} illumination is calculated as follows:

$$\varphi(\lambda) = \frac{L_S(\lambda)}{L_W(\lambda)}$$

$$k_{10} = \frac{100}{\int E_{D65}(\lambda)\,\bar{y}_{10}\,d\lambda}$$

$$X_{10} = k_{10}\int \varphi(\lambda)\,\bar{x}_{10}(\lambda)\,d\lambda \qquad X_{n10} = k_{10}\int \bar{x}_{10}(\lambda)\,d\lambda$$

$$Y_{10} = k_{10}\int \varphi(\lambda)\,\bar{y}_{10}(\lambda)\,d\lambda \qquad Y_{n10} = k_{10}\int \bar{y}_{10}(\lambda)\,d\lambda$$

$$Z_{10} = k_{10}\int \varphi(\lambda)\,\bar{z}_{10}(\lambda)\,d\lambda \qquad Z_{n10} = k_{10}\int \bar{z}_{10}(\lambda)\,d\lambda$$

with λ as the wavelength in nm, $E_{D65}(\lambda)$ as the relative spectral irradiance distribution of the CIE standard D_{65} light source, $\bar{x}_{10}(\lambda)$, $\bar{y}_{10}(\lambda)$, en $\bar{z}_{10}(\lambda)$ as the spectral tristimulus values according to CIE 1964. These spectra can be found in table 1 en table 2. Now we can calculate:

$$X^* = \sqrt[3]{X_{10}/X_{n10}} \quad \text{if} \quad X_{10}/X_{n10} > 0.008856$$
$$X^* = 7.787(X_{10}/X_{n10}) + 0.138 \quad \text{if} \quad X_{10}/X_{n10} \le 0.008856$$

in the same way the values of Y^* and Z^* have to be calculated. These values have to be used to calculate the CIELab (1976) colour coordinates:

$$L^* = 116Y^* - 16$$

$$a^* = 500\,(X^* - Y^*)$$

$$b^* = 200\,(Y^* - Z^*)$$

Sometimes only the colour difference between two objects is important, so the distance between two points in the three dimensional colour space. This colour difference dE between an object (1) with colour coordinates L^*_1 a^*_1 b^*_1 and the other object (2) with colour coordinates L^*_2 a^*_2 b^*_2 is expressed as:

$$dE = \sqrt{(L^*_2 - L^*_1)^2 + (a^*_2 - a^*_1)^2 + (b^*_2 - b^*_1)^2}$$

In general if $dE \le 0.2$ the two objects are considered to have the same colour.

4 Remarks

Colour differences easily lead to debates. Once, the owner of an eatery ordered six tables of the same colour. After delivery he was convinced that the tables could be divided into colour groups, so he claimed the supplier to bring a set of exactly equal tables or pay indemnification. We were consulted by the claimant to perform colour measurements, in order to support his claim. However, we were convinced that the surfaces of the tables were not equal, we could not measure any colour difference. More investigations demonstrated that differences in the surface roughness of the tables were responsible for the colour differences.

Table 1. Spectra of a D_{65} light source, wavelength λ in nm

λ	D_{65}	λ	D_{65}	λ	D_{65}	λ	D_{65}	λ	D_{65}
		450	117.0	550	104.0	650	80.0	750	63.6
355	45.8	455	117.4	555	102.0	655	80.1	755	55.0
360	46.6	460	117.8	560	100.0	660	80.2	760	46.4
365	49.4	465	116.3	565	98.2	665	81.2	765	56.6
370	52.1	470	114.9	570	96.3	670	82.3	770	66.8
375	51.0	475	115.4	575	96.1	675	80.3	775	65.1
380	50.0	480	115.9	580	95.8	680	78.3	780	63.4
385	52.3	485	112.4	585	92.2	685	74.0	785	63.8
390	54.6	490	108.8	590	88.7	690	69.7	790	64.3
395	68.7	495	109.1	595	89.3	695	70.7	795	61.9
400	82.8	500	109.4	600	90.0	700	71.6	800	59.5
405	87.1	505	108.6	605	89.8	705	73.0		
410	91.5	510	107.8	610	89.6	710	74.3		
415	92.5	515	106.3	615	88.6	715	68.0		
420	93.4	520	104.8	620	87.7	720	61.6		
425	90.1	525	106.2	625	85.5	725	65.7		
430	86.7	530	107.7	630	83.3	730	69.9		
435	95.8	535	106.0	635	83.5	735	72.5		
440	104.9	540	104.4	640	83.7	740	75.1		
445	110.9	545	104.2	645	81.9	745	69.3		

Table 2. Values of $\bar{x}_{10}$, $\bar{y}_{10}$ and $\bar{z}_{10}$ as a function of the wavelength λ in nm

λ	$\bar{x}_{10}$	$\bar{y}_{10}$	$\bar{z}_{10}$	λ	$\bar{x}_{10}$	$\bar{y}_{10}$	$\bar{z}_{10}$	λ	$\bar{x}_{10}$	$\bar{y}_{10}$	$\bar{z}_{10}$
				525	0.1096	0.7932	0.0573	675	0.0636	0.0232	0.0000
380	0.0014	0.0000	0.0065	530	0.1655	0.8620	0.0422	680	0.0468	0.0170	0.0000
385	0.0022	0.0001	0.0105	535	0.2257	0.9149	0.0298	685	0.0329	0.0119	0.0000
390	0.0042	0.0001	0.0201	540	0.2904	0.9540	0.0203	690	0.0227	0.0082	0.0000
395	0.0076	0.0002	0.0362	545	0.3597	0.9803	0.0134	695	0.0158	0.0057	0.0000
400	0.0143	0.0004	0.0679	550	0.4334	0.9950	0.0087	700	0.0114	0.0041	0.0000
405	0.0232	0.0006	0.1102	555	0.5121	1.0002	0.0057	705	0.0081	0.0029	0.0000
410	0.0435	0.0012	0.2074	560	0.5945	0.9950	0.0039	710	0.0058	0.0021	0.0000
415	0.0776	0.0022	0.3713	565	0.6784	0.9786	0.0027	715	0.0041	0.0015	0.0000
420	0.1344	0.0040	0.6456	570	0.7621	0.9520	0.0021	720	0.0029	0.0010	0.0000
425	0.2148	0.0073	1.0391	575	0.8425	0.9154	0.0018	725	0.0020	0.0007	0.0000
430	0.2839	0.0116	1.3856	580	0.9163	0.8700	0.0017	730	0.0014	0.0005	0.0000
435	0.3285	0.0168	1.6230	585	0.9786	0.8163	0.0014	735	0.0010	0.0004	0.0000
440	0.3483	0.0230	1.7471	590	1.0263	0.7570	0.0011	740	0.0007	0.0003	0.0000
445	0.3481	0.0298	1.7826	595	1.0567	0.6949	0.0010	745	0.0005	0.0002	0.0000
450	0.3362	0.0380	1.7721	600	1.0622	0.6310	0.0008	750	0.0003	0.0001	0.0000
455	0.3187	0.0480	1.7441	605	1.0456	0.5668	0.0006	755	0.0002	0.0001	0.0000
460	0.2908	0.0600	1.6692	610	1.0026	0.5030	0.0003	760	0.0002	0.0001	0.0000
465	0.2511	0.0739	1.5281	615	0.9384	0.4412	0.0002	765	0.0001	0.0000	0.0000
470	0.1954	0.0910	1.2876	620	0.8544	0.3810	0.0002	770	0.0001	0.0000	0.0000
475	0.1421	0.1126	1.0419	625	0.7514	0.3210	0.0001	775	0.0000	0.0000	0.0000
480	0.0956	0.1390	0.8130	630	0.6424	0.2650	0.0000	780	0.0000	0.0000	0.0000
485	0.0580	0.1693	0.6162	635	0.5419	0.2170	0.0000				
490	0.0320	0.2080	0.4652	640	0.4479	0.1750	0.0000				
495	0.0147	0.2586	0.3533	645	0.3608	0.1382	0.0000				
500	0.0049	0.3230	0.2720	650	0.2835	0.1070	0.0000				
505	0.0024	0.4073	0.2123	655	0.2187	0.0816	0.0000				
510	0.0093	0.5030	0.1582	660	0.1649	0.0610	0.0000				
515	0.0291	0.6082	0.1117	665	0.1212	0.0446	0.0000				
520	0.0633	0.7100	0.0782	670	0.0874	0.0320	0.0000				