

Output Linearization Method *OLM16* for Displays, Offset, and Printers

Remark in June 2019: All old links <http://www.ps.bam.de> in the text (and not in figures and tables) are replaced by the new links <http://farbe.li.tu-berlin.de/A>

This technical paper describes the application of the Output Linearization Method 2016 (*OLM16*). It covers the *device* hue output according to IEC 61966-2-1 and the device-independent *elementary* hue output for displays, offset, and printers according to proposals in the Reportership Report CIE R1-47:2009. There is a former method *OLM04* for *device* hue output which has been used in ISO/IEC TR 19797:2004 for printers. The *OLM04* method has been used for display output in ISO 9241-306:2008 for eight ambient reflections at work places. The revision of ISO 9241-306:2008 which is under work in TC159/SC4/WG2 *Ergonomics - Visual Display Requirements* may use the *OLM16* for both the eight ambient reflections at work places and the device-independent hue output. See now ISO 9241-306:2018: <http://standards.iso.org/iso/9241/306/ed-2/index.html>

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for this paper see for example http://farbe.li.tu-berlin.de/OUTLIN16_01.PDF

Application examples of the Output Linearization Method OLM16

In 2012 a publication *Colour and Colour Vision - Elementary colours in colour image technology* was published by K. Richter. This TUB publication has applied the *OLM16* for the *sRGB* display output, the offset print output, and the laser printer output. Many colorimetric results of the publication *Colour and Colour Vision* are included now in this present paper.

Free offset prints of the paper *Colour and Colour Vision* may be ordered by email to klaus.richter@mac.com.

For many people the real output is much more impressive compared to the technical matter in the present paper which is intended for people with some technical knowledge in the colour area.

In addition the paper *Colour and Colour Vision - Elementary colours in colour image technology* is available in different PDF file versions for mobile reading (format A5), for monitor, offset, and printer output (format A4), and in the different languages German, English, French, Spanish, Italian, and Norwegian, see <http://farbe.li.tu-berlin.de/color>

In addition the *OLM16* was used to print the colour atlas *Relative Elementary Colour System (RECS)* with 16 step colour scales and about 2000 colour samples. The offset print file includes the *OLM16* within a Frame File which steers the output of all pages (compare Table 7 on page 42). The following file output shows 8 RECS example pages and the layout and the 4 separations for the undercolor removal method (grey is printed by the black colorant only), see (15 pages, 4,5 MB, format A4)

<http://farbe.li.tu-berlin.de/B/Fe46/10L/L46e00FP.PDF>

The RECS atlas is produced with standard offset inks, on standard offset paper (APCO II), for the CIE standard illuminant D65, and for the CIE 2-degree observer, see for short information (1 page, 50KB) <http://farbe.li.tu-berlin.de/RECS08.PDF>

Free examples of *Colour and Colour Vision* and one example of the RECS colour atlas are available by the author at the CIE and some ISO meetings.

One can find a so called *white standard document* which includes some first technical information compared to this paper, and more information about output linearization on the web site <http://farbe.li.tu-berlin.de/outlin>

Technical remark about the availability of figures and tables of the present and similar papers in the internet.
Any figure and table includes usually a code of two letters followed by a number between 00 and 99, for example the code "ME08". One can find the figures and tables and similar ones on the above two TUB servers by adding this code, and the code "/index.html" to the server address, for example <http://farbe.li.tu-berlin.de/ME08/index.html>

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1 Summary

The Output Linearization Method *OLM16* is appropriate for the *rgb* data output on printers, in offset printing, on displays, and data projectors with different reflections on the projection screen.

The *rgb* file data are interpreted in a special *colorimetric* manner with a linear relation to the CIELAB data L^* , C^*_{ab} , and h_{ab} . If a colour output device interprets the *rgb* data according to *OLM16*, then it is called an ***rgb* colour device***. Any two *rgb** colour devices produce a *colorimetric affine match* in CIELAB with equal hue angles h_{ab} and usually different values in lightness L^* and chroma C^*_{ab} . This *colorimetric affine match* is different compared to the usual *colorimetric match* with equal CIELAB data on different devices. The usual *colorimetric match* produces a clipping of colour areas and this disadvantage disappears with the *colorimetric affine match*.

In colorimetry there is the term *colorimetric appearance match*, for example of samples of equal appearance in different chromatic surrounds. These samples have usually *different* CIELAB data. Similar the samples of the *colorimetric affine match* have usually *different* CIELAB data (in lightness and chroma). However, the CIELAB hue data are the same for this *colorimetric affine match*. The hue is often considered as the most important colour attribute and remains constant on different *rgb** output devices.

The consideration of basic colour device properties and visual ergonomic requirements lead to this *colorimetric affine match*. In applications three device colours white, black and the maximum chroma colour of any hue defines a hue triangle in CIELAB. The hue triangles of 48 hues are used in *OLM16*. They cover approximately all device colours on any device. The CIELAB lightness and chroma is usually different on two devices. The *rgb** file data, for example the *rgb** data sets (0, 0, 0), (1/8, 0, 0), (2/8, 0, 0), ..., (8/8, 0, 0) produce equally spaced colour series between Black and Red on any device. However, the CIELAB difference of black and red may be different on two *rgb** devices. Similar equally spaced colour series are produced on any device for this and other *rgb** data series. However, the maximum chroma and the corresponding lightness is still device-dependent.

There are several advantages of the *colorimetric affine match* with the *rgb** colour devices:

1. The whole device gamut is used on any *rgb** device.
2. The hue output remains constant on any *rgb** device.
3. The elementary hue, for example Red as neither yellowish nor bluish, is produced for $rgb^*=(1,0,0)$
4. Equal relative spacing in CIELAB is realized on any *rgb** device.
5. There is no clipping of colour areas on any *rgb** device and the output may be called a *trusted* output.

If the *colorimetric affine match* is realized for any *rgb** device according to *OLM16*, then

1. many user wishes of DIN 33872-X are solved
2. the undefined colour output properties change to the *rgb** device output property.
3. according to ISO/IEC 19797 the intended startup_stage for colour management is reached.
4. the output accuracy is by a factor 5 higher compared to the ICC encoding with 8 bit in CIELAB.

A disadvantage may be the usually *different* chroma and lightness on two *rgb** devices. However, the colour gamut of two colour devices is usually different. Based on this device property the *colorimetric affine match* seems an appropriate solution which solves for example the many user wishes of DIN 33872-X.

2 Terms and definitions

2.1

rgb* device

output device which produces a *colorimetric affine match* in the CIELAB space on any device.

NOTE: The *colorimetric affine match* in CIELAB space is a *colorimetric match* in hue (equal CIELAB values h_{ab}) and produces usually different CIELAB lightness L^* and different CIELAB chroma C^*_{ab} on two devices compared to the CIELAB data of a most chromatic hue circle and the CIELAB data of white and black.

2.2

colorimetric affine match

three colour data rgb^* have a defined and linear relation to the standard CIELAB data $LCh^* = L^*, C^*_{ab}, h_{ab}$

NOTE: The linear relation between rgb^* and LCh^* data is defined in OLM16 by 48 hue triangles. The three corners of these triangles are defined by white and black and the colour with the largest chroma of the device. For any hue the maximum chroma colour is usually produced if one of the three rgb values is one and another zero.

2.3

CIELAB uniform colour space

three-dimensional space for the geometrical representation of colorimetric data with rectangle or cylindrical standard or adapted CIELAB coordinates, see ISO 11664-4.

NOTE: The terms "linearity", "uniformity", and "evenness" of the equally spaced output series of the OLM16 *colorimetric affine match* are under discussion.

NOTE: ISO/IEC 15775 defines a regularity index for the deviation of the intended equally spaced output series of the OLM16 *colorimetric affine match*. This index is 100 if the 15 colour differences of the 16 steps are equal, and the index is zero if at least one pair of neighboring colours is not distinguishable.

2.4

device system colours

Output colours of a device system which are dependent on the hard and software properties including the viewing illumination.

NOTE 1: Examples are the reflective colours of standard offset printing (ORS18, $Y=2,5$, $L^*=18$ for black), the luminous colours of a sRGB monitor (TLS18 with the standard screen luminance reflection $L_r=2,5\%$ in offices) or the projected colours of a data projector (with 8 L_r reflections between 0% and 40% in offices according to ISO 9241-306).

2.5

Colour difference

Amount of the perceived difference between two colours.

NOTE: The colour difference ΔE^*_{ab} between two colours is calculated according to ISO 11664-4 with the CIELAB colour difference formula.

NOTE 2: In the standard series DIN 33872-X ($X=1$ to 6) the colour difference of 3-, 5-, 9-, 16-, and 17-step colour series is evaluated visually and/or specified by colorimetry.

2.6

Colour order system

Three-dimensional order of colours by visual and/or colorimetric criteria.

NOTE 1: Examples for the order according to visual criteria are the colour order systems: *Natural Colour System (NCS)*, *Ostwald*, *Munsell*, and of the *Optical Society of America (OSA)*, compare [1].

NOTE 2: Examples for the order according to colorimetric criteria are the colour order systems according to DIN 6164-1 and the *RAL Design System* with a regular cylindric order in the CIELAB colour space for the CIE standard illuminant D65 and the CIE 10 degree observer, compare [1].

3 Symbols (and abbreviated terms)

PS	<i>PostScript</i> (programming language which allows colour operators with <i>rgb</i> and <i>cmYk</i> data)
PDF	<i>Portable Document Format</i> (file format)
ORS18	Offset Reflective System with lightness $L_a^* = 18$ for Black <i>N</i>
TLS00	Television Light System with lightness $L_a^* = 0$ for Black <i>N</i>
TLS18	Television Light System with lightness $L_a^* = 18$ for Black <i>N</i> (<i>standard for offset and displays</i>)
$RYGCBM_d$	Device (<i>d</i>) colours (Colours of the device hue hexagon): Red (R_d), Yellow (Y_d), Green (G_d), Cyan blue (C_d), Blue (B_d), and Magenta (M_d)
$RYGCBM_e$	Elementary (<i>e</i>) colours (Colours of the elementary hue hexagon): Red (R_e), Yellow (Y_e), Green (G_e), Cyan blue (C_e), Blue (B_e), and Magenta (M_e)
Lab^*	coordinates lightness L^* , <i>RG</i> -chroma a^* and <i>YB</i> -chroma b^* of the CIELAB uniform colour space
LCh^*	coordinates lightness L^* , chroma C_{ab}^* and hue h_{ab} of the CIELAB uniform colour space
RGB^*	coordinates redness R^* , greenness G^* , and blueness B^* (in the value range 0 to 100). The coordinates RGB^* have a linear relation to the coordinates LCh^* of CIELAB.
$=RGB_e^*$	
rgb^*	<i>relative</i> coordinates redness r^* , greenness g^* , and blueness b^* (in the value range 0 to 1). The coordinates rgb^* have a linear relation to the coordinates LCh^* of CIELAB.
$=rgb_e^*$	
ICE^*	coordinates brilliance I_e^* , chroma C_e^* , and hue E_e^* of the device-independent visual elementary (index <i>e</i>) colour system. All coordinates are in the range 0 to 100.
ice^*	<i>relative</i> coordinates brilliance I_e^* , chroma c_e^* , elementary hue e_e^* of the device-independent visual elementary (index <i>e</i>) colour system The ice^* coordinates are in the range 0 to 1.
D65	Daylight with correlated colour temperature 6500° Kelvin (CIE Standard illuminant according to CIE 15.2)
<i>Ostwald colours</i>	special complementary optimal colours. Any complementary pair of <i>Ostwald</i> colour mix to white. It can be assumed that the human visual system divides the reference white in separate parts <i>Y-B</i> and <i>R-G</i> . Therefore appropriate elementary <i>Ostwald</i> colours may be used as reference colours of a <i>complete device-independent RGB^*</i> colour system (see CIE R1-57 and Fig. 23 on page 26 and Table 9 on page 58)

3.1 Key issues for the Output Linearization Method OLM16

start	produce and measure or calculate (for standard <i>sRGB</i> display) the output of a TUB test chart.
48 step device hue angles	The TUB test chart produces 1080 output colours. A 48 step continuous hue circle is included Fig. 39 on page 43, Fig. 49 on page 54, Fig. 51 on page 56, and Fig. 52 on page 57 show for the 48 device hues (<i>index d</i>) in column 2 the continuous rgb_d and measured LCh_d^* data.
360 step device hue angles	By interpolation of the 48 output hue angles $h_{ab,d}$ (known from previous step) the $rgb_{d,i}$ and $LCh_{d,i}^*$ data are calculated for 360 device hue angles ($i = 0, 1, 2, \dots, 360$). This table is used as index based table for calculations of the rgb_d and LCh_d^* data for any hue h_{ab} .
any elementary hue angle	For any given elementary hue angle $h_{ab,e}$, for example $h_{ab} = 26, 92, 162, 272$ for $RYGB_e$, and any hue angle h_{ab} , the index based table of the previous step includes the <i>new input</i> data. For the output of the 48 elementary hues column 3 includes the necessary <i>new input</i> data.
result: elementary hue circle	If the 48 start input data are transferred to the <i>new input</i> data, called rgb_e^* in Fig. 31 on page 32, then the result is the intended elementary hue circle LCh_{ie}^* . The real output data LCh_e^* have usually a colour difference $\Delta E_{ab}^* < 1$ compared to the intended LCh_{ie}^* data given in column 3.
any colour	For the interpolation of <i>any</i> intended colour LCh_i^* within the hue triangle see Fig. 22 on page 25.

4 Proposals for future work on standard documents in the colour area

1. Three experts may apply and further develop the content in 3 separate standard documents for linearized output on displays, in offset and on printers.
2. Two experts may apply the linearized output of the TUB test chart with 1080 colours for linearized input with scanners and digital cameras. This completes the whole colour loop Output - Input - Output by the *colorimetric affine match*.
3. CIE Division 1 may decide on a public Reportership which may study the demands of users and ISO committees in the colour area. The reporter may propose solutions for a device-independent visual RGB^* colour space. This space may be based on the proposals in CIE R1-47 and CIE R1-57.

Table 1 - Possible Time scale related to International Standardization of DIN 33872-X

Possible time scale related to international standardization of DIN 33872-X				
<i>possible standard and market developments between 2009 and 2026</i>				
Time scale for Standard Development or technical publications				
2009	2016	2021	2026	
●				DIN 33872-1 to -6:2009 User wish satisfied (Yes/No)?
●				CIE R1-47:2009 with the four hue angles $h_{ab,e} = 26, 92, 162, \text{ and } 271$.
	●			CIE R1-57:2013 with rgb^* coordinates for <i>Ostwald</i> colours.
	●			Paper: Output Linearization OLM16 for displays, offset and printers.
		●		CIE? Technical report with four elementary hue angles $h_{ab,e}$ of $RYGB_e$.
		●		CIE? Technical Report with definition of visual rgb^* colour coordinates.
			●	ISO/CIE Standard with four elementary hue angles $h_{ab,e}$ of $RYGB_e$.
			●	ISO/CIE Standard with definition of the visual RGB^* colour space.
			●	ISO/CIE Standards: Output Linearization for displays, offset, printers.
			●	ISO/CIE Standards: Input Linearization for scanners and cameras.
Time scale for Market Development with the motivation of fast solutions for user wishes				
1. Use of DIN-test charts and the above documents within new rgb^* workflow.				
2. Production of <i>reference</i> test charts with OLM16 for many output devices.				
3. Use of <i>reference</i> test charts for colour calibration of scanners and cameras.				
4. Optimizing the output-input-output linearization loop for rgb^* colour management.				
5. 5-fold higher accuracy (triangle coding) for <i>Profile Connection Space</i> RGB^* instead of <i>CIELAB</i> .				
2009	2016	2018	2020	
	●			Device Output Linearization, and production of test charts $rgb \rightarrow rgb^*$.
		●		Linearized <i>reference</i> test charts for calibration of scanners & cameras.
		●		Colour workflow loop output-input-output and calculation of accuracy.
			●	Advantages & disadvantages of rgb^* ; smooth transfer $rgb_{sRGB} \rightarrow rgb^*$.

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The proposals of the Author are based on the present Technology and the recent Standard Development. Many users and companies seem not to be happy with the present implementation of colour in the computer operating system. The *device-independent* methods of OLM16 are based on the *colorimetric affine match*. Any rgb^* device includes by definition this *colorimetric affine match* and solves many user wishes of the standard series DIN 33872-X, see Fig. 4 on page 11 up to Fig. 9 on page 14.

Table 2 - Device colours and elementary colours with visual criteria

Achromatic colours, intermediate colours	Chromatic colours, Elementary colours	Chromatic colours, Device colours
five achromatic colours:	"Neither-nor"-colours	TV, Print (PR), Photo (PH)
<i>N</i> black (French noir)	<i>four elementary (e) colours:</i>	<i>six device (d) colours:</i>
<i>D</i> dark grey	$R = R_e$ red	$C = C_d$ cyan blue (cyan)
<i>Z</i> central grey	<i>neither yellowish nor bluish</i>	$M = M_d$ magenta red (magenta)
<i>H</i> light grey	$G = G_e$ green	$Y = Y_d$ yellow
<i>W</i> white	<i>neither yellowish nor bluish</i>	$O = R_d$ orange red (red)
<i>two intermediate colours:</i>	$B = B_e$ blue	$L = G_d$ leaf green (green)
$C_e = G50B_e$ green-blue	$J = Y_e$ yellow (French jaune)	$V = B_d$ violet blue (blue)
$M_e = B50R_e$ blue-red	<i>neither greenish nor reddish</i>	
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Table 2 shows the device colours (index d) and the elementary colours (index e) and the visual criteria for the elementary colours. ISO/IEC 15775 uses for example the letters O, L and V instead of R_d , G_d , and B_d which indicate the difference to the letters R, G, and B. However, in this paper we prefer to use the index **d** or **e** to distinguish between device and elementary colours or hues. The elementary hues are one basis for a device-independent colorimetry and the definition of the *rgb** devices. The devices produce a device-independent hue match on any device. Further steps will be discussed later in this paper.

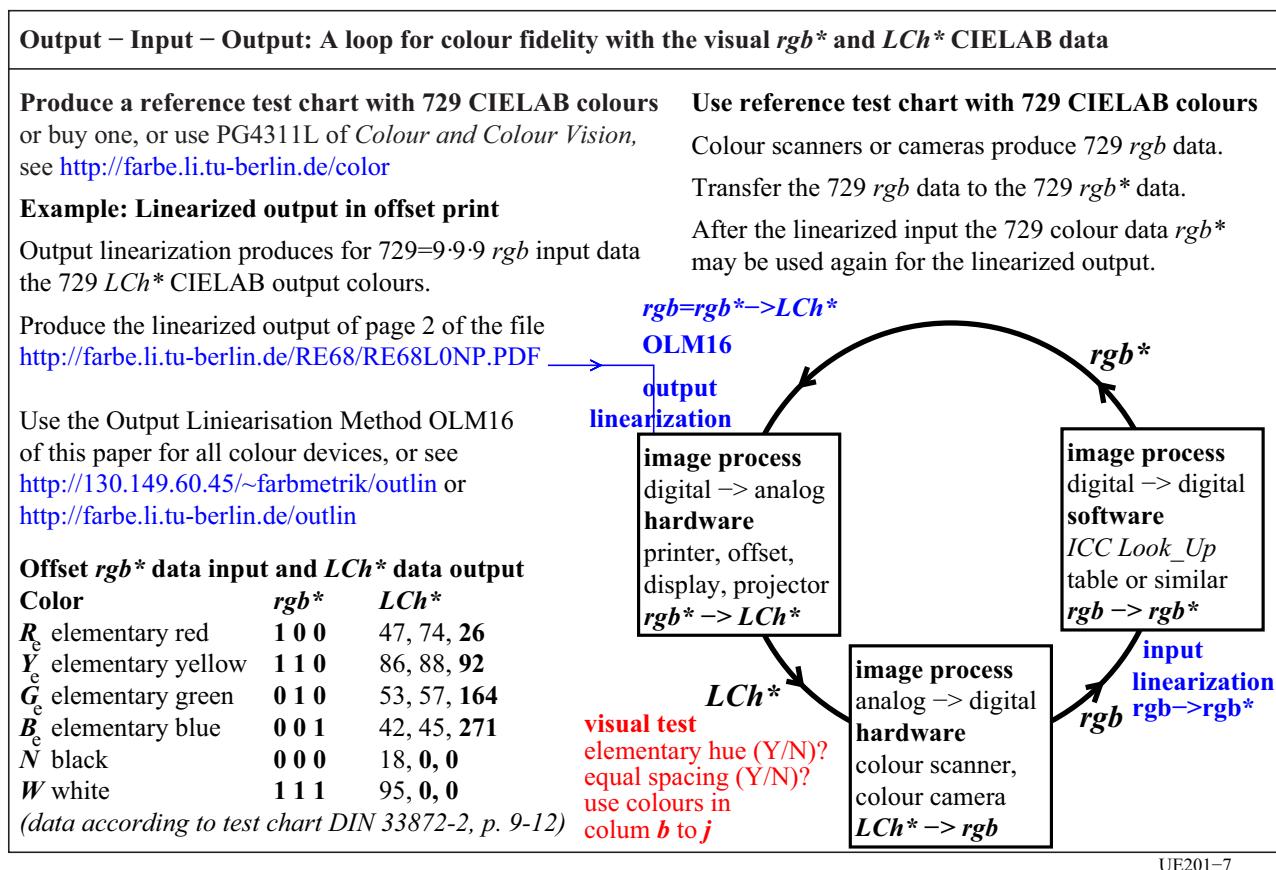
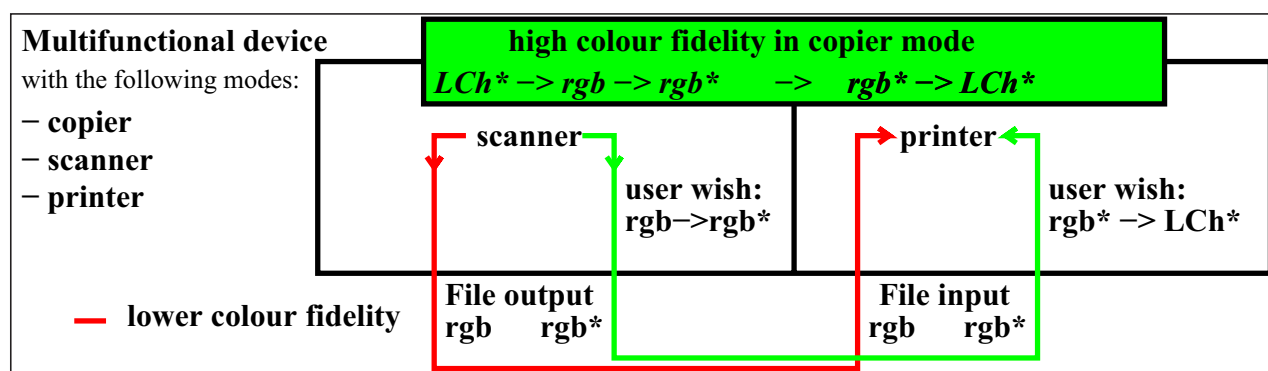
Fig. 1 - Output - Input - Output: A loop for colour fidelity with the visual *rgb** and *LCh** data

Fig. 2 includes the available information for output and input linearization based on measured CIE data. It takes below one hour to measure the 1080 output colours of a display, of offset, or of a printer. A first test chart in offset (PG4311L) with 729 reference colours is available within a free booklet. Standard documents will allow the *colorimetric affine match* for the output and input of 16 step colour series.



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Fig. 2 - File output and file input of multifunctional devices

Fig. 2 shows components of a multifunctional device which usually can be used as copier, scanner, and printer.

If for example the reference test chart with the 1080 colours printed in offset is copied then the reproduction quality is usually evaluated high compared with the original. The copier function is shown by a green rectangle.

However, if the reference test chart is scanned and the scan file is printed, then the reproduction quality is often not acceptable. This method is shown by a red line.

The solution is simple. One must transfer the undefined rgb data of the scan file to the reference data rgb^* of the original. If in addition the printer part is an rgb^* device, then the result is very similar to the original. This method is shown by a green line.

The filter or the profiles which allow the transfer include tables for the transfer of 729 rgb colour data to rgb^* or $cmyk^*$ colour data. For intermediate rgb data an appropriate interpolation method is used.

For digital cameras a similar colorimetric calibration method is possible. However, good results need a fixed exposure of the camera. Many cameras allow to fix the exposure, for example if at first a viewing field with the tristimulus value $Y=18$ (mean grey) is used.

The accuracy of colour measuring instrument can be improved with the 729 reference colours and their CIELAB LCh^* data. If for example instead of a *Macbeth Colour Checker* with much less colour samples the analogue TUB-test chart RE69 is used for the calibration, then the accuracy will increase.

The 1080 colours can be measured within an hour on a displays or in the print output. This allows to produces appropriate filters or profiles (for example of *ICC*) to reach the intended colorimetric results.

Fig. 2 has been included here because many users like to see more applications.

For example the calibration of scanners based on the analogue output of an rgb^* device (in this paper the available analogue test chart in offset print produced with an rgb^* offset device) is an essential part of the loop Input - Output - Input in image technology.

The properties of this loop *Input - Output - Input* may be one key issue for a future colorimetric colour management. The other key issue is the international definition and the agreement of a simple and effective visual device-independent RGB^* human colour space.

The properties of the rgb^* devices described in this paper are **not** dependent on the loop properties and the definition of the RGB^* human colour space. However, in this paper many solutions appear based on the properties of the rgb^* devices.

The following sections *background* and *introduction* include more application examples.

5 Background

5.1 History of this paper

This work is based on requests of both ISO TC159/ SC4/WG2 *Ergonomics - Visual display requirements* and ISO/ISC JTC1 SC28 *Office systems* for work within CIE Division 8 and 1 to support the solutions of ISO problems in the field of colour. The two reports CIE R1- 47: 2009 and CIE R1-57: 2013, see for free download under MINUTES & REPORTS on the CIE Division 1 web site <http://www.cie.co.at>

and this paper support the ISO requests for a device-independent visual RGB^* colour space for many applications.

The two reports of CIE Division 1 propose CIELAB data and elementary hue angles which are to a high degree applied in the paper. Technically there are many device dependent RGB colour spaces, for example $sRGB$, $ROM RGB$, $Adobe RGB$, and others.

The device-independent colour space may use rgb^* coordinates which have a *linear* relation to the CIELAB coordinates of the *Ostwald* optimal colours. All surface colours are within the Ostwald colour solid. Table 1 in CIE R1-57 includes the CIELAB data of maximum chroma $C^*_{ab,e,o}$ and the lightness $L^*_{e,o}$ of a 16 step elementary hue circle. For any CIELAB hue angle these colours form a hue triangle together with the data for white W and black N . Table 9 on page 58 include all necessary rgb^* and LCh^* data.

5.2 Standard documents with visual evaluation of output/input and colorimetric specification

Table 3 - Standard documents which use CIE colorimetry for the specification of output and input

Input	Output	Input and output media and applications			Technical Report (TR) or Standard	Method & Test: Linearization	
		Input media	Output media	Application			
—	—	—	—	Basis	ISO/IEC TR 24705	{ DIN 33866–1 DIN 33872–1	
analog	analog	ISO/IEC-file series equally spaced in <i>rgb</i> + ISO/IEC-test chart (hardcopy) series equally spaced in <i>LCh</i> *	Hardcopy	Copier	ISO/IEC 15775	{ DIN 33866–2 JIS X 6933	
analog	digital	ISO/IEC-test chart (hardcopy) series equally spaced in <i>Lch</i> *	File	Scanner	ISO/IEC TR 24705	DIN 33866–4	
digital	analog	ISO/IEC-test chart (File) series equally spaced in <i>rgb</i>	{ Hardcopy Softcopy	Printer Display	ISO/IEC TR 24705 ISO 9241–306:2008	{ DIN 33866–3 DIN 33872–2,4 DIN 33866–5 DIN 33872–2,4	
The ISO/IEC-input linearisation method produces an ISO/IEC-file from an ISO/IEC-original scene: Flower motiv with 16 equidistant grey steps, and 14 CIE-test colours according to CIE 13.3							
The ISO/IEC-output linearisation method produces from an ISO/IEC-file a linearized display, offset or printer output:							
ISO/IEC-input linearisation method				ISO/IEC-output linearisation method			
Input	Output	Application	Technical Report (TR) or Standard	Input	Output media	Application	Standard document Technical Paper
Original scene + CIE colours	ISO/IEC Image File	Reference Image File	ISO/IEC 15775 ISO/IEC TR 24705	ISO/IEC File	Hardcopy	Printer	ISO/IEC TR 19797
				ISO/IEC File	Softcopy	Display	ISO 9241–306:2008 8 viewing conditions
				ISO/IEC/ TUB Files	{ Softcopy Hardcopy Hardcopy	Display Offset Printer	{ ISO?/CIE?: intended device space + device-independent visual RGB* space

SE200–7N

Table 3 shows many International and National Standards and Technical Reports of ISO, IEC, DIN, and JIS. The common basis is the input or output evaluation or colorimetric specification based on CIE colorimetry.

In the different application fields the standard document overview is highly based on CIE colorimetry. Most of the standard documents are directed to only one application, for example copiers, scanners, printers, or displays. However there are multifunctional devices (a copier may be at the same time a scanner and a printer) which need in addition separate evaluations or specifications.

Table 3 shows that the *OLM16* of this paper includes the three *devices display, offset, and printer* in **one** standard document. This paper covers the device-dependent colour output, and in addition the **device-independent** elementary colour output.

5.3 Test chart with equally spaced *rgb* colour data



Fig. 3 - 1080 colours including 729 (=9x9x9) colours of the *rgb* cube and other series

Fig. 3 includes 1080 colours including 729 (=9x9x9) colours of the *rgb* cube, colour opponent series in opponent hue triangles $R_d - C_d$, $Y_d - B_d$, and $G_d - M_d$ and 9 and 16 step achromatic series. For download, see <http://farbe.li.tu-berlin.de/RE69/RE69L0NP.PDF>

The intention is to make the 9 step colour series, for example between the three series $W-R_d$, $N-R_d$, and $W-N$ equally spaced in CIELAB. For example the remaining colour difference is $\Delta E^*_{ab}=0,6$ for displays and 2,0 for offset, if the OLM16 is applied.

5.4 Examples of DIN 33872-2 and -5 and advantages of the OLM16

The German Standard Series DIN 33872-1 to -6:2010, see

<http://farbe.li.tu-berlin.de/33872E.html>

has defined user wishes for colour output. These wishes lead to the output properties of the *rgb** de-

vices. The properties of these devices will be defined in the following. Example outputs of the file with *rgb* data and Yes/No-Output questions of DIN 33872-X are used in the following to show the user wishes. The OLM16 allows to realize most of the user wishes related to the colour output of printers and displays.

5.5 File output examples DIN 33872-2 and Yes/No-questions according to the hue output

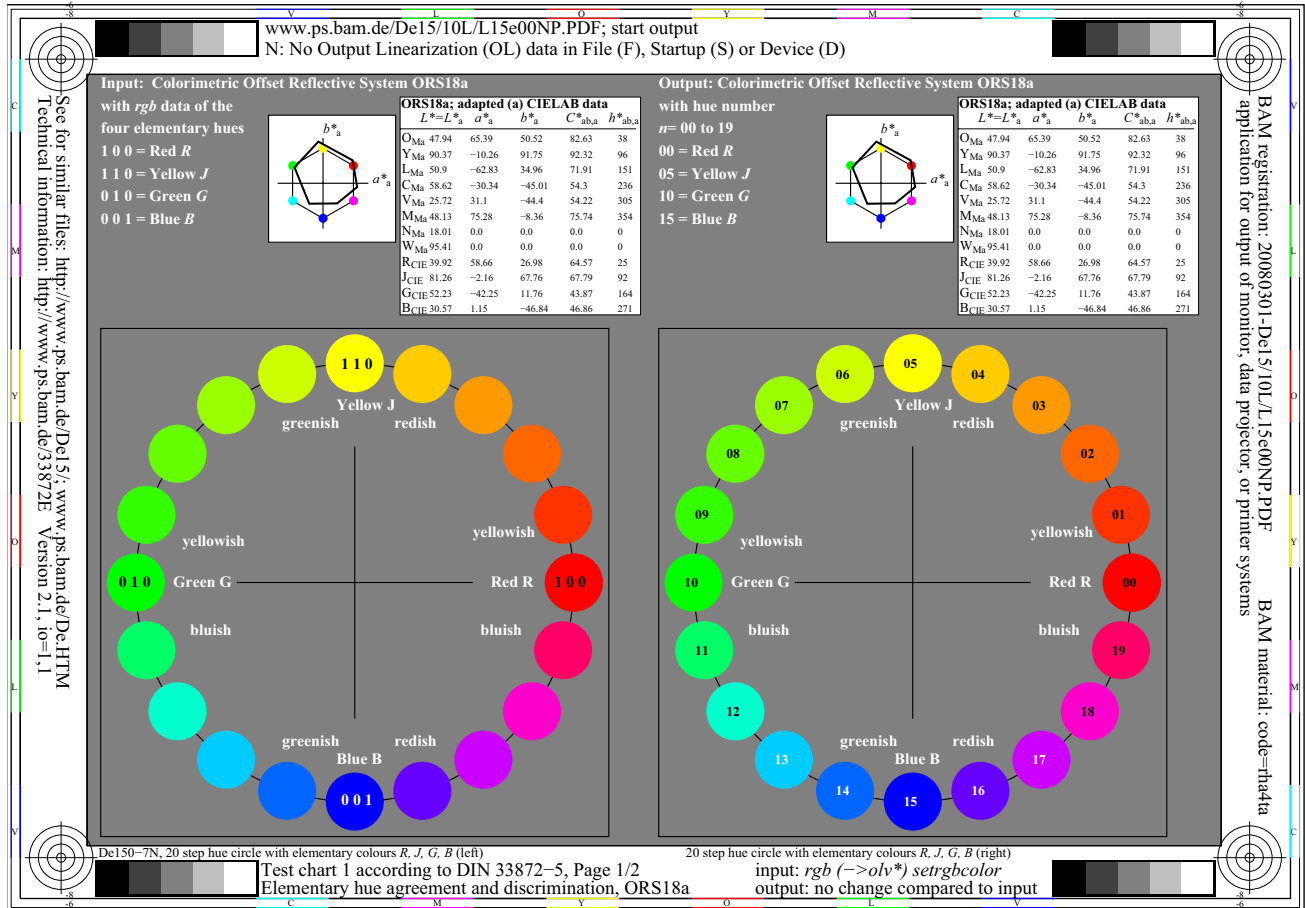


Fig. 4 - Test chart 1 with *rgb* colour data according to DIN 33872-5

Fig. 4 shows the test chart 1 with *rgb* data according to DIN 33872-5 which produces the output of a 20 step hue circle. The four elementary colours $RYGB_e$ with the *rgb* data (1 0 0), (1 1 0), (0 1 0), and (0 0 1) given in the last part shall produce for example the elementary Red R_e according to the visual criteria as neither yellowish nor bluish on the right side.

The appropriate hue output is often considered as more important compared to the lightness and chroma output. In colorimetry CIE LAB is defined as a uniform colour space. The CIE LAB data hue angle h_{ab} , chroma C^*_{ab} and lightness L^* are used. The average colour differences ΔE^*_{ab} of the intended (ideal) and a real *rgb** colour device are used to specify the colorimetric output properties.

5.6 File output examples of DIN 33872-2 and Yes/No-questions

DIN 33872-5 comes with questions about the output properties. Users evaluate in Fig. 5 and 6 on page 12 the output properties of Fig. 4 by Yes/No-questions.

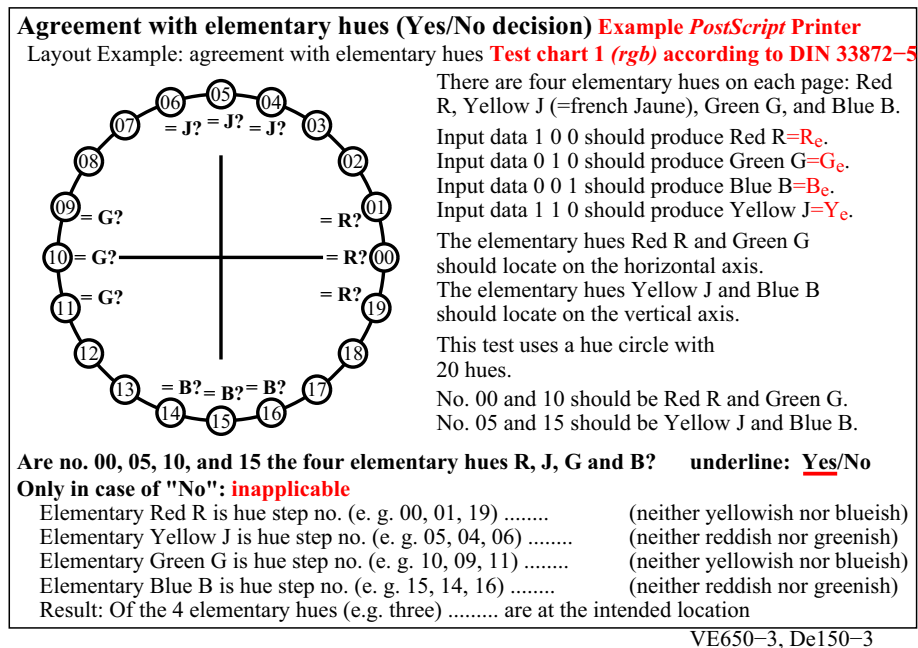


Fig. 5 - Agreement with elementary hues (Yes/No decision)

Fig. 5 shows the Yes/No-questions of DIN 33872-5 about the agreement of the samples no. 0, 5, 10, and 15 with the elementary hues. It is intended that the samples with the given input data produce the elementary colours. DIN 33872-5 uses the letters *RJGB* for the elementary colours instead of the letters *RYGB_e* in this paper.

In Fig. 5 the example *PostScript* printer produces for the samples no. 00, 05, 10, and 15 the four elementary colours R_e , Y_e , G_e , and B_e . In this case all user wishes are fulfilled.

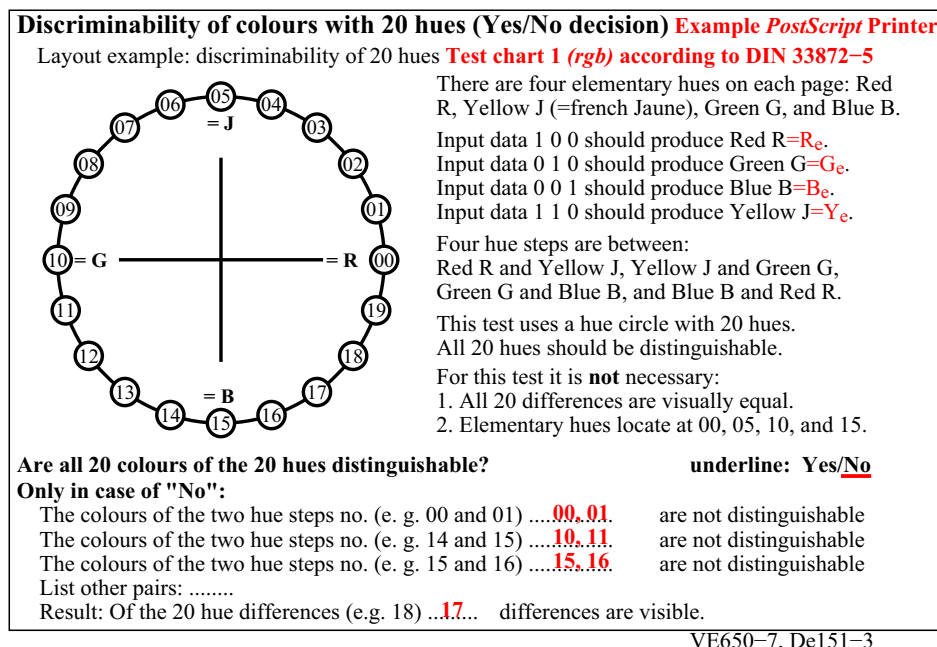


Fig. 6 - Discriminability of colours with 20 hues (Yes/No decision)

Fig. 6 shows the Yes/No-questions of DIN 33872-5 about the discriminability of the colours with the 20 hues. It is intended that all the 20 samples are distinguishable. The answers show, that only 17 of 20 samples are distinguishable. Especially near the elementary colours 0, 10 and 15 problems of the output appear.

Remark: the question is weaker than a question: Are the 20 steps equally spaced? For many users the spacing question seems too complicated. However by colorimetric measurement this question can be solved with the measurement of the colour differences ΔE^*_{ab} .

5.7 File output examples DIN 33872-5 and Yes/No-questions according to the 16 step spacing

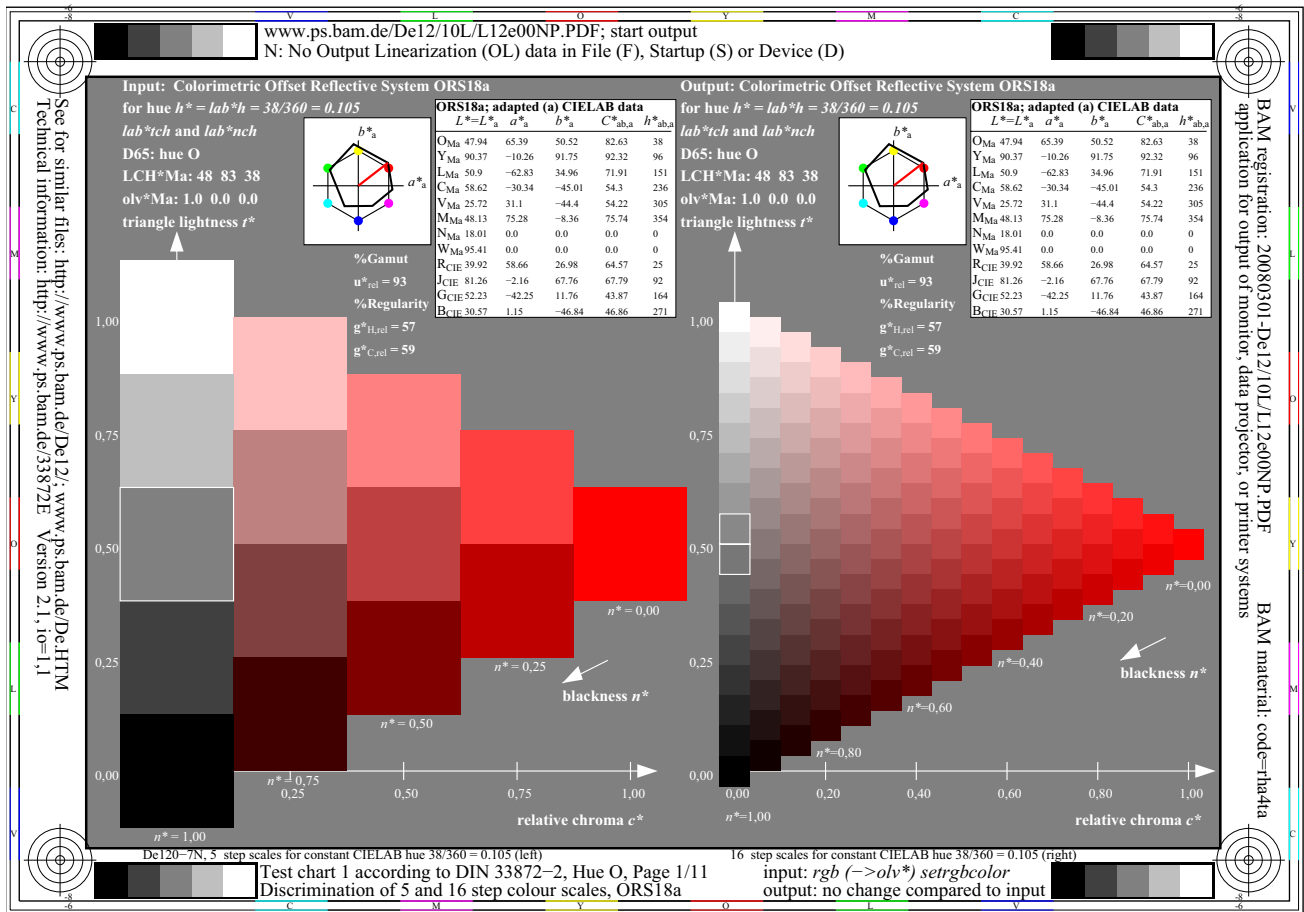


Fig. 7 - Test chart 1 with rgb colour data according to DIN 33872-2

Fig. 7 show the test chart 1 with rgb data according to DIN 33872-2 which produces the output of 5 and 16 step colour scales, for example of the equal red hue and the three corners White, Black and the most chromatic device Red R_d (page 1) or the most chromatic elementary Red R_e .

The horizontal axes is the relative chroma c^* with values between 0 for achromatic colour and the value 1 for the most chromatic colour. Similar the triangle lightness t^* varies between 0 and 1 on the vertical axis. In addition an attribute relative blackness n^* with values between zero and 1 is defined in Fig. 4.

The test file of DIN 33872-2 produces the output of 5 and 16 step colour scales defined by the six device hues $RYGCBM_d$ and the four elementary hues $RYGB_e$. The output properties of all pages are evaluated by users.

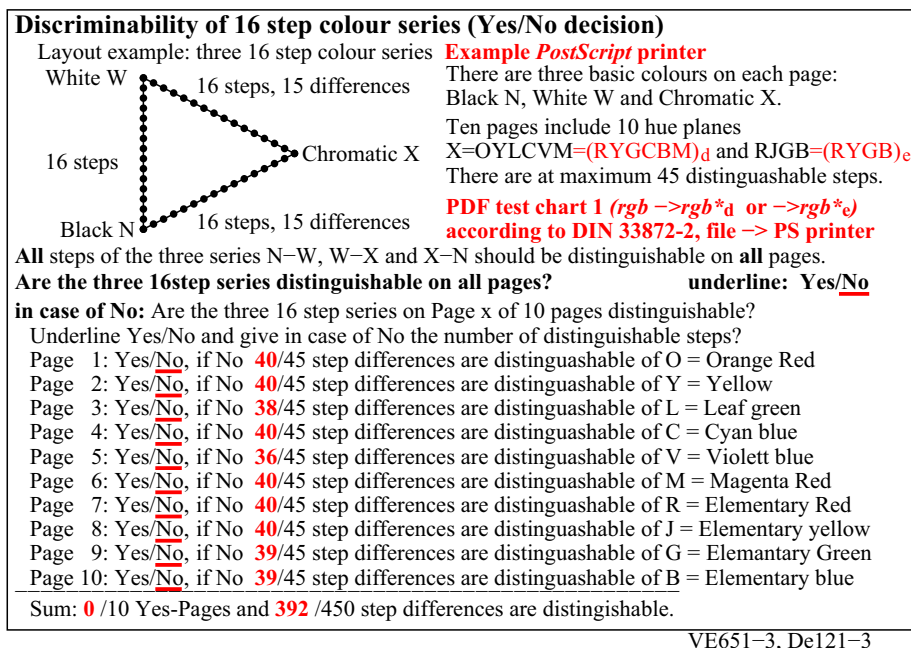


Fig. 8 - Discriminability of 16 step colour series (Yes/No decision) for a PS printer

Fig. 8 shows the discriminability of the 16 step colour output by an example *PostScript* printer. On all of the 10 pages some samples are not distinguishable. About 10% of the neighbouring samples are not distinguishable. This question is weaker compared to the question: Are the colour series equally spaced? Usually only colorimetric measurement can produce an appropriate answer of this question.

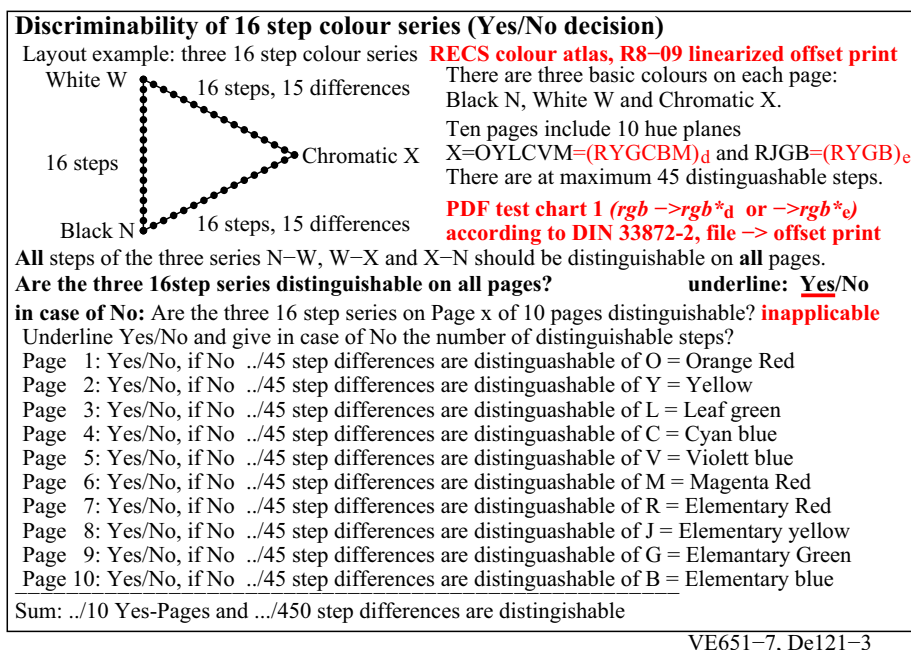


Fig. 9 - Discriminability of 16 step colour series (Yes/No decision) for linearized offset print

Fig. 9 shows the discriminability of the 16 step colour output by an example *offset print* which is linearized by the OLM16 method. On all of the 10 pages all samples are distinguishable. This question is weaker compared to the question: Are the colour series equally spaced? Colorimetric measurement has produced an appropriate answer of this question for the samples of the Relative Elementary Colour System (RECS) with about 2000 samples. The CIELAB data are defined by the colorants of the standard offset process on standard offset paper for the CIE 2 degree observer, for the CIE D65 illuminant and for the CIE 45/0 measurement geometry. Examples of this atlas, see <http://farbe.li.tu-berlin.de/RECS08.PDF> are available by the author.

5.8 ISO/IEC requests to the CIE for a human visual RGB system and work results within CIE

Conclusion 31/2007 ISO TC159/SC4/WG2

Ergonomics – Visual Display Requirements

ISO TC159/SC4/WG2 realizes that the colour spaces CIELAB and CIELUV of **CIE Division 1** will soon become ISO/CIE standards. In applications we use these CIE colour spaces and *device-dependent* relative RGB colour spaces. For users of visual display systems a *device-independent* RGB colour space is useful. This produces via software the elementary hues Red, Green and Blue for the RGB data 100, 010 and 001 and equally spaced output in CIE colour spaces for equally spaced RGB input. We recommend that **CIE Division 1** study the colorimetric definition of such a space, which can be used in visual display applications.

Remark: We have realized that an example colour space of this type is published in CIE X030:2006, p. 139–144.

Note: For this table text compare the identical content on page 2 of the public document CIE R1-47.

SE380–1

Fig. 10 - Conclusion of ISO TC159/SG4/SC2 for a device-independent RGB colour space

Fig. 10 shows a conclusion of ISO TC159 which includes a request of the ISO committee *Visual Display Requirements* for the definition of the elementary hues by CIE Division 1 *Colour and Vision*. Different ISO committees have problems with the application of colour in ISO International Standards and Technical Reports. CIE Division 1 is the appropriate body to study the colour problems and to produce guidance.

Resolution Busan 18/2009 of ISO/IEC JTC1/SC28 "Office Equipment"

SC28 Review of the AWG recommendation on jn28n1280 (DIN 33872–1 to 6)

The German proposal included the concept of a human visual RGB. SC28 recognizes the importance of correct understanding of the human visual system and the potential importance and application of this understanding to office equipment and office systems. SC28 welcomes the German plan to continue development of the human visual RGB within **CIE Division 1 and Division 8**.

In addition SC28 welcomes a new proposal from Germany in the future based on this CIE human visual RGB work, potentially in relation to AWG/PWG5 NWI–9 (*Office colour space*).

SE380–5

Fig. 11 - Resolution on a human visual RGB of ISO/IEC JTC1/SC28 Office Equipment

Fig. 11 shows the Resolution *Busan 18/2008* of ISO/IEC JTC1/SC28 *Office Equipment*. An English translation of the German Standard series DIN 33872-1 to 6, see <http://farbe.li.tu-berlin.de/33872E.html>, has been discussed in SC28. According to Fig. 7 further ISO processing in SC28 has been stopped until a human visual RGB system is developed within CIE Division 1 and 8.

The German standard series DIN 33872-1 to -6 is addressed to many applications of different specialized ISO committees, for example TC 42 (Photography), TC 130 (Graphic Technology), TC 159 (Displays), and ISO TC 171 (Document Management). Therefore there are many possibilities to proceed in this standard area by further national DIN-documents or for example international standard documents within ISO or CIE.

At the CIE meeting in South Africa, June 2011, **CIE Division 1** decided to establish the Reportership **CIE R1-57 Border between Luminous and Blackish Colours** by *Thorstein Seim (Norway)* in response to the resolution 18/2009 of ISO/IEC JTC1/SC28.

The Reportership Report **CIE R1-57:2013 Border between Luminous and Blackish Colours** is based on a surface colour property:

All surface colours define a hue circle of maximum chroma located within the CIE (x,y) chromaticity diagram. **CIE R1-57** proposes to use the CIELAB chroma C^*_{ab} and the lightness L^* of this circle as function of hue h_{ab} as reference points for a *device-independent visual RGB^*_e system*

The C^*_{ab}, L^* hue circles of the *Natural Colour System NCS* and of the *sRGB* standard IEC 61966-2-1 are similar.

For the text of the CIE decision, the terms of reference, and free download of CIE R1-57 see the CIE web site <http://www.cie.co.at> under Division 1 and MINUTES & REPORTS

SE380-7

Fig. 12 - Work in CIE Division 1 and 8 to solve the request of ISO/IEC JTC1/SC28

Fig. 12 indicates that a larger step towards a human visual and device-independent RGB^*_e system may be reached with the available Reportership Report CIE R1-57:2013.

According to Fig. 11 ISO/IEC SC28 has asked Germany to produce the output according to a **human visual RGB system**. The present paper tries to include some steps in this direction. In addition this paper allows to realize a lot of the user wishes according to DIN 33872-1 to -6 for display, offset, and printer output. For examples of the output of these test charts for eight ambient display reflections, see

<http://farbe.li.tu-berlin.de/OE.HTM> and study the TUB test charts and the output of the pages OE70 to OE99

At the CIE meeting in Stockholm, June 2008, **CIE Division 1** decided to establish the CIE Reportership R1-47 **Hue Angles of Elementary Colours** by *Thorstein Seim (Norway)* in response to a request of ISO TC 159 SC4/WG2 **Visual Display Requirements** and to present the result at the next CIE meeting in Budapest 2009.

The report **CIE R1-47:2009 Hue Angles of Elementary Colours** lists in chapter 3.6 the average CIELAB hue angles 26, 92, 166, and 270 of *Miescher, NCS, and the CIE*.

CIE R1-47 defines the CIELAB hue angles **25, 92, 162 and 271** of the CIE test colours no. 9 to 12 according to CIE 13.3 for the four elementary colours R_e , Y_e , G_e , and B_e .

For the text of the request of ISO TC159/SC4/WG2, the text of the decisions of CIE Division 1, the result, and the free download of CIE R1-47 see the CIE Division 1 web site <http://cie.co.at> under MINUTES & REPORTS

SE380-3

Fig. 13 - Decision of CIE Division 1 and Report CIE R1-47 with definition of elementary hue angles

Fig. 13 shows the decision and answer of CIE Division 1 on the request of ISO TC159. The four CIELAB hue angles $h_{ab,e} = 25, 92, 162$ and 271 of the CIE test colours no. 9 to 12 according to CIE 13.3 are proposed for the four elementary colours R_e , Y_e , G_e , and B_e . This is a CIE basis to define the device-independent rgb_e coordinates which produce the visual elementary hues. The report includes the standard deviation of the elementary hue angles. For R_e , Y_e , and G_e the values $h_{ab,e} = \pm 4$, and for B_e the value $h_{ab,e} = \pm 8$ is given. However, for example the standard *sRGB* colour space produces $h_{ab,d} = 305$ and an example printer of a leading printer company $h_{ab,d} = 260$. The hue angle $h_{ab,d} = 305$ is far outside the visual range $h_{ab,e} = 271 \pm 8$. For the two example devices the shift is in the display case towards the reddish and in the printer case towards the greenish side. Therefore, if the proposal $h_{ab,e} = 271 \pm 8$ of CIE R1-47 is reached on most devices, this will be a large improvement for users.

One must consider that there are hundreds of *RGB* colour spaces, including the IEC standard space *sRGB*, and the ISO spaces *RIM RGB*, *ROM RGB*, *Adobe RGB*, *ECI RGB*. All are device specific and not related to the visual elementary hue proposals of CIE R1-47.

5.9 Further ISO/IEC request to the CIE for a human visual *RGB* system (2014)

Before and during the Plenary of ISO/IEC JTC1 SC28 *Office Systems* in Berlin (June 2014) about 15 ISO documents and two ISO resolutions were produced in the colour field of Image Technology. The starting point of this activity was a decision of the German National Body to discuss the German intention to start an ISO Fast Track Procedure on DIN 33872-1 to -6:2010

Finally the following two resolutions were adopted at the SC28 Plenary:

Resolution Berlin 1/2014 Human Visual RGB development

SC 28 welcomes the German plan to continue development of the human visual *RGB* within CIE Division 1 and CIE Division 8 (Unanimous).

Resolution Berlin 2/2014 N1805 Fast Track Recommendation for DIN 33872-X

SC 28 recommends DIN not to initiate the fast track process based upon the work described in N1805 prior to the publication of a CIE International Standard

(Unanimous).

5.10 Summary of this section *Background*

The series DIN 33872-X is based on visual evaluations and allows colorimetric specifications according to ISO/IEC 15775. In future there is a wish to have colorimetric specifications based on CIE colorimetry. The present CIE documents CIE R1-47, and CIE R1-57 show pieces towards this goal. Both CIE documents are not CIE recommendations or CIE standards. Therefore only new developments within the CIE Divisions 1 and 8 and other standard groups may reach the ISO/IEC JTC1 SC28 goal of a International Standard in the colour field of Colour Image Technology, see Table 1 on page 6.

A device-independent *RGB** colour space (coordinates in the range 0 to 100) and the device-independent *rgb** colour data (coordinates in the range 0 to 1) may be one solution in this direction.

The long background section and the following long introduction are based on wishes of users to have much background information and application examples. After the following introduction the development of the *colorimetric affine match* with the OLM16 will be described and discussed.

6 Introduction

The colour output is an important part of our digital world. The CIE has the Division 1 *Vision and Colour* and the Division 8 *Image Technology* which are producing basic International Technical Reports and Standards in the colour area.

ISO 15076-1 defines a colour management method which uses for example 729 (9x9x9) colours as basis for the colour management of devices. ISO 15076-1 is a basic standard for ICC colour management.

The OLM16 uses a colour test file with 1080 colours (TUB RE69, see Fig. 3 on page 10) and there is a subset of 729 colours in the test chart output. The three (unspecified) *rgb* data in this file are changed in 9 steps between 0, 1/8, 2/8, ..7/8, 1. This results in 729 (9x9x9) output colours.

Colour devices produce usually the most chromatic colours, if one of the three *rgb* values is 1 and one is zero. There are 48 such cases out of the 729 colours, which produce a 48 step hue circle, usually with maximum CIELAB chroma on any device (sometimes only with colour management OFF). The CIELAB data LCh^* of this circle are usually different on any device. The OLM16 produces the same CIELAB hue angle h_{ab} on any device and a *colorimetric affine match* for lightness L^* and chroma C^*_{ab} .

This paper uses the CIELAB device data of a 48 step colour circle and white and black. These data and in addition the four elementary hue angles $RYGB_e$ according to CIE R1-47 allow to steer the output according to the user wishes defined by ISO TC 159/SC4/WG2 *Ergonomic - Visual display requirements* to the CIE Division 1 (see Fig. 10 on page 15) and in DIN 33872-5 (see Fig. 5 on page 12).

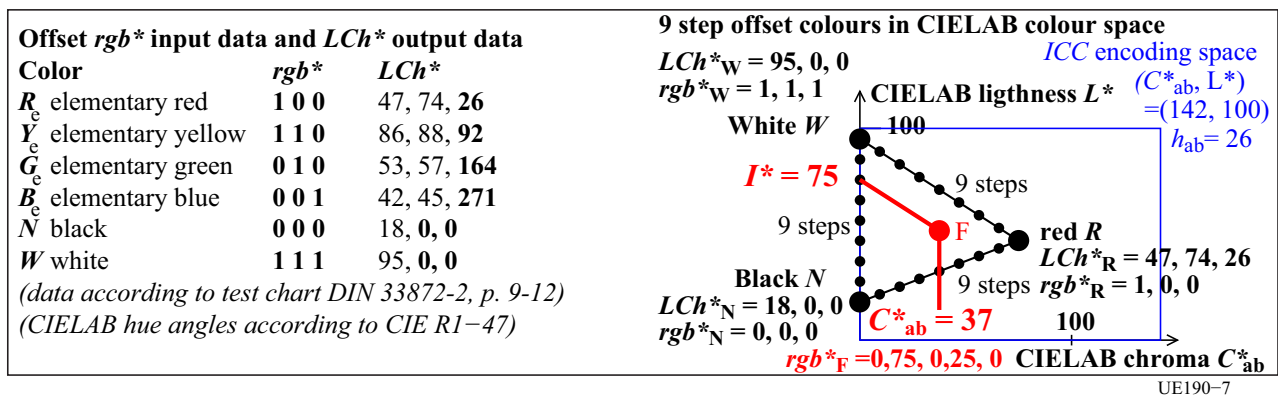


Fig. 14 - Elementary hue data of offset print and triangle and square colour encoding

Fig. 14 (left) shows the *rgb** and the intended CIELAB LCh^* output data of an example offset print. The hue angles of the four elementary colours (bold numbers) are proposed in CIE R1-47 and are identical to the four hue angles of the CIE-test colours no. 9 to 12, according to CIE 13.

Fig. 14 (right) shows the CIELAB hue plane $h_{ab}=26$ with the corresponding *rgb** data and the CIELAB LCh^* data at the three corners of a triangle. The 8 steps between the corners of a triangle indicate equally spaced *rgb** data.

For example between black $rgb^*_N = (0, 0, 0)$ and red $rgb^*_R = (1, 0, 0)$ the r^* value changes between 0 and $i/8$ ($i=1$ to 8). For these values the CIELAB chroma C^*_{ab} changes linearly between 0 and 74 in 9 steps or between $C^*_{ab}=0$ and $C^*_{ab}=i*74/8$ ($i=1$ to 8). Similar L^* changes in 9 steps are between $L^*=18$ and $L^*=18+i(47-18)/8$ ($i=1$ to 8).

In this paper this linear relation between the rgb^* data and the LCh^* data produces a table with corresponding rgb^* and LCh^* data, in this example only for the lower boundary of the triangle. Fig. 14 on page 18 shows an example how the rgb^* data and the corresponding LCh^* data are calculated within the triangle. By linear equations for any of the 729 rgb^* data the corresponding LCh^* data can be calculated.

In any application the intended (index i) CIELAB LCh^*_i data set are needed. One can find the device dependent rgb_d data to output this intended LCh^*_i data, for example on a display or a printer. Based on the file device data rgb_d and the corresponding measured CIELAB LCh^*_d data, the OLM16 uses a search method for the neighboring 4 device LCh^*_d - rgb_d data of any LCh^*_i data. A 3-dimensional interpolation method, similar to the method given in IEC 61996-2-1 (sRGB standard), calculates the rgb_i data to produce the intended LCh^*_i data. For more information see Fig. 22 on page 25.

The accuracy of the output depends on the efficiency of the encoding. Fig. 14 on page 18 allows us to guess the efficiency of the encoding method. The ICC method encodes the CIELAB value range $-127 \leq a^*$ and $b^* \leq 128$ towards the range $0 \leq rgb \leq 1$.

For offset printing the average chroma may be only 64 (compare Fig. 30 on page 32). The triangle area include only half of the rectangle encoding area towards $a^* = \pm 64$. In addition the encoding is more ineffective in the diagonal directions, with $C^*_{ab} = 90$ ($= 64 \cdot 1,41$).

Therefore the standard ICC method may use only 20% of the encoding space. This reduces the accuracy by a factor 5, compared to OLM16, which fills by the triangle encoding 100% of the encoding space for any hue triangle.

There is an additional method to understand the difference of the accuracy. If the lightness between $L^* = 0$ and $L^* = 100$ (100%) is encoded by 8 bit then the quantification error (only integer values are allowed) is 0,4 ($= 100/255$). If only 20% of this range is used, then the quantification error is 5 times larger. This happens in the L^* direction of the CIELAB space in offices. The actual L^* range is $L^* = 18$ to $L^* = 95$.

For the data projector output in an office with daylight reflection on the screen, the L^* range sometimes shrinks by a factor 3 and not only by 20%, and similar for the C^*_{ab} range. Then the ICC-coding efficiency may decrease by an additional factor 27 ($= 3^3$). In offices for the standard display with the luminance reflection $L_r = 2,5\%$ (lightness $L^* = 18$) compared to the white screen the lightness range decreases to 80% and the colour gamut decreases by a factor 2 ($= 1,25^3$) and similar the efficiency.

For example for a photo printer and for the 729 colours an average colour difference of $\Delta E^*_{ab} = 0,4$ is reached with the OLM16, see Witt (2006), Table 6.3. The measured accuracy (or the inverse value of the average colour difference) was 4 times higher compared to ICC colour management with a similar test chart.

In applications OLM16 interprets the 1080 *rgb* data in the test file as the *rgb** data.

Possible applications are:

1. ICC-colour management can use the 729 table data *rgb** - *rgb_{de}* as a *rgb_DeviceLink Profile* to produce an output according to the *rgb** coordinates of the OLM16.
2. If a device manufacturer uses the 729 table data *rgb** - *rgb_{de}* then an *rgb** device is produced. In addition this device has an appropriate linearized setup_stage for colour management according to ISO/IEC TR 19797.
3. A colour display manufacturer can use eight tables *rgb** - *rgb_{de}* for his display to offer eight *rgb**-display devices on the market with 8 appropriate setup_stages for colour management according to the 8 display reflections of ISO 9241-306:2008 at work places.
4. The test file TUB RE69 or similar ones with the 1080 *rgb* data is programmed in the programming language *PostScript* and includes the OLM16 interpolation code. Input of the 729 *LCh** data and a Yes-Parameter produces the intended output automatically.
5. In the Professional Graphics area of TC130 a *PS*-frame file, which includes the OLM16 Interpolation code, can steer the output for example in offset printing. This method has been used to produce a booklet of K. Richter (2012) with an *rgb** - *LCh** reference test chart, see Table 7 on page 42.
6. A *trusted output* may be defined as an output with no loss of the equal spacing of colour series. The OLM16 realizes such a need for example for medical diagnostics.

According to ISO 9241-306:2008, Annex D, and for example at (office) work places the following achromatic test file can be used to look at first for the most ergonomic output. The most ergonomic output out of 8 possibilities of the file output is given, if the 16 grey steps are visually approximately equally spaced. This ISO test file has the following URL (16 pages, 1,7MB)

<http://farbe.li.tu-berlin.de/B/Fe46/10L/L46e00FP.PDF>

A similar test file for colour with an image has the URL (8 pages, 20MB)

<http://farbe.li.tu-berlin.de/OE58/OE58D1P0.PDF>

One application is for example a data projector output on a screen with 8 possible luminance reflections between $L_r=0\%$, 1,3%, 2,5%, 5%, 10%, 20%, 40% compared to the projector luminance of white. With these 8 reflections the luminance contrast between white W and black N (L_W/L_N) changes between 288:1 via 36:1 (standard for $L_r=2,5\%$) to 2.25:1.

One can output the file and look for the one equally spaced output out of 8 spacing possibilities. If the gamma of the output display is adjusted according to the standard *sRGB* display with the $\gamma=1/2,4$, then in offices the contrast 36:1 is the visual ergonomic solution for both the achromatic and the chromatic output. Otherwise the gamma has to be changed.

For the ISO methods to create the best ergonomic visibility at work places see ISO 9241-306:2008. At present ISO TC159/SC4/WG2 works on a revision, see the ISO web

<http://www.iso.org>

For the ISO-test charts ISO EN DIN9241-306:2018, see <http://standards.iso.org/iso/9241/306/ed-2/index.html>

and for many achromatic and chromatic draft ISO-test charts for the revision on the page

<http://farbe.li.tu-berlin.de/AE.HTM>

Summary: The output intention of the ISO-files according to ISO 9241-306 and the OLM16 is identical.

7 Start and linearized output on displays and in print

The basic ideas and different applications of the OLM16 will be discussed in the following. The elementary hues (see definition in Table 2 on page 7) will play a special role towards the intended device-independent output.

The OLM16 output of elementary hues and the equal spacing of colour series can be proved visually without devices to measure colours. In this case the direct use of the human visual system is an advantage compared to the existing measurement methods of ICC-colour management.

7.1 Output of a 16 step device colour circle and definition of elementary colours

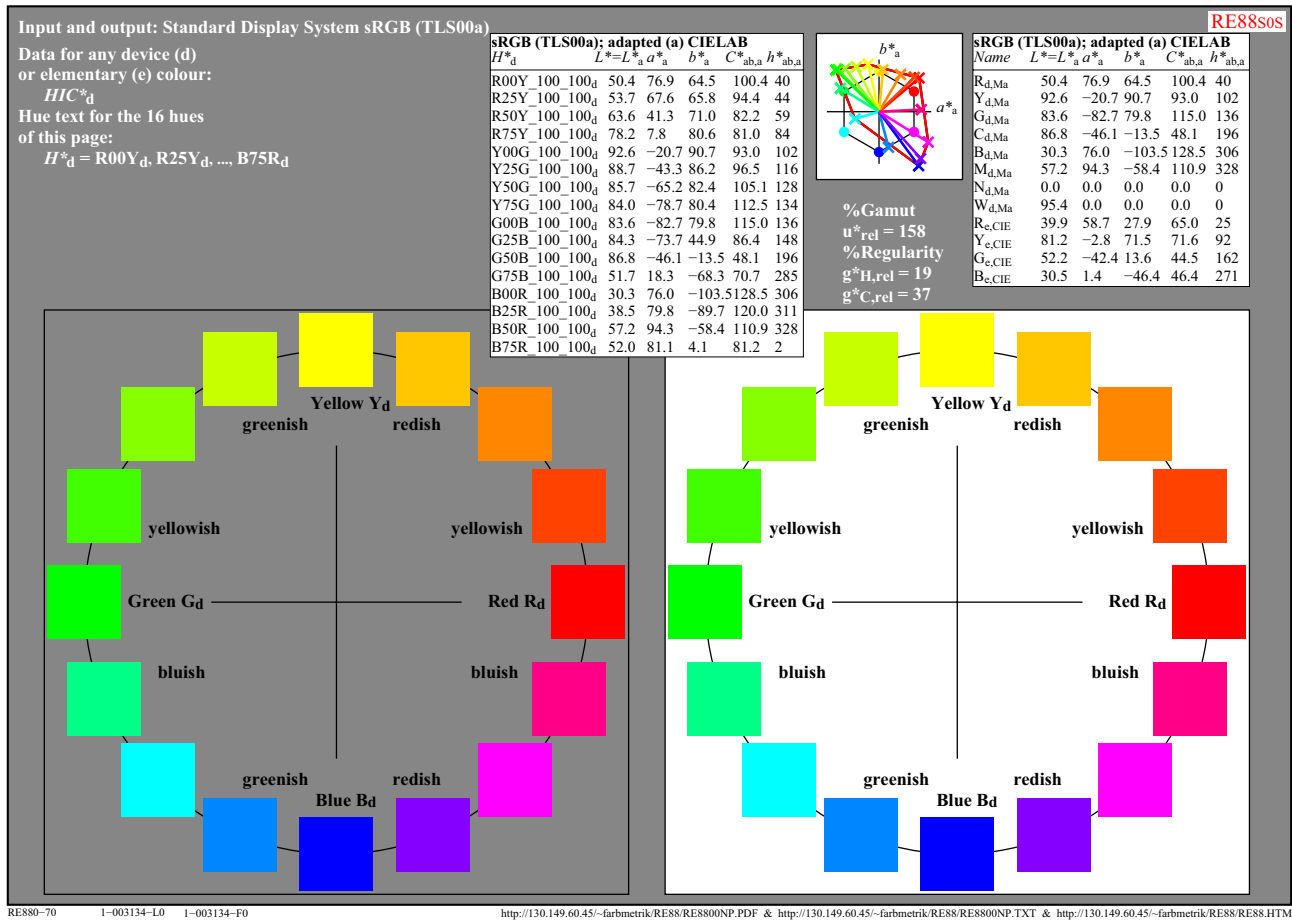


Fig. 15 - Hue circle with 16 colour steps and with device (d) colours

Fig. 15 shows a 16 step hue circle of device (d) colours. The four colours Red R_d , Yellow Y_d , Green G_d , and Blue B_d are produced by the rgb_d data $(1, 0, 0)_d$, $(1, 1, 0)_d$, $(0, 1, 0)_d$, and $(0, 0, 1)_d$. The CIELAB data L^* , a^* , b^* , C^*_{ab} and h^*_{ab} are given in the right table. The hue angles $h^*_{ab,d}$ 40, 102, 136, 306 belong to the output colours on the standard sRGB display. For comparison the elementary hue angles $h^*_{ab,e}$ of the CIE test colours 9 to 12 of CIE 13.3 are given. These four colours with the elementary hue angles $h^*_{ab,e} = 25, 92, 162, \text{ and } 271$ represent the CIE elementary hue angles proposed in CIE R1-47. The standard deviation of the hue angle is ± 4 for R_e , Y_e , and G_e , and ± 8 for B_e .

Fig. 15 includes a special colour code HIC^*_d , for example $HIC^*_d = R00Y_100_100_d$ for device red. According to DIN 33872-1 the three colour coordinates HIC^*_d are called hue text H^*_d , Brilliance I^*_d and Chroma C^*_d . Brilliance I^*_d is equal to 100 times the relative brilliance i^*_d and Chroma C^*_d is equal to 100 times of the relative chroma c^*_d .

In addition the CIELAB data L^* , a^* , b^* , C^*_{ab} and h_{ab} are given. For many real applications for black N and white W there is a small difference compared to the ideal values ($a^*_N=0$, $b^*_N=0$) and ($a^*_W=0$, $b^*_W=0$). Then some “adaptation” (index a) is necessary for a useful calculation of the hue angles. For the standard (ideal) $sRGB$ device the coordinates $L^*a^*b^*$, C^*_{ab} , h_{ab} and $(L^*a^*b^*C^*_{ab}h_{ab})_a$ are identical, compare Fig. 29 on page 31.

Usually for the values $rgb_{_}$ (index $_$ unspecified) the device blue is produced and this colour appears reddish blue. The $sRGB$ hue angle is $h_{ab,d} = 305$. However the elementary hue angle is $h_{ab,e}=272$

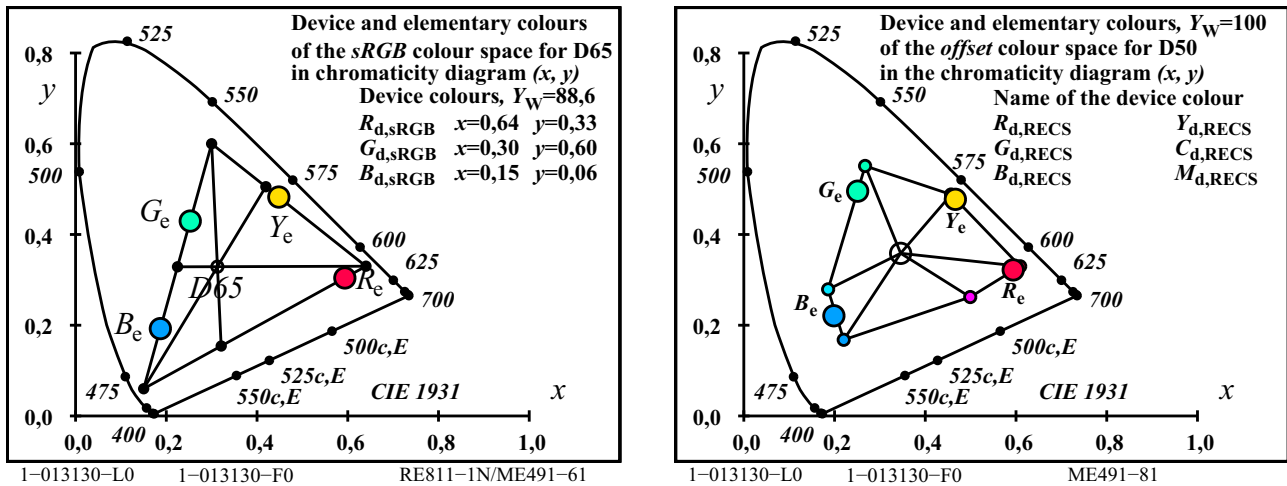


Fig. 16 - $sRGB$ and offset device colours and elementary colours in the CIE (x,y) chromaticity diagram

Fig. 16 shows the six device colours (*black balls*) and the four elementary colours in the CIE chromaticity diagram. The left diagram shows the device colours of the standard $sRGB$ display according to IEC 61966-2-1. The right diagram shows the device colours of offset printing according to ISO/IEC 15775.

Fig. 16 shows that both the six device colours $RYGCBM_d$ of the $sRGB$ display and of offset printing have different chromaticities. Both devices can produce the elementary hues $RYGB_e$ with the intended hue angles h_{ab} in CIELAB. However, the chromaticities (and the lightness and chroma) of these elementary hues are different.

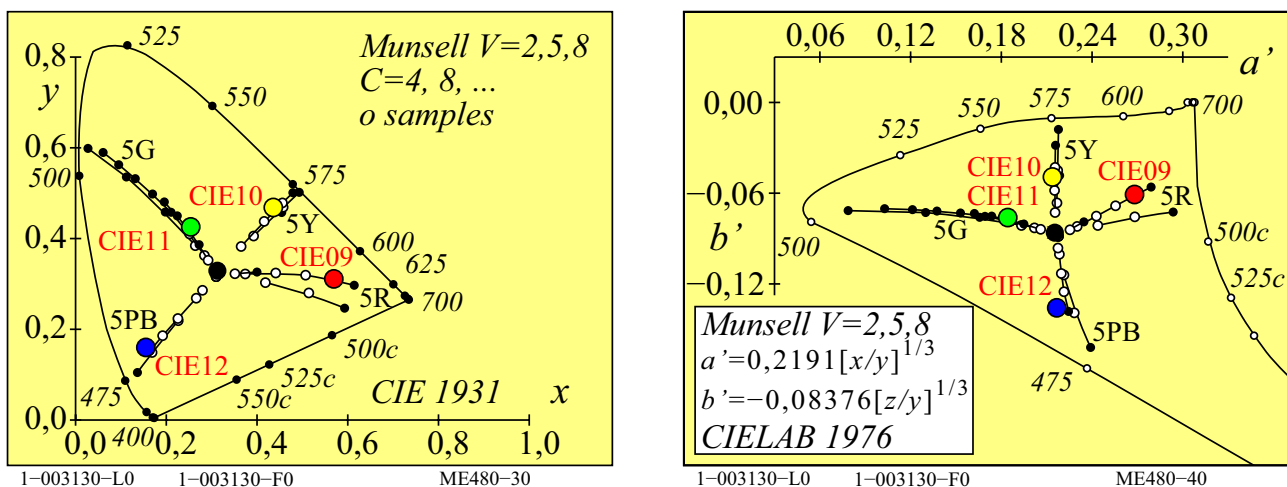


Fig. 17 - The elementary colours CIE test colours no. 9 to 12 and model for $RYGB_e$

Fig.17 (*left*) shows the four CIE test colours no. 9 to 12 which represent the elementary hues together with the samples of the hues $5R$, $5Y$, $5G$ and $5PB$ of the *Munsell* colour order system for the three *Values* $V=2, 5$, and 8

(approximately $L^*=20, 50, 80$ in CIELAB). Yellow and blue are opposite in the chromaticity diagram. This is not the case for red and green.

Similar Fig. 17 (right) shows the same data in the cube root chromaticity diagram (a', b'). Fig. 17 includes the definition of the coordinates a' and b' . Yellow and blue are opposite in this diagram. This is again not the case for red and green. However, now the hue angles of $RYGB_e$ are identical to the CIELAB hue angles $h_{ab}=26, 92, 162, \text{ and } 272$ of CIE R1-47.

For the device colour series between red R of maximum chroma towards black N the chromaticity remains constant. This is a physical relation for $sRGB$ displays. Only the luminance of the red device primary changes from zero to a maximum. In offset printing the device primary is usually overprinted by the black primary. Near black there is some change of the chromaticity if both are overprinted. However, in applications at black only the black colorant shall be used and therefore the chromaticity of black will occur. This is reached by the so called *complete undercolor removal* for offset print and for printers.

If *complete undercolor removal* is not used then the printing cost per page increase a lot. The chromatic colorant is often three time more expensive than the black colorant. If black is printed with three chromatic colorants then the cost per page may increase by a factor 9. Any increase is not intended and therefore the chromaticity is constant between the most chromatic red and black for printers and for offset print.

Therefore for displays and in print in a CIELAB hue plane all the device colours are approximately on a line between black and the most chromatic colour. This line forms the lower part of the hue triangle. All achromatic colours of both the displays and the printers, and for offset printing are on a line in the CIELAB space.

The colours between for example the red of maximum chroma and white are produced by an additive mixture and are located on a line in any linear colour space. The nonlinearity of the CIELAB space seem not to change this property by an considerable amount. This is therefore no problem for the application of the OLM16.

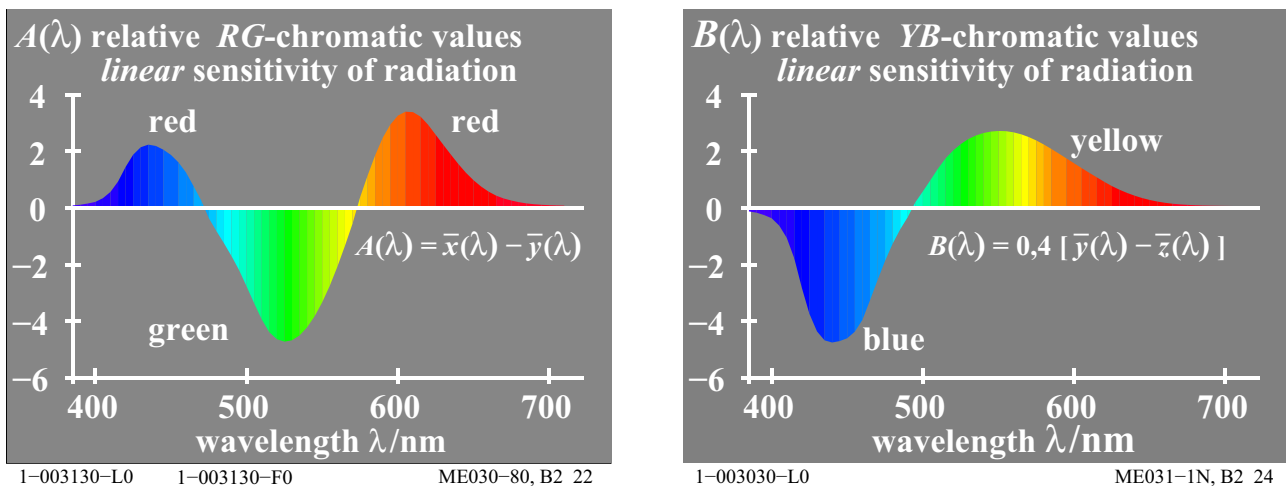


Fig. 18 - RG-chromatic values and YB-chromatic values

Fig. 18 shows a model for the relation of colorimetry and physiology. *Hurvich and Jameson* (1955) calculated a yellow-blue and a red-green process from the colorimetric spectral tristimulus values. The mathematical relation is given in the figure. Only one yellow-blue response exists according to this model with the cut points "elementary green G_e " at the wavelength 503nm and the "opposite elementary red G_e " 503c nm.

However, this model of *Hurvich and Jameson* could not describe an appropriate hue location for the experimental elementary hues red R_e and green G_e which are **not** opposite in the chromaticity diagram. It is expected that the present Technical Committee CIE TC1-76 *Unique Hues* will come with a CIE recommendation for the elementary hue angles h_{ab} . Up to now we have only the proposal in CIE R1-47. The present values of the CIELAB hue angles are $h_{ab}=26, 92, 162, \text{ and } 272$ for $RYGB_e$. This corresponds approximately to the dominant wavelength 700nm, 572nm, 515nm, and 472nm, see also Fig. 17 on page 22 and Fig. 28 on page 30.

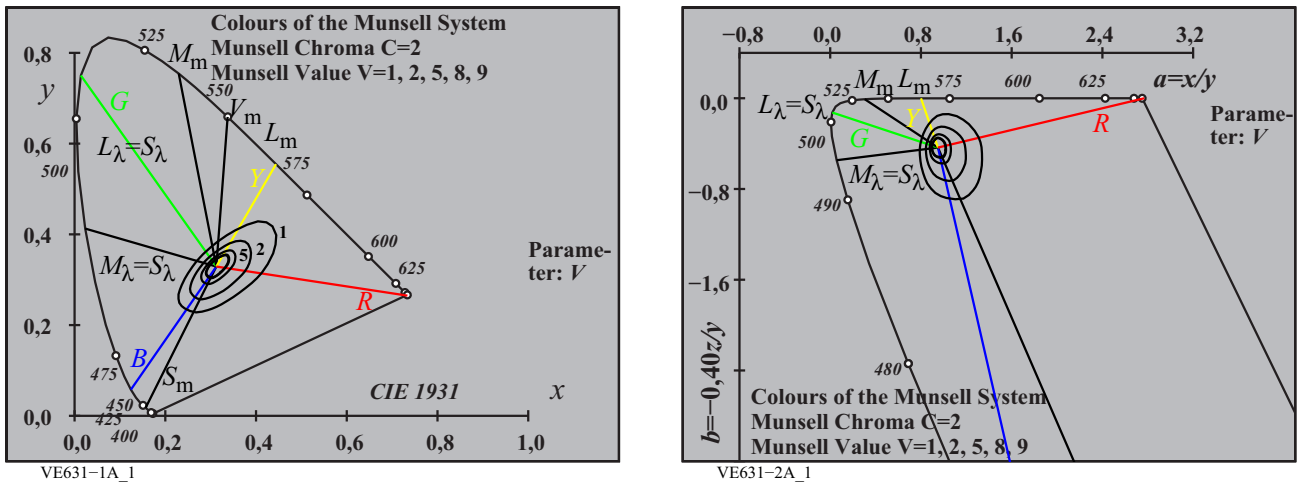


Fig. 19 - Yellow-blue and red-green visual processes according to *Hurvich and Jameson (1955)*

Fig. 19 (left and right) shows a simple model which uses the responses of the 3 fundamental cone sensitivities L , M , and S with maximum (m) sensitivities near 570, 540 and 450nm. Elementary green G is located near 510nm at the same spectral response of the cone sensitivities L and S (with an appropriate normalisation). Elementary red R is located near 700nm (complementary to 495c nm) at the same spectral response of the cone sensitivities M and S .

This explanation shows a model relation of colorimetry and physiology. *Valberg and Seim (2008)* have shown, that especially two blue-yellow response combinations are found in the retina: $L - S$ and $M - S$. The combination $(L+M) - S$ which is usually assumed according to *Hurvich and Jameson* (with the difference $Y - Z$ in colorimetry) seems not present in physiology.

The publication CIE 170-2:2015 of the Technical Committee CIE TC1-36 has now defined a fundamental chromaticity diagram based on the cone sensitivities. The coordinates are calculated in luminance units, for example $L/(L+M)$ and $S/(L+M)$ with appropriate normalizations. These coordinates are called cone excitations. In colorimetry similar ratios in luminance units are used. The chromaticity ratios in luminance units are used in Fig. 19 (right) and Fig. 17 on page 22 which is connected to the CIELAB space, see *Richter (2012)*. Fig. 19 (right) shows similar hue angles compared to the CIELAB colour space and Fig. 17 on page 22. In addition *Munsell* colours of chroma 2 are approximately on circles (the diameter changes with the cube root of the luminance factor of the *Munsell* samples).

Therefore the model shown here may be one basis for a device independent human RGB^* colour space to be developed by the CIE Division 1 *Vision and Colour*. **CIE 230:2019 uses the chromaticities (a,b) within the colour difference formula LABJND. For small colour differences in the range $0 < \Delta E^*_{ab} < 5$ the performance of the modification LABJND_PF is better than CIELAB and similar to CIEDE2000.**

7.2 Device output colours in elementary hue triangles

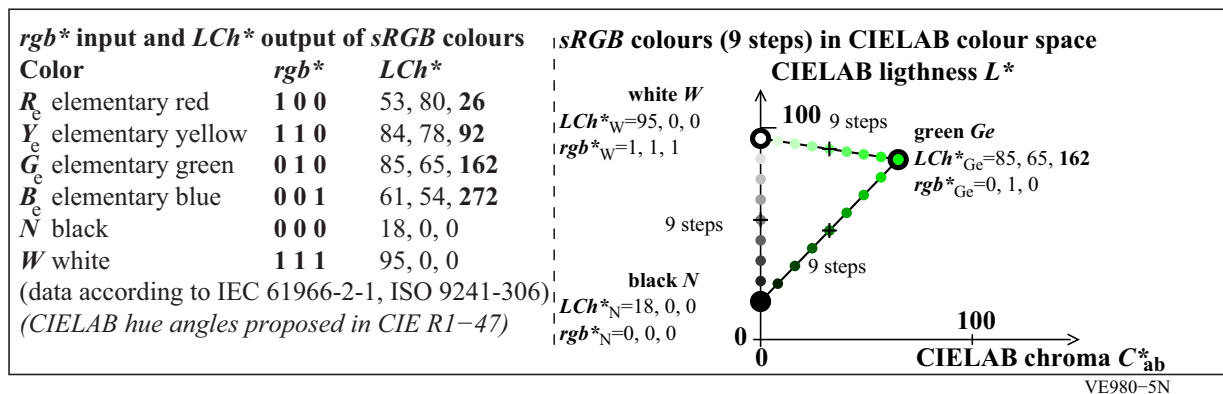


Fig. 20 - rgb^* input and LCh^* output data of $sRGB$ display colours

Fig. 20 (*left*) shows rgb^* input and LCh^* output data of the standard $sRGB$ display colours with the luminance reflection $L_r=2,5\%$ compared to the white screen. More data are given in Table 4 on page 33. Fig. 20 (*right*) shows the 9 colours of the three series by balls in a CIELAB hue triangle with the real data LCh^* and rgb^* at the three corners. The data for the elementary green colour with the hue angle $h_{ab}=162$ are given.

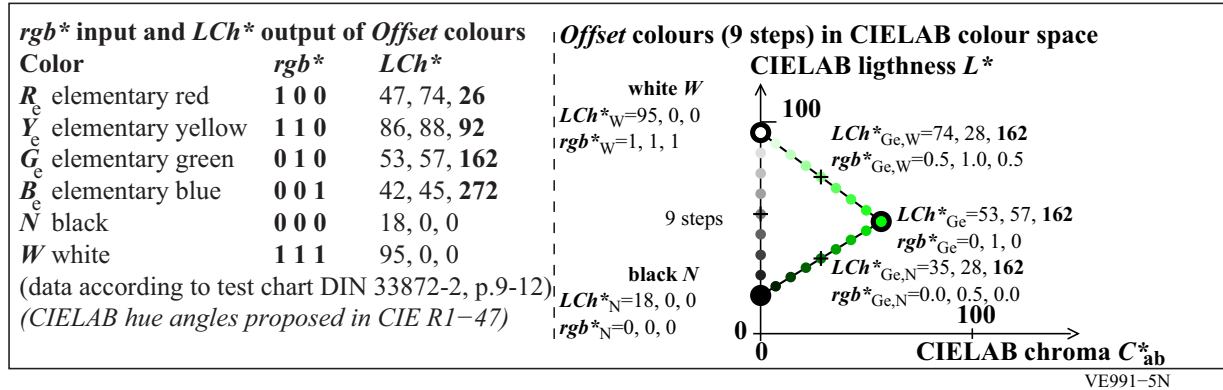


Fig. 21 - rgb^* input and LCh^* output data of offset printing colours

Fig. 21 (*left*) shows rgb^* input and LCh^* output data of the standard *offset* printing colours. The 9 colours of the three series are shown by balls in a CIELAB hue triangle with the real data at the three corners. The data for the elementary green colour with the hue angle $h_{ab}=262$ are given.

In addition to Fig. 20 (*right*) the Fig. 21 (*right*) includes the data of the colours located intermediate between black and green, and between green and white. As expected the three rgb^* and LCh^* data are the intermediate data. Therefore Fig. 21 (*right*) matches the intended linear relationship between the rgb^* and LCh^* data.

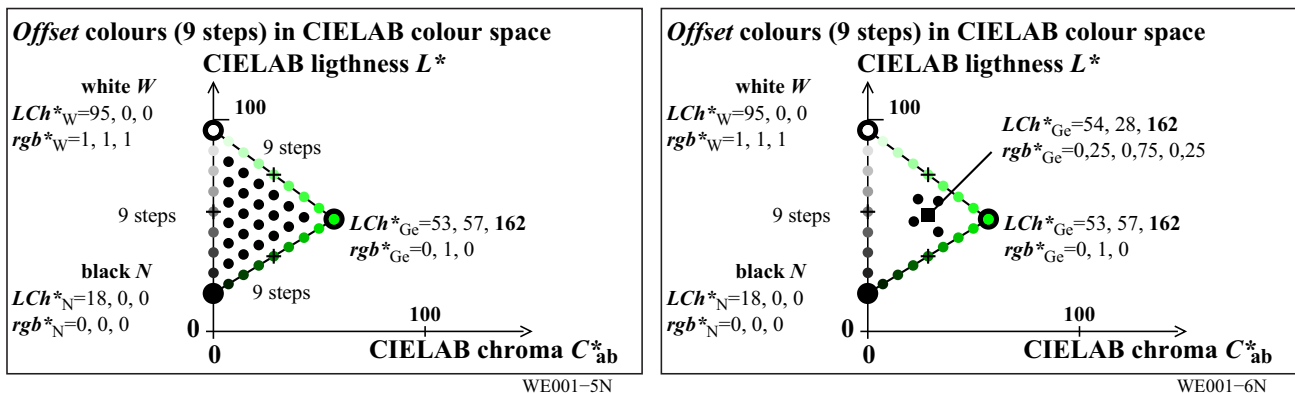


Fig. 22 - Offset colours (9 steps) in CIELAB hue triangle and rgb^* interpolation method

Fig. 22 (*left*) shows additional black balls within the green hue triangle. The order is regular. One can find this arrangement also in the test chart with the 1080 colours, see column b to j and line 19 to 27 and in Fig. 3 on page 10.

If a device is offered as an rgb^* device on the market then a user can output the TUB RE69 reference test chart with the 1080 colours, and can proof visually if a *colorimetric affine match* is produced. A user will first evaluate if the elementary green G_e (visually neither yellowish nor bluish) is produced. Then he will check according to a weaker criteria if all colours in the hue triangle can be distinguished. In addition an expert user may evaluate if all the relative differences (about $\Delta E^*_{ab}=5$ between all steps) are approximately equal. There may be larger differences between two rgb^* devices for this strong visual criteria, For example the colorimetric regularity index g of two devices according to ISO/IEC 15775 may be 0,2 (low value, $1<\Delta E^*_{ab}<9$ for all steps) or 0,9 (best value 1, $4,5<\Delta E^*_{ab}<5,5$ for all steps). In both cases it may be possible to distinguish visually all the colours in the triangle.

Fig. 22 (*right*) shows as example an intended (i) CIELAB colour with LCh^*_i and rgb^*_i data by a square. There are of course for output colours in the CIELAB space, out of the 729 output colours in the neighbourhood. Four

colours of the 729 are shown by black balls in Fig. 22 (right). They have four lowest colour differences $\Delta E_{ab,i}^*$ ($i=1,2,3,4$) to the intended colour LCh_i^* . In an ideal case the intended colour LCh_i^* is in the middle of a 3-dimensional regular tetrahedron with the same CIELAB difference to the four corners of the tetrahedron. Then the rgb_i input data for the output of the intended LCh_i^* can be calculated by linear interpolation of the rgb_i data of the four neighbouring colours. In any case the intended colour LCh_i^* is somewhere within an irregular tetrahedron. However, in any case the input rgb_i data can be calculated for the intended output data LCh_i^* . This is of course possible for any of the 729 intended LCh_i^* output data.

The OLM16 interpolation method may produce one of the rgb_i^* data larger one or below zero, if the intended output data LCh_i^* is outside the device range. However, this is forbidden and then one of the rgb data is reduced to one or to zero by any real output device.

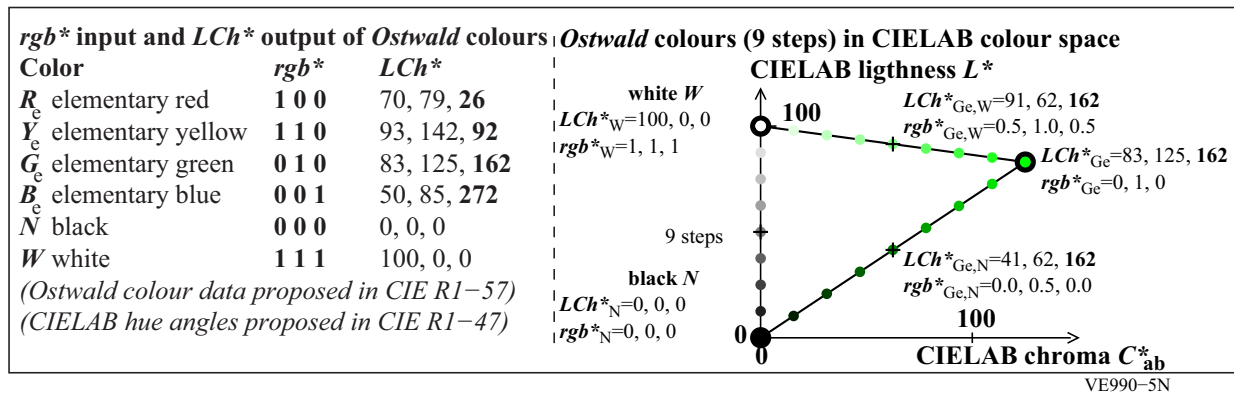


Fig. 23 - rgb^* input and LCh^* output data of Ostwald optimal colours

Fig. 23 (left) shows the rgb^* input and LCh^* output data of Ostwald optimal colour with the elementary hue angle $h_{ab} = 162$ of elementary green G_e .

Fig. 23 (right) gives in addition to Fig. 23 (left) the data of the colours located intermediate between black and green, and between green and white. The three rgb^* and LCh^* data are the intermediate data. Therefore Fig. 23 (right) matches the intended linear relationship between the rgb^* and LCh^* data.

For the intended standard documents which describe a complete device-independent human RGB^* colour space the Ostwald colours may play a special role. The *colorimetric affine match* produces a device-independent hue match. However, lightness L^* and chroma C_{ab}^* are usually different on any two devices. In other words: the reference values (L^* , C_{ab}^*) differ usually for any two devices and in addition for any hue.

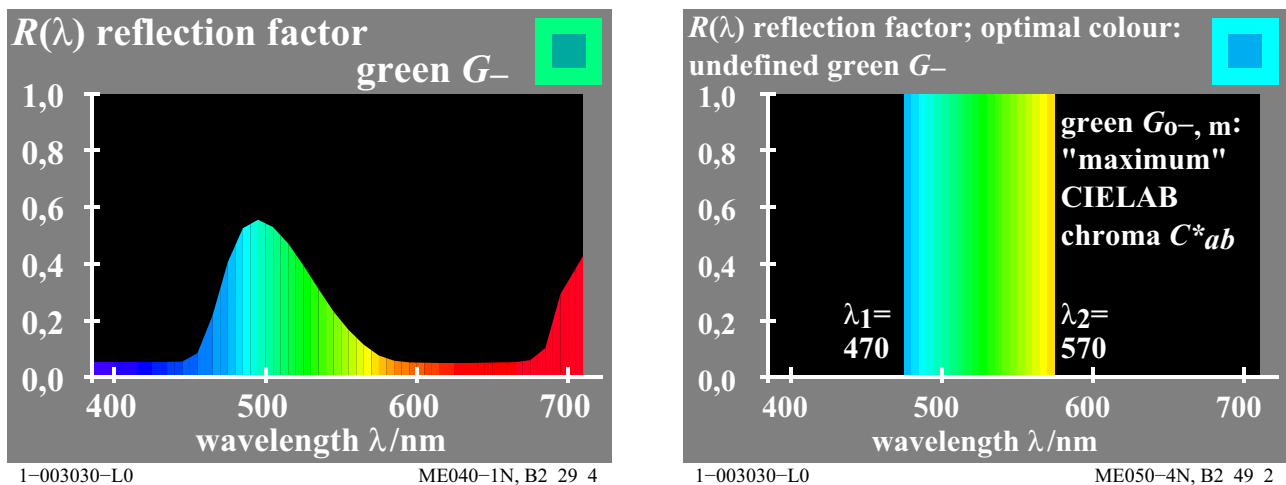


Fig. 24 - Elementary green surface colour and Ostwald optimal colour

Fig 24 (left) shows a green surface colour of high chroma C_{ab}^* . Fig. 24 (right) shows an Ostwald optimal colour which has a much higher chroma. Both have the elementary hue green (CIELAB hue angle near $h_{ab}=162$). The

chroma of the *Ostwald* optimal colour is much higher compared to the surface colour. In addition the lightness L^* is larger.

Two complementary *Ostwald* colours with the wavelength limits $\lambda_1=470\text{nm}$ and $\lambda_2=570\text{nm}$ and vice versa $\lambda_1=570\text{nm}$ and $\lambda_2=470\text{nm}$ mix together to the reference white of colorimetry. The first has the dominant wavelength 520nm and the second is labelled by 520c nm (c = complementary).

According to some vision models the visual system divides the reference white in nature in two complementary pairs: Red - Green and Yellow - Blue. The *Human Visual System* may produce for any *Ostwald* colour pair the same chroma (because they mix to the achromatic white). The CIELAB data for the *Ostwald* colour do not include this property. However, the chromatic moment of the linear *Hurvich and Jameson* model, see Fig. 18 on page 23, produce the same chromatic value for complementary *Ostwald* colours. In other words the *Ostwald* colour may be used as reference colours similar as the elementary hues.

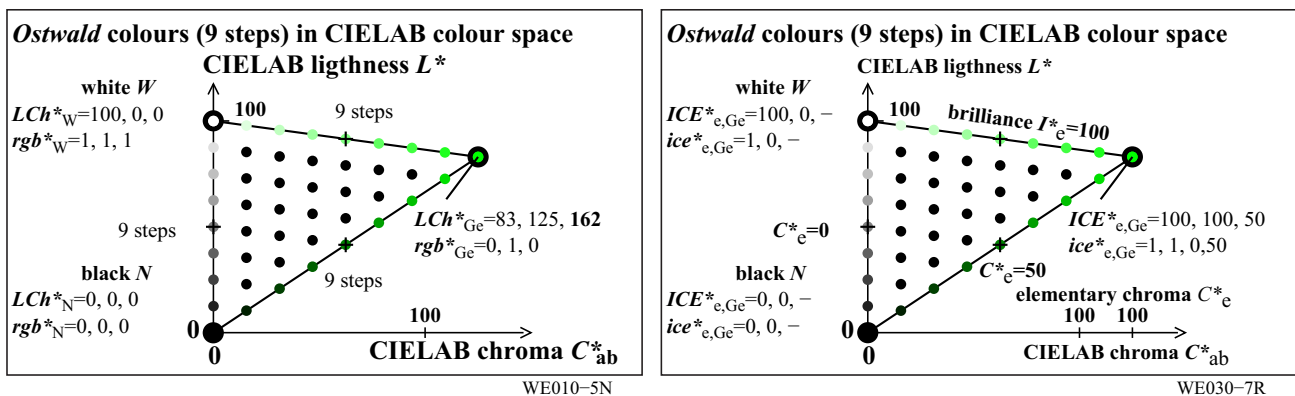


Fig. 25 - Visual attributes ICE^* (brilliance, chroma, elementary hue)

Fig. 25 (left) shows additional black balls within the green hue triangle. The order is regular. One can produce these colour only by a *spectral colour integrator*. This special optical instrument mix (integrates) different parts of the spectrum. All parts of the spectrum mix to white.

Fig. 25 (right) shows the special visual attributes ICE^* (brilliance, chroma, elementary hue). The brilliance is more important, especially in art and design, compared to the lightness. The *Swedish Natural Colour System* (NCS) use already a similar coordinate which is called blackness $N^*=100 - I^*$ and counts therefore in the opposite direction. The NCS system uses virtual reference colours for any hue triangle. The Reportership Report CIE R1-57 has shown that the CIELAB data of the *Ostwald* colours and the CIELAB data of the NCS colours are similar. Therefore colours of equal elementary (e) brilliance I_e^* are shown in the right side of Fig. 25. In addition the relative coordinates ice^* are given.

7.3 Application: Colorimetric filter transfer with rgb^* devices

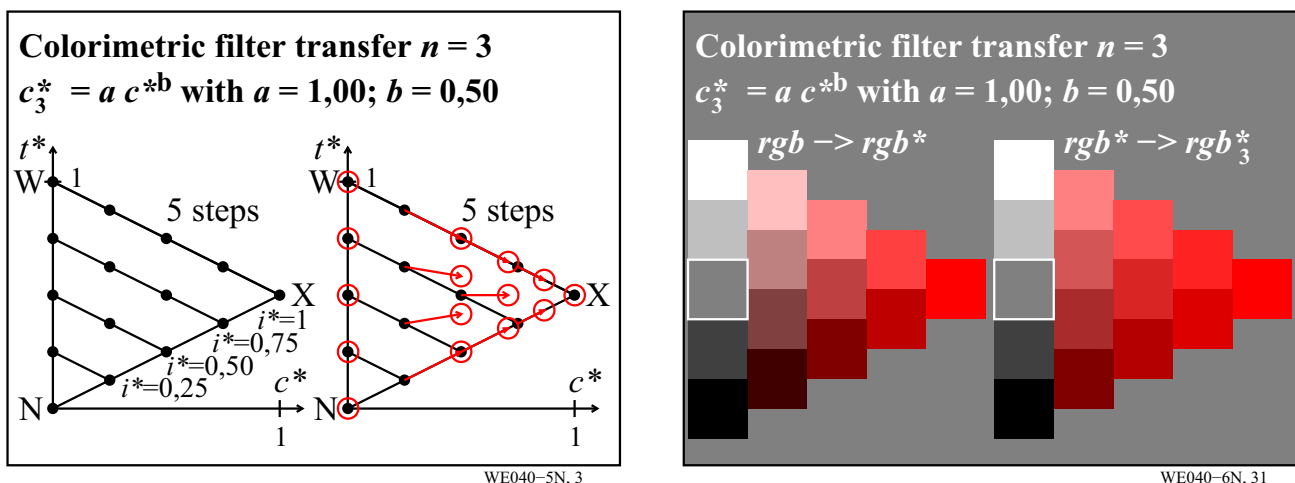


Fig. 26 - Colorimetric filter-transfer example

Fig. 26 (*left*) shows a hue triangle with 5 steps of the colour series. For an rgb^* device, the output series will be equally spaced. If there is for example a wish to change the relative chroma c^* by a potential colorimetric formula

$$c_i^* = a c^{*b} \quad (a=1, b=0,5, i=1 \text{ to } 8)$$

then the shift according to the red arrows is the colorimetric solution for the parameters $a=1$ and $b=0,5$. This transfer is therefore defined by a colorimetric equation and produces the same chroma shift for all hues.

Fig. 26 (*right*) shows the original output (*left*) and the transfer (*right*). All colours are more chromatic except the red with the maximum chroma and the achromatic colours.

This colorimetric filter may be applied if an image shall look more chromatic. No colour is shifted outside the device colour space.

For users this is a large advantage of this colorimetric transfer. By the change of the parameters a and b an image can be made more or less chromatic and also achromatic. For more examples look visually at the six file output pages

<http://farbe.li.tu-berlin.de/WE04/WE04L0FP.PDF>

7.4 Application: Output of the elementary colour circle with rgb^* devices

The output of the elementary colour circle on a standard $sRGB$ display needs hue shifts, compare Fig. 49 on page 54. For example the three rgb_d values $(0 \ 0 \ 1)_d$ (d =device) produce the hue angle $h_{ab,d}=305$ and the three rgb_e values $(0 \ 0 \ 1)_e$ produce the hue angle $h_{ab,e}=271$.

For a 16 step device and a elementary hue circle the hue angles $h_{ab,d}$ and $h_{ab,e}$ are given in the tables of Fig. 15 on page 21 and Fig. 27 respectively. For example for the device hue $Y00G_d$ and the elementary hue $Y00G_e$ the hue angles are $h_{ab,d}=102$ and $h_{ab,e}=92$. The device hue angle $h_{ab,d}=102$ produces a greenish yellow compared to the elementary hue angle $h_{ab,e}=92$ with the standard deviation ± 4 .

The colour code $Y00G_100_100_e$ belongs to the rgb values $rgb_e=(1 \ 1 \ 0)_e$. The first value $Y00G_e$ is called the hue text, the following two values are 100 times the relative brilliance i^* and the relative chroma c^* . One can use the capital letters $I^* = 100 i^*$ and $C^* = 100 c^*$.

There are two equations which allow to transform between values of rgb^* and c^* and i^* for both the device and the elementary colours:

$$\begin{aligned} c^* &= \max(rgb^*) - \min(rgb^*) \\ i^* &= \max(rgb^*) \end{aligned}$$

Example: For a greyish red with $rgb^* = (0,75, 0,50 \ 0,25)$ it is valid $c^* = 0,5$ and $i^* = 0,75$ (compare also Fig. 34 on page 36).

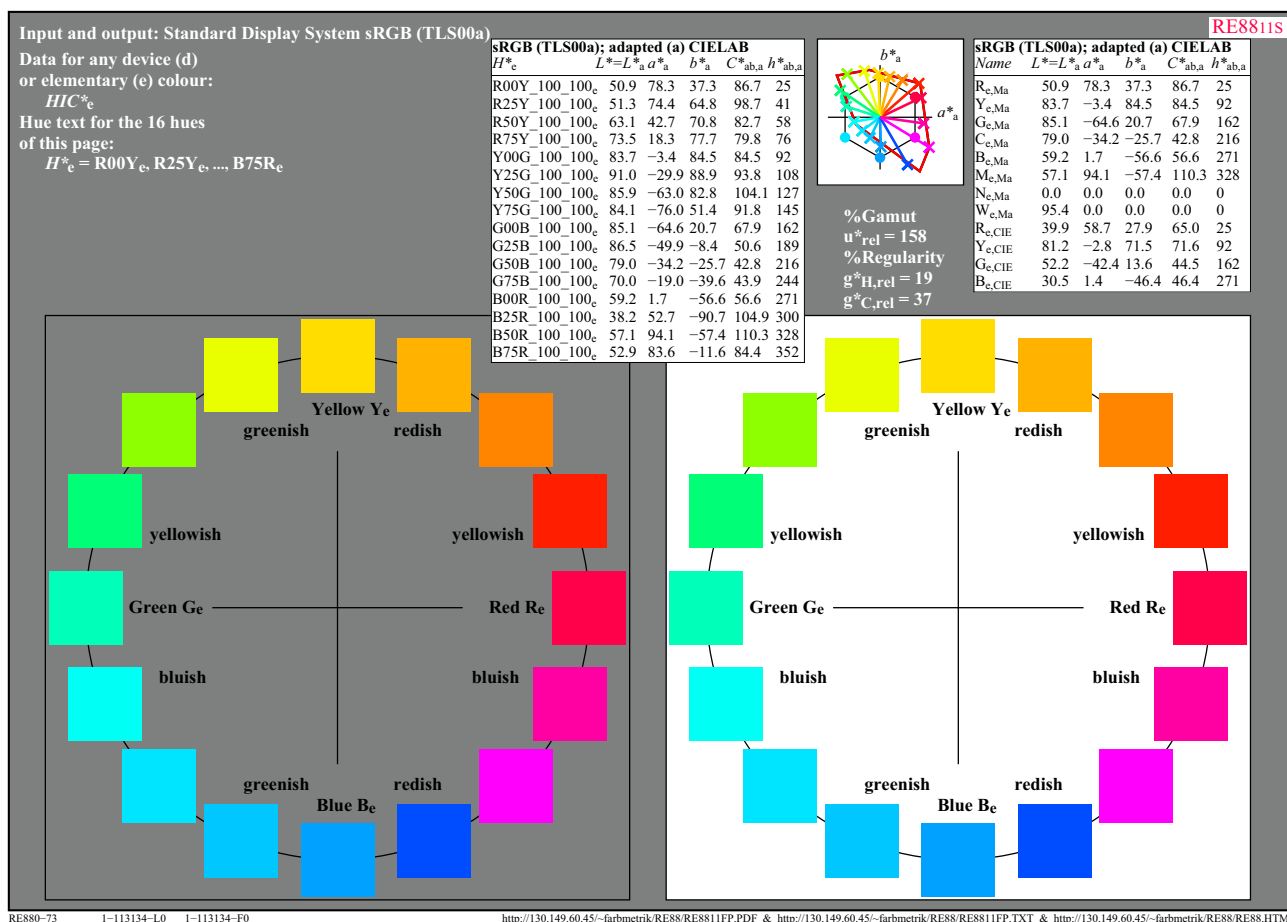


Fig. 27 - 16 step hue circle of elementary (e) colours

Fig. 27 shows a 16 step hue circle which shall produce the elementary colours R_e , Y_e , G_e , and B_e according to the criteria given in the figure. There may be a small visual difference on the grey and white background. One may realize that Yellow $Y_e=Y00G_e$ is visually darker compared to the next greenish step $Y25G_e$. This is a special disadvantage of the sRGB display system, Usually both printers and standard offset produce a lighter and more natural yellow.

7.5 Application: Equal chroma steps between white and chromatic for ORS18 and TLS00

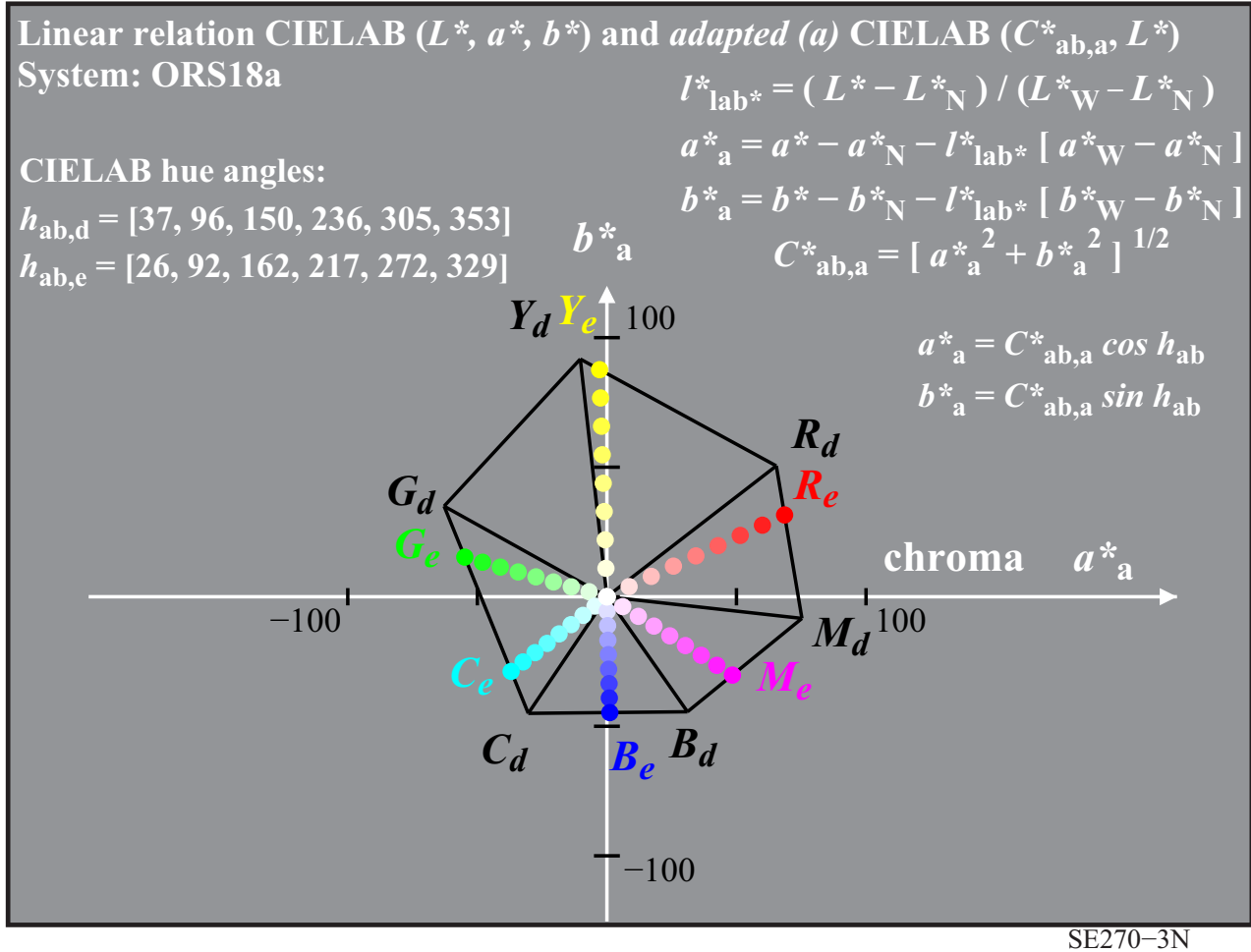


Fig. 28 - Device and elementary colours of standard offset according to ISO/IEC 15775

Fig. 28 shows the device colours $RYGCBM_d$ of standard offset according to ISO/IEC 15775 and the elementary colours $RYGB_e$ which are produced in standard offset for the four elementary hue angles $h_{ab,e} = 25, 92, 162$, and 271 . In addition the mean hue angles $h_{ab,C_e} = 217 = 162 + (271 - 162)/2$ and $h_{ab,M_e} = 329 = 271 + (385 - 271)/2$ are given for C_e and M_e . Most of the so called RGB and $CMYK$ printers use similar device colours compared to offset. The colour difference is about $\Delta E_{ab}^* = 20$ compared to the standard $sRGB$ display colours.

Fig. 28 shows some equations to calculate the CIELAB coordinates with the index a (= adapted). If the CIELAB coordinates of black N (a_N^* , b_N^*) and white W (a_W^* , b_W^*) are all zero (which is not true for standard offset and most printers) then the coordinates with the index a are identical to the coordinates without the index. In any case the adapted coordinates (index a) have the values 0 for both the black N and white W . For the calculation of the hue angle this property is necessary.

If the CIELAB (a^* , b^*) coordinates of black N and W are known one can transfer to the adapted coordinates and backwards.

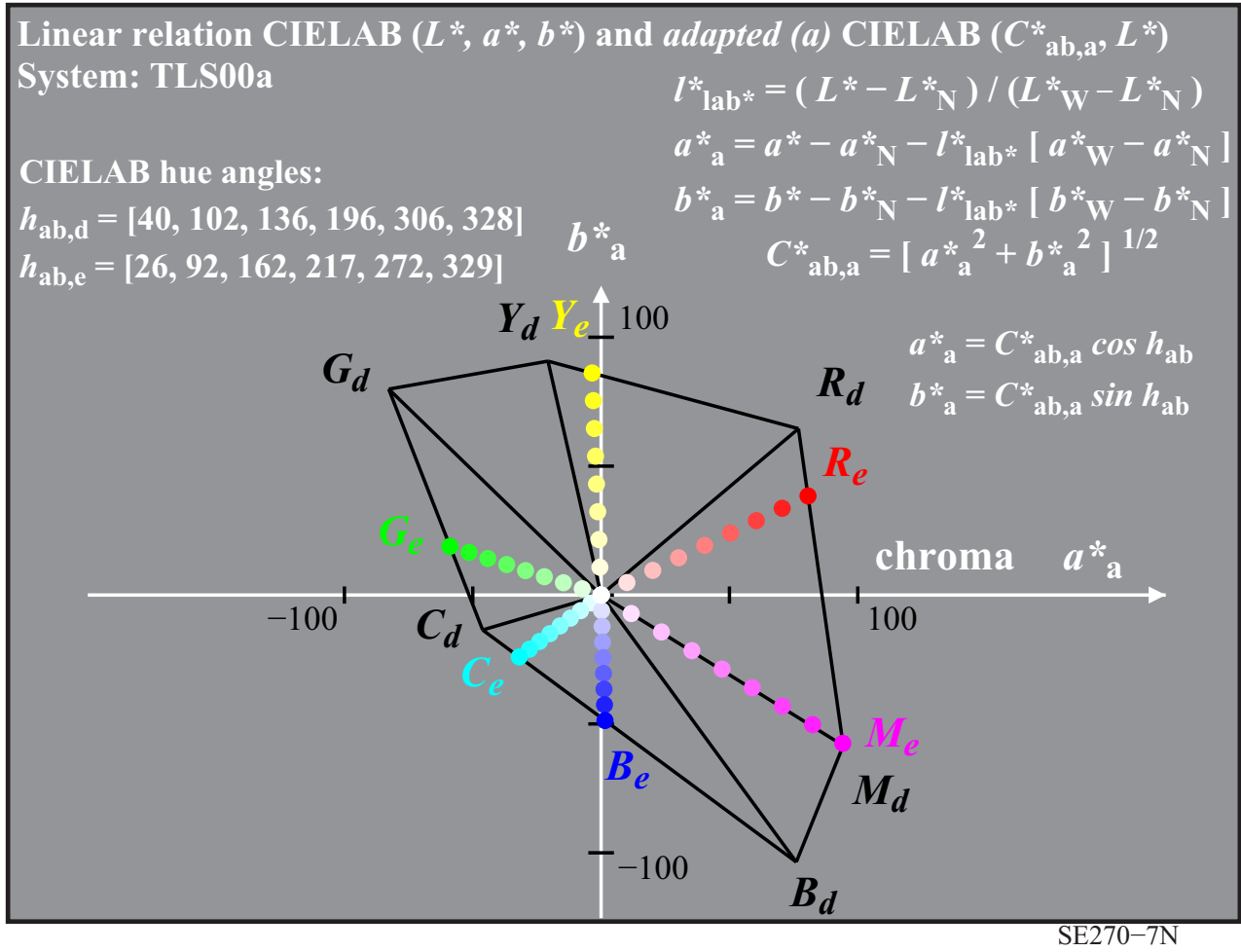


Fig. 29 - Device and elementary colours of the standard sRGB display according to IEC 61966-2-1

Fig. 29 shows the device colours $RYGCBM_d$ of the standard sRGB display according to IEC 61966-2-1. The elementary colours $RYGB_e$ have the four elementary hue angles $h_{ab,e} = 25, 92, 162$, and 271 . In addition the colours C_e and M_e are shown for the hue angles $h_{ab,Ce} = 217 = 162 + (271 - 162)/2$ and $h_{ab,Me} = 329 = 271 + (385 - 271)/2$.

Fig. 29 shows some equations to calculate the CIELAB coordinates with the index a (= adapted), similar as Fig. 28. The standard sRGB device produces the colours B_d and M_d with a high chroma. This is the case in a dark room without reflection on the display. In offices with a standard luminance reflection of $L_r = 2,5\%$ (CIE tristimulus value $Y = 2,5$ compared to the white reference) the chroma $C_{ab,a}^*$ decreases by about 10% and is still much larger compared to the chroma $C_{ab,a}^*$ of standard offset ORS18a, compare Fig. 28 on page 30.

The different chroma of standard offset ORS18a and the standard display sRGB indicate that a colorimetric reproduction with the same $L^*C_{ab}^*h_{ab}$ values on the display and in print is not possible.

A comparison of Fig. 28 on page 30 and Fig. 29 shows similar chroma $C_{ab,a}$ for the elementary blue B_e . However, the lightness L^* on the screen is larger. Both values $(L^*C_{ab,a}^*)_e$ are needed for the comparison and the reproduction.

Table 4 - Coordinates rgb^*_e and CIELAB $(L^*a^*b^*C^*_{ab}h_{ab})_e$ of a 16 step hue circle and mixture colours

rgb^*_e and CIE data of a elementary (e) hue circle according to CIE R1-47:2009 for sRGB display $L_r=2,5\%$							rgb^*_e and CIE data of a elementary (e) hue circle according to CIE R1-47:2009 for sRGB display $L_r=2,5\%$						
16 step elementary hue circle with hues: $h_{ab,a,e} = 25.4, 92.3, 162.2, 271.7$							3 colours of the elementary hues $RYGB_e$: $h_{ab,a,e} = 25.4, 92.3, 162.2, 271.7$						
Code	$L^*_{a,e}$	$a^*_{a,e}$	$b^*_{a,e}$	$C^*_{ab,a,e}$	$h_{ab,e}$	rgb^*_e	Code	$L^*_{a,e}$	$a^*_{a,e}$	$b^*_{a,e}$	$C^*_{ab,a,e}$	$h_{ab,e}$	rgb^*_e
$R00Y_e = R_e$	53.0	72.6	34.5	80.4	25.4	1.00 0.00 0.00	$R00Y_e = R_e$	53.0	72.6	34.5	80.4	25.4	1.00 0.00 0.00
$R25Y_e$	57.1	59.5	53.9	80.3	42.1	1.00 0.25 0.00	$0,5R_e + 0,5N_e$	35.5	36.3	17.2	40.2	25.4	0.50 0.00 0.00
$R50Y_e$	65.7	37.3	61.7	72.1	58.8	1.00 0.50 0.00	$0,5R_e + 0,5W_e$	74.2	36.3	17.2	40.2	25.4	1.00 0.50 0.50
$R75Y_e$	74.0	17.7	69.0	71.2	75.6	1.00 0.75 0.00							
$Y00G_e = Y_e$	83.8	-3.0	77.4	77.5	92.2	1.00 1.00 0.00	$Y00G_e = Y_e$	83.8	-3.0	77.4	77.5	92.2	1.00 1.00 0.00
$Y25G_e$	91.2	-29.9	83.0	88.2	109.8	0.75 1.00 0.00	$0,5Y_e + 0,5N_e$	50.9	-1.5	38.7	38.7	92.2	0.50 0.50 0.00
$Y50G_e$	86.5	-58.7	77.1	96.9	127.2	0.50 1.00 0.00	$0,5Y_e + 0,5W_e$	89.6	-1.5	38.7	38.7	92.2	1.00 1.00 0.50
$Y75G_e$	84.4	-73.5	51.9	90.0	144.7	0.25 1.00 0.00							
$G00B_e = G_e$	85.4	-61.5	19.7	64.6	162.1	0.00 1.00 0.00	$G00B_e = G_e$	85.4	-61.5	19.7	64.6	162.1	0.00 1.00 0.00
$G25B_e$	87.4	-47.7	-8.0	48.4	189.5	0.00 1.00 0.50	$0,5G_e + 0,5N_e$	51.7	-30.7	9.8	32.3	162.1	0.00 0.50 0.00
$G50B_e$	79.7	-32.6	-24.6	40.8	217.0	0.00 1.00 1.00	$0,5G_e + 0,5W_e$	90.4	-30.7	9.8	32.3	162.1	0.50 1.00 0.50
$G75B_e$	71.1	-18.0	-37.5	41.6	244.3	0.00 0.50 1.00							
$B00R_e = B_e$	60.9	1.6	-53.5	53.6	271.7	0.00 0.00 1.00	$B00R_e = B_e$	60.9	1.6	-53.5	53.6	271.7	0.00 0.00 1.00
$B25R_e$	40.5	50.3	-86.6	100.2	300.1	0.50 0.00 1.00	$0,5B_e + 0,5N_e$	39.4	0.8	-26.7	26.8	271.7	0.00 0.00 0.50
$B50R_e$	59.0	89.1	-54.4	104.4	328.6	1.00 0.00 1.00	$0,5B_e + 0,5W_e$	78.1	0.8	-26.7	26.8	271.7	0.50 0.50 1.00
$B75R_e$	54.5	77.1	-4.0	77.2	357.0	1.00 0.00 0.50							
5 step equidistant grey scale: $L^*_e = 18.0, 37.3, 56.7, 76.0, 95.4$							5 step equidistant grey scale: $L^*_e = 18.0, 37.3, 56.7, 76.0, 95.4$						
Code	$L^*_{a,e}$	$a^*_{a,e}$	$b^*_{a,e}$	$C^*_{ab,a,e}$	$h_{ab,e}$	rgb^*_e	Code	$L^*_{a,e}$	$a^*_{a,e}$	$b^*_{a,e}$	$C^*_{ab,a,e}$	$h_{ab,e}$	rgb^*_e
$N000W_e = N_e$	18.0	0.0	0.0	0.0	0.0	0.00 0.00 0.00	$N000W_e = N_e$	18.0	0.0	0.0	0.0	0.0	0.00 0.00 0.00
$N025W_e$	37.3	0.0	0.0	0.0	325.3	0.25 0.25 0.25	$N025W_e$	37.3	0.0	0.0	0.0	325.3	0.25 0.25 0.25
$N050W_e$	56.7	0.0	0.0	0.0	324.8	0.50 0.50 0.50	$N050W_e$	56.7	0.0	0.0	0.0	324.8	0.50 0.50 0.50
$N075W_e$	76.1	0.0	0.0	0.0	323.7	0.75 0.75 0.75	$N075W_e$	76.1	0.0	0.0	0.0	323.7	0.75 0.75 0.75
$N100W_e = W_e$	95.4	0.0	0.0	0.0	0.0	1.00 1.00 1.00	$N100W_e = W_e$	95.4	0.0	0.0	0.0	0.0	1.00 1.00 1.00

SE301-7N, LAB*la3, adapted=not adapted

SE301-8N, LAB*la3, adapted=not adapted

Table 4 shows the coordinates rgb^*_e and the corresponding CIELAB data $(L^*a^*b^*C^*_{ab}h_{ab})_e$ for the standard sRGB colour space with the standard luminance reflection $L_r=2,5\%$ according to ISO 9241-306 in offices. On the left side the data are given for a 16 step elementary hue circle and on the right side for mixture colours between the most chromatic colours and both black N and white W . On both sides a 5 step grey scale is added. For the normalization of the data for white W the standard L^*_W data of the standard offset paper according to ISO/IEC 15775 are used ($Y=88,6$, $L^*=95,4$). In addition for $L_r=2,5\%$ the CIELAB L^* data for black N are equal.

It is very essential to understand the goal of this report which uses the term output linearization. For output linearization a regular double cone forms the colour space with a circular instead of the hexagon basis, and with the coordinates tcu^* to be defined. The next two figures will include some example data and the definitions of this coordinates which can be calculated either from the data rgb^*_e or $(L^*C^*_{ab}h_{ab})_e$.

Table 4 shows the data $L^*_{a,e} = L^*_e$ for the 16 step hue circle. The largest value $L^*_e=91,2$ is reached for $Y25G_e$ and the lowest value $L^*_e=40,5$ for $B25R_e$. The coordinate triangle lightness t^*_e for only the most chromatic colour circle in Table 4 is defined as

$$t^*_e = 0,5 (L^*_e / L^*_{e,M}) \quad (=0,5 \text{ for } L^*_e = L^*_{e,M})$$

For the achromatic colour series the triangle lightness t^*_e is equal to the relative CIELAB lightness L^*

$$t^*_e = (L^* - L^*_N) / (L^*_W - L^*_N)$$

Relative chroma c^* is defined as relative CIELAB chroma C^*_{ab} compared to the maximum chroma $C^*_{ab,M}$

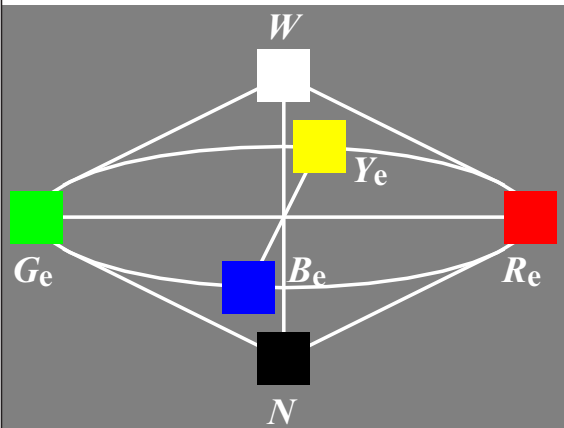
$$c^*_e = C^*_{ab,e} / C^*_{ab,e,M} \quad (=1 \text{ for } C^*_{ab,e} = C^*_{ab,e,M})$$

Therefore the most chromatic colour circle of Table 4 (*left*) has the coordinates $t_e^*=0,5$ and $c_e^*=1$ for any hue.

What is Output Linearization? (For the elementary hues, see CIE R1-47:2009.)
 The colour space of a double cone includes 6 colours. The six colours can be the device-dependent device colours (index d): $(R, Y, G, B, N, W)_d$ or the device-independent elementary colours (index e): $(R, Y, G, B, N, W)_e$. Elementary red appears neither yellowish nor bluish. The hue angle is $h_{ab,e} = 26$.
 For example for the *sRGB* colours according to IEC 61966-2-1 it is valid:
 Device red R_d has the coordinates rgb^*R_d and $LCh^*R_d=(L^*, C^*_{ab}, h_{ab})_{R_d}$
 Elementary red R_e has the coordinates rgb^*R_e and $LCh^*R_e=(L^*, C^*_{ab}, h_{ab})_{R_e}$
 Corresponding data are given in the following for R_d, R_e , and $W=W_d=W_e$

$rgbW = (1\ 1\ 1)_W$
 $LCh^*W=(L^*, C^*_{ab}, h_{ab})_W = (95, 0, -)_W$

$rgb^*R_d = (1\ 0\ 0)_{R_d}$
 $LCh^*R_d = (50, 100, 40)_{R_d}$
 $rgbR_e = (1\ 0\ 0)_{R_e}$
 $LCh^*R_e = (50, 87, 26)_{R_e}$



Output Linearization Method OLM16
 produces for the hue angle $h_{ab,R_e} = 26$
 the CIELAB data $L^*_{R_e} = 50$ and $C^*_{ab,R_e} = 87$.
 These CIELAB data are produced with the device to elementary input data (de)
 $rgb_{de,R_e} = (1\ 0\ 0, 26)_{de,R_e}$
 A calculated table for 360 hue angles includes:

h_{ab}	LCh^*_{de}	rgb_{de}
26	50 87 26	1 0 0,26

Fig. 32 - Answer of the Question: What is Output Linearization?

Fig. 32 tries to answer the question: What is output linearization? With Fig. 31 on page 32 it was possible to understand the transfer from the coordinates $L^*C^*_{ab}h_{ab}$ to the double cone coordinates t_e^* with a circular basis. For a mean grey and the most chromatic colours the value of the triangle lightness is $t_e^*=0,5$. For the circle the relative chroma is $c_e^*=1$. Both the device colours and the elementary colours are located on this circle. However, they have different CIELAB hue angles, for example $h_{ab,R_d} = 40$ and $h_{ab,R_e} = 26$.

Fig. 32 shows that the data rgb_{de} (index de = device to elementary) are needed to produce the output of the elementary hue red R_e with the calculated CIELAB data $LCh^*_{de} = (50, 87, 26)$. Fig. 39 on page 43 includes in the second column the 48 equally spaced device data rgb_d and the corresponding *sRGB* output data LCh^*_d . The output data of the first line are for R_d and agree with the data for R_d in Fig. 32.

In the last column of Fig. 39 on page 43 the table data for the 4 elementary hue angles R_e, Y_e, G_e , and B_e are within the data for the 48 step elementary hue circle. The first line is for the elementary hue angle $h_{ab,R_e} = 26$ and includes in this line the data $rgb_{de} = (1, 0, 0, 26)$ and $LCh^*_{de} = (50, 87, 26)$ of Fig 32.

The next figure will give more example data how to transfer between the different coordinates. The user friendly coordinates are based on the request of ISO TC 159 *Ergonomics - Visual Display Requirements* (compare Fig. 10 on page 15).

At the same time a further step seem to be reached towards a human visual RGB^*_e colour space. This development of the CIE Division 1 was requested by ISO/IEC JTC1/SC28 (Fig. 11 on page 15) and in Section 5.9 on page 17

7.7 Colour in daily life and definition of user friendly relative colour coordinates

Application of colour in daily life or in Colour Information Technology (IT)	
Design, architecture, art, industrial products Measured for CIE standard illuminant D65	Colour Information Technology Measured for CIE illuminants D65 and D50
colour order system; name and coordinates: <i>RAL Design System (CIELAB)</i> $L^*C^*_{ab}h_{ab}$, lightness, chroma, hue angle <i>Munsell Colour System</i> <i>VCH</i> , lightness (Value), Chroma, Hue text <i>Natural Colour System (NCS)</i> ncu^*_e : relative blackness, relative chroma relative elementary hue text	Device system name and coordinates: Printer system (illuminants D50 or D65): cmy_d , content of "cyan, magenta, yellow" Display system (standard illuminant D65): $rgb_d/sRGB_d$, content of "red, green, blue" <i>No user friendly colour coordinates</i> <i>Nearly no connection to colour order systems</i>
Aim: define user friendly connection New: Interpretation of the rgb colour data in the range 0 to 1 as elementary colour data rgb^*_e Linear relations between <i>relative</i> and <i>absolute</i> coordinates $lab^*_d - LAB^*_d$ and $lab^*_e - LAB^*_e$ $rgb^*_d - (L^*a^*b^*C^*_{ab}h_{ab})_d$ and $rgb^*_e - (L^*a^*b^*C^*_{ab}h_{ab})_e$ (CIELAB) $rgb_d - cmy_d, rgb^*_d - cmy^*_d$ and $rgb_e - cmy_e, rgb^*_e - cmy^*_e$ ("1-minus"-relation) $rgb^*_d - nce^*_d, rgb^*_d - ncu^*_d$ and $rgb^*_e - nce^*_e, rgb^*_e - ncu^*_e$ <i>relative</i> coordinates lab^*_e: elementary redness r^*_e , greenness g^*_e , blueness b^*_e , blackness n^*_e chroma c^*_d , elementary hue e^*_e , elementary hue text u^*_e	

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Fig. 33 - Application of colour in daily life or in colour information technology (IT)

Fig. 33 shows colour coordinates used in daily life in the field of colour order systems, for example the CIELAB coordinates $L^*C^*_{ab}h_{ab}$. There are other coordinates used in information technology, for example rgb_d of the $sRGB$ colour space. There seems to be nearly no user friendly colour coordinates in information technology, for example those requested by ISO TC159 *Ergonomics - Visual display requirements*. The coordinates rgb_e of Fig. 33 and the coordinates cmy^*_e used in offset printing seem to fill this gap. Both are connected by the so called 1-Minus-Relation (1MR) which is based on the three equations

$$c^*_e = 1 - r^*_e \quad m^*_e = 1 - g^*_e \quad y^*_e = 1 - b^*_e$$

It is one main goal of this paper to define more user friendly coordinates for image technology and a user friendly connection to CIELAB and other colorimetric systems based on CIE colour measurement and colour appearance.

Usually the colour considered here are presented either on a white display surround or on a white paper. This presentation mode is called surface colour mode in CIE colorimetry. The standard illuminance on the white paper is 500 lux in offices. For the white standard offset paper with the standard reflection of 88,6% this produces the luminance $L = 142 \text{ cd/m}^2$. The same luminance is possible on many modern $sRGB$ or other devices.

There are many real device arrangements where it is hard to answer the question if the output of a test chart is produced by the reflection of light on paper or by the emission of light on a screen. So we may have surface colour mode either by the reflection of light or by the emission of light. Both are in many cases physically (by measurement) and visually equivalent. In addition there are screen technologies which produce the colours by both the emitting of light in a dark environment, and the reflection of light in sunshine

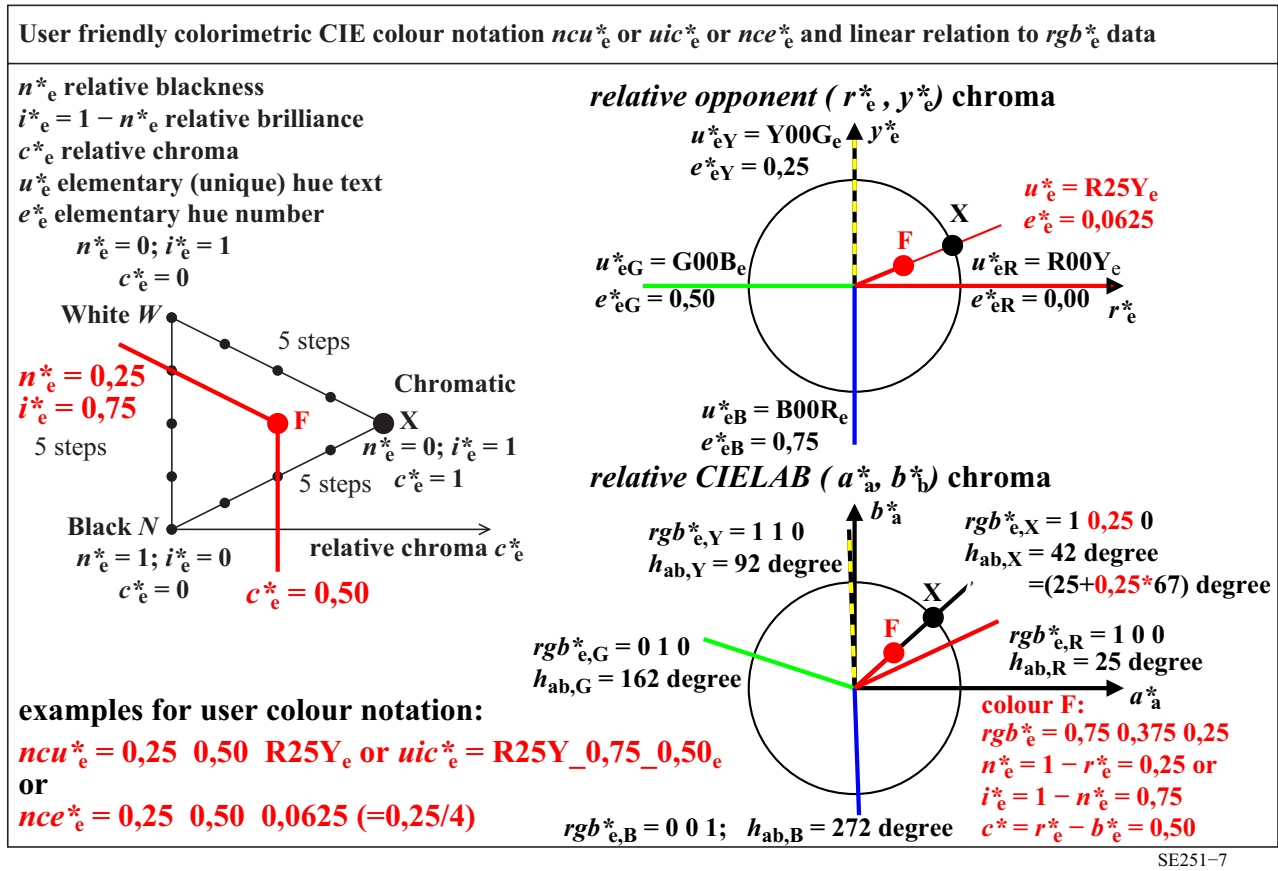


Fig. 34 - User friendly colorimetric CIE colour notations ncu_e^* , uic_e^* or nce_e^*

Fig. 34 shows user friendly colorimetric CIE colour notations ncu_e^* , uic_e^* , and nce_e^* . Some examples show the transfer between the many possible data sets rgb_e^* , ncu_e^* , uic_e^* , and nce_e^* . The CIELAB hue angles for the four elementary colours $RYGB_e$ are given. Instead of the CIELAB coordinates (a_e^* , b_e^*) and the CIELAB hue angle h_{ab} the relative opponent coordinates (r_e^* , y_e^*) and the relative elementary hue e_e^* in the range between 0 to 1 may be used.

On the front cover of the book *Colour and Colour Vision*, see also the next figure, the coordinates rgb_e^* and HIC_e^* are given. These coordinates are shown above and below with some examples.

It is valid

$$I_e^* = 100 i_e^* \text{ and}$$

$$C_e^* = 100 c_e^*$$

Then in Fig. 34 the colour notation

$$uic_e^* = R25Y_0,75_0,50_e$$

changes to (without any comma)

$$HIC_e^* = R25Y_075_050_e$$

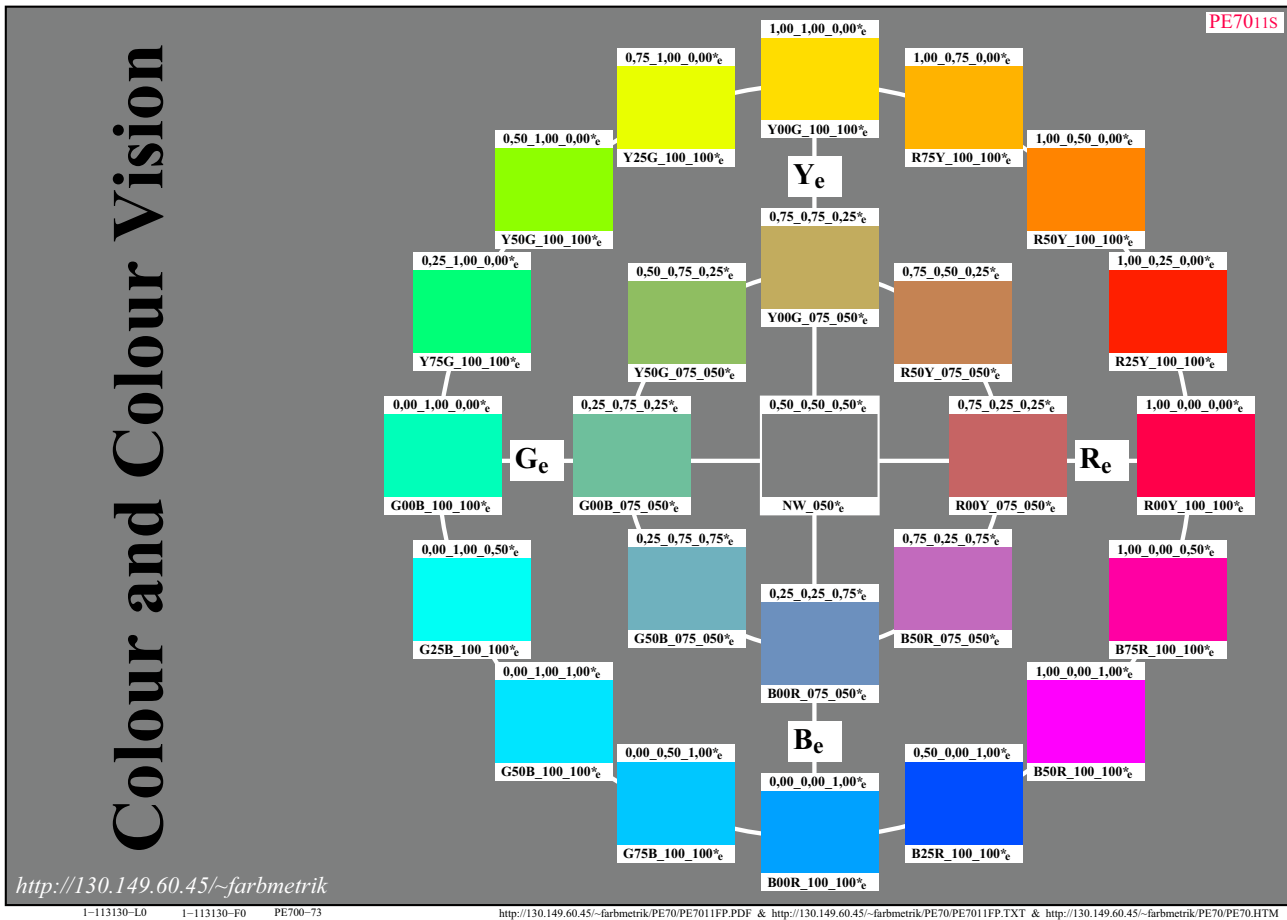


Fig. 35 - Elementary colour circle with 16 samples and colorimetric coordinates rgb^*_e and HIC^*_e

Fig. 35 shows the 16 step elementary colour circle together with the CIE colorimetric coordinates rgb^*_e on the top and HIC^*_e on the bottom. This colour circle is on the top cover of a book and available in offset print. The inner circle has half the CIELAB chroma $C^*_{ab,e}$ of the outer circle. The grey is in CIELAB lightness L^* in the middle between the lightness L^*_N of black N and the lightness L^*_W of white W .

The four elementary colours shall have the CIELAB hue angles $h_{ab,e} = 26, 92, 162, \text{ and } 271$. The visual test shall clearly show that for example $R25Y_e$ appears yellowish red and $B75R_e$ appears bluish red.

Output linearization has been used to produce this colour circle on displays and as offset output.

For the linearized elementary output of the 25 samples and for the standard $sRGB$ display the calculations show an average colour difference $\Delta E^*_{ab,e} = 0,4$ for the outer circle and of $\Delta E^*_{abe} = 0,7$ for the inner circle. The largest difference appears for the sample $Y50G_{075_050_e}$.

The calculated data are available as tables on the page 52 (page 19 of second series) of the file output <http://farbe.li.tu-berlin.de/RE69/RE69L0FP.PDF>

Measurement of the linearized device and elementary output for the 25 samples, and for the offset output, show between the intended and measured colours the colour differences $\Delta E^*_{ab,dd}=2,0$ and $\Delta E^*_{ab,de}=2,4$, see page 19 (series 1 and 2) of the file output <http://farbe.li.tu-berlin.de/RE83/RE83L0FA.PDF>

The file outputs show many additional data and figures, for example the device colours on page 8 and the data rgb_{de} and $(L^*a^*b^*C^*_{ab,a})_e$ for the 360 hue angles $h_{ab,e}$ between zero and 360 in steps of $\Delta h_{ab,e}=1$.

7.8 Device and Elementary colour circles

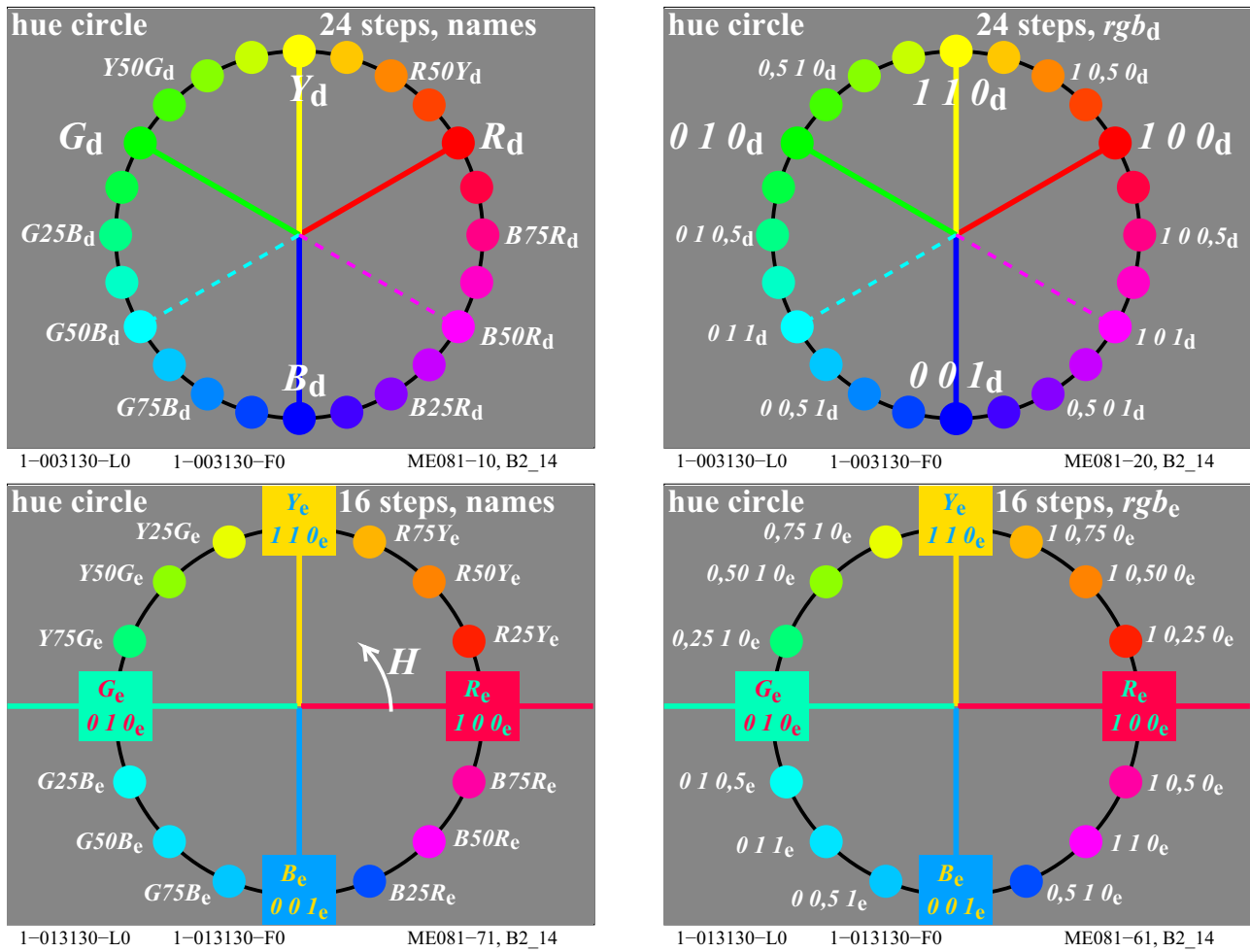


Fig. 36 - Device hue circle with 24 steps and elementary hue circle with 16 steps

Fig. 36 shows two device hue circles with 24 steps on the top. The hue text H_d^* is given on the left side, and the rgb_d data are given on the right side.

Fig. 36 shows two elementary hue circles with 16 steps on the bottom. The hue text H_e^* is given on the left side, and the rgb_e data are given on the right side.

A comparison of the device and elementary hue circle (top and bottom) shows an increase of the hue angle range from 60 to 90 for the sectors R_e to Y_e and Y_e to G_e . This is the lighter side of the colour circle.

At the same time there is a decrease of the hue angle range from 120 to 90 for the ranges between G_d via C_d to B_d , and B_d via M_d to R_d . This is the darker side of the colour circle.

This change is used in the *Natural Colour System NCS*, and is appropriate for applications by at least two reasons:

- The CIELAB chroma of surface colours is for the darker side between G_e via B_e to R_e roughly half compared to the lighter side. Therefore the ratio colour difference/hue angle difference $\Delta E_{ab}^*/\Delta h_{ab}$ is roughly half for the darker side. Therefore it is appropriate to reduce the hue angle range from 120 to 90 for the darker side and to increase the hue angle range from 60 to 90 for the lighter side.

- in many applications, for example house and wall paintings, clothes and advertising, the lighter colour side is much more important compared to the darker colour side. Therefore the elementary (e) hue scaling by rgb_e^* is more appropriate compared to the present device (d) colour scaling by rgb_d^* .

8 Equivalent relative coordinates *rgb* and *cmymk* for digital and analogue colours

8.1 Test chart output with 1080 colours on a displays with different software

By CIE colorimetry and according to the *PostScript Reference Manual* there are many equivalent relative coordinates *rgb* and *cmymk* which describe colours in digital files and for example display colours

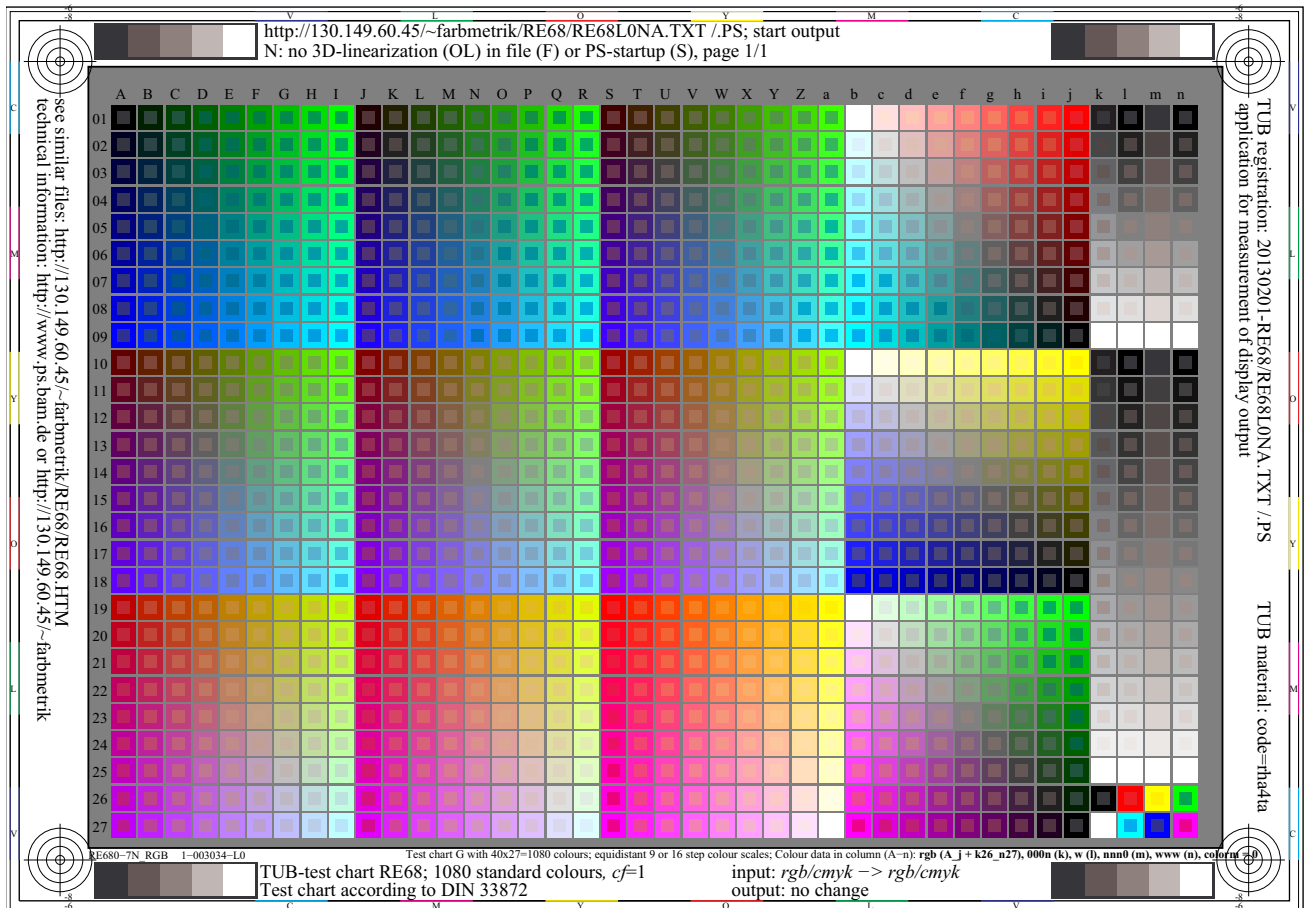


Fig. 37 - TUB RE68 colour test chart with 1080 colours defined by *rgb* and equivalent data

Fig. 37 shows the TUB RE68 colour test chart with 1080 colours. The left 729 (=9x9x9) colours (columns A to a and rows 01 to 27) show a standard grid (Grid G) which is often used for output colour measurement.

The following 243 (=3x9x9) colours (columns b to j, and rows 01 to 27) show opponent colour planes $R_d - C_d$, $Y_d - B_d$, and $G_d - M_d$ with three times the achromatic series in the diagonal.

At least there are 9 step grey scales (columns k to n, rows 01 to 09) and 16 step grey scales (columns k to n, rows 10 to 25) and the six most chromatic device colours and black and white (columns k to n, rows 26 and 27). There are two equivalent definitions for *chromatic* colours by two *PostScript* operators:

rgb setrgbcolor
cmymk setcmymkcolor

The output looks usually different and the difference is device-dependent. The two version are realized in Fig. 37. The large square sample colour are defined with the PS operator *rgb setrgbcolor* and the inner square colours are defined by the PS operator *cmymk setcmymkcolor*.

All values of *rgb* and *cmymk* are in the range 0 to 1, otherwise a negative value is set to zero, and for values larger 1 the value is set to one. There is the so called 1-Minus-Relation (1MR) between *rgb* and *cmymk* which is given by

$$c = 1 - r \quad m = 1 - g \quad y = 1 - b \quad k = n = 1 - w = 0.$$

If the lowest value $w = \min(r, g, b)$ which is called the white value w of the three is larger than zero then the following relations are equivalent:

$$c = 1 - r - w \quad m = 1 - g - w \quad y = 1 - b - w \quad k = n = 1 - w.$$

There are four equivalent definitions for achromatic (grey) colours with $r=g=b=w$ by the PS operators

$w \ w \ w \ \text{setrgbcolor}$
 $n \ n \ n \ 0 \ \text{setcmymcolor}$
 $0 \ 0 \ 0 \ n \ \text{setcmymcolor}$
 $w \ \text{setgray}$

These definitions are used in the four rows k to n of the TUB RE68 test chart. The output looks usually different and is device-dependent.

8.2 Screen shot of the display output with the software Adobe FrameMaker

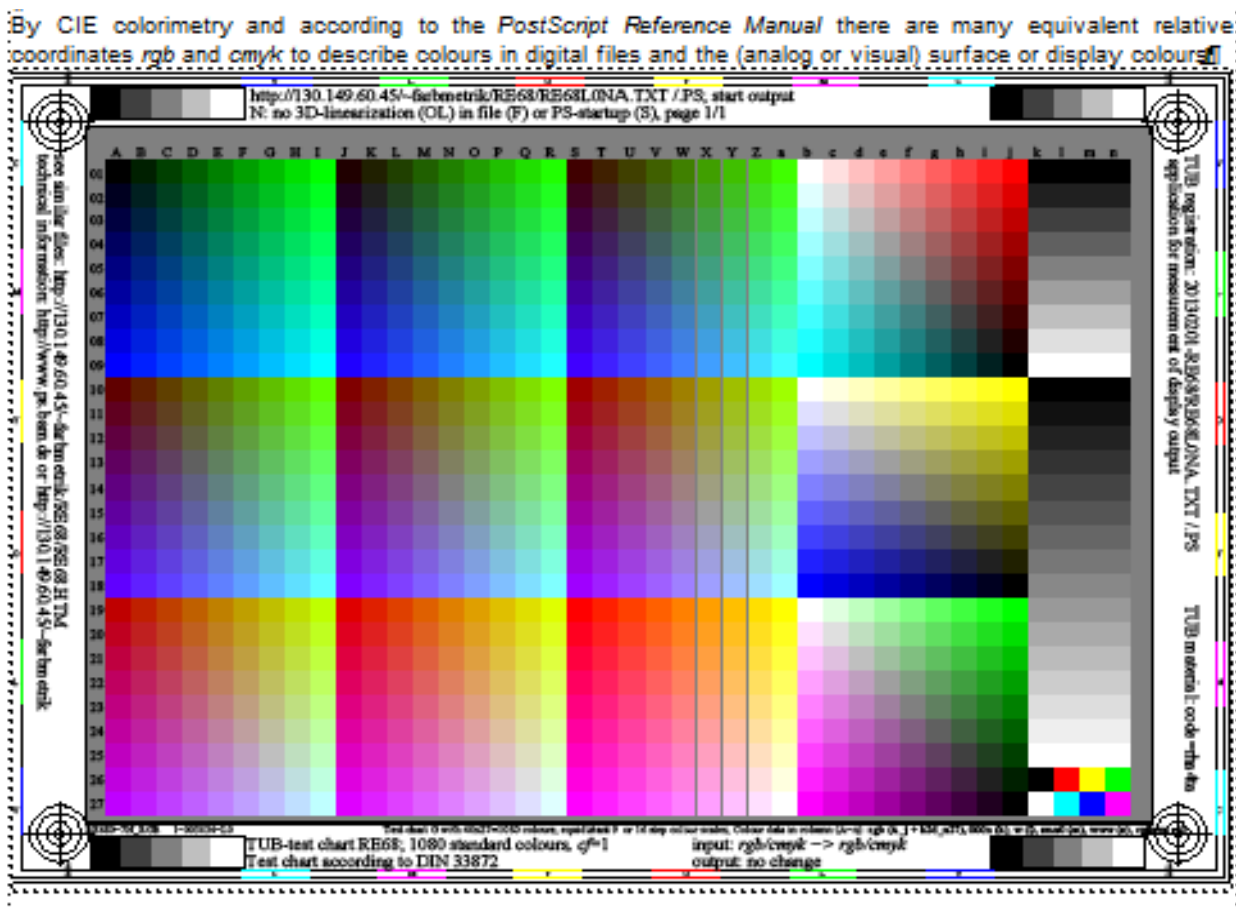


Fig. 38 - Screen shot of the 1080 colour output by the software Adobe Frame Maker

Fig. 38 shows a screen shot of the output of the 1080 standard colours defined by the four PS operators:

- $r \ g \ b \ \text{setrgbcolor}$
- $c \ m \ y \ 0 \ \text{setcmymcolor}$ (always in addition as the inner square with half of the diameter for any colour)
- $0 \ 0 \ 0 \ n \ \text{setcmymcolor}$
- $w \ \text{setgray}$

with corresponding values defined by the 1-Minus-Relation. The output is **equal** with Adobe Frame Maker.

Therefore the display output of Fig. 38 (a screen shot produces a *tiff*- or *pdf*-file) is equal. However, the printer output of Fig. 38 (based on the *PDF*-file created by the software Adobe Frame Maker Version 8) shows up to four different colour outputs for the four equivalent PS operators, similar as the present version of the software Adobe Reader

The software *Adobe Frame Maker* produces for the four PS operators

- **equal output** on the screen as intended for the four equivalent PS operators by CIE colorimetry,
- and a PDF file for later print if requested.

The software *Adobe Reader* produces with the same PDF-file (which includes the four PS-operators)

- **a different device-dependent output on the screen and in print** for the four equivalent PS operators.

It is obvious that a device-independent standard of ISO, IEC or the CIE is needed. At present many of the devices produce for values around $cm\dot{y}_d = (0,45 \ 0,32 \ 0,32)$ a mean grey and **not** for $cm\dot{y}_e = cm\dot{y}_d = (0,5 \ 0,5 \ 0,5)$. There is a historic basis for this strange $cm\dot{y}_d$ values. A special offset process has produced for the values $cm\dot{y}_d = (0,45 \ 0,32 \ 0,32)$ a mean grey. However, by many reasons grey shall now be produced by the black colorant N (K) only, if the device has a black colorant (and for example the three additional colours CMY).

Note: The software *Preview* of the *Mac* operating system OSX up to Version 10.2 includes the 1-Minus-Relation and has produced equal colour output for equivalent colour definitions. Since Version 10.3 the output is different.

Note: In addition the software *Preview* of the *Mac* operating system OSX changes any PS file to a PDF file by a double click on the PS file. Therefore output linearization is possible with the software *Preview* of the *Mac* operating system OSX without additional software. For this purpose usually the software *Adobe Distiller* on a *Mac* or on a Windows operating system is used.

Table 5 - Equivalent PS operators for grey colours by CIE colorimetry and PostScript

5 steps of grey series black – white ($N_d - W_d$)	Colour space, colour space coordinates and PostScript operator calculations according to ISO/IEC 15775:1999-12											
Linear mixture between black and white in CIELAB colour space	<i>relative</i> CIELAB											
	lab^*w_d	$lab^*000n_d=000n_d$				$lab^*cm\dot{y}0_d=cm\dot{y}0_d$				$lab^*rgb_d=rgb_d$		
	<i>setgray</i>	$000n_d$ <i>setcmykcolor</i>				$cm\dot{y}0_d$ <i>setcmykcolor</i>				rgb_d <i>setrgbcOLOR</i>		
$1,00N_d+0,00W_d$ (Black N_d)	0,00	0,00	0,00	0,00	1,00	1,00	1,00	1,00	0,00	0,00	0,00	0,00
$0,75N_d+0,25W_d$	0,25	0,00	0,00	0,00	0,75	0,75	0,75	0,75	0,00	0,25	0,25	0,25
$0,50N_d+0,50W_d$	0,50	0,00	0,00	0,00	0,50	0,50	0,50	0,50	0,00	0,50	0,50	0,50
$0,25N_d+0,75W_d$	0,75	0,00	0,00	0,00	0,25	0,25	0,25	0,25	0,00	0,75	0,75	0,75
$0,00N_d+1,00W_d$ (white W_d)	1,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,00	1,00	1,00

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Table 6 - Equivalent PS operators for cyan blue colours C by CIE colorimetry and PostScript

5 steps of colour series cyan blue – white ($C_d - W_d$)	Colour space, colour space coordinates and PostScript operator calculations according to ISO/IEC 15775:1999-12											
Linear mixture between cyan blue and white in CIELAB colour space	<i>Standard</i> CIELAB				<i>relative</i> CIELAB				<i>relative</i> CIELAB			
	$LAB^*LAB_d = LAB_d$				$lab^*cm\dot{y}0_d = cm\dot{y}0_d$				$lab^*rgb_d = rgb_d$			
	LAB_d <i>setcolor</i>				$cm\dot{y}0_d$ <i>setcmykcolor</i>				rgb_d <i>setrgbcOLOR</i>			
$1,00C_d+0,00W_d$ (cyan blue C_d)	58,62	-30,62	-42,74		1,00	0,00	0,00	0,00	0,00	1,00	1,00	1,00
$0,75C_d+0,25W_d$	67,82	-23,21	-30,86		0,75	0,00	0,00	0,00	0,00	0,25	1,00	1,00
$0,50C_d+0,50W_d$	77,02	-15,80	-18,98		0,50	0,00	0,00	0,00	0,00	0,50	1,00	1,00
$0,25C_d+0,75W_d$	86,21	-8,39	-7,11		0,25	0,00	0,00	0,00	0,00	0,75	1,00	1,00
$0,00C_d+1,00W_d$ (white W_d)	95,41	-0,98	4,76		0,00	0,00	0,00	0,00	0,00	1,00	1,00	1,00

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Table 5 and Table 6 show equivalent PS operators for grey colour series between black N and white W , and for a 5 step colour series between cyan blue C_d and white W . The output with the four standard PS operators shall be the same by CIE colorimetry and the *PostScript* programming language, see *PostScript Reference Manual*.

8.3 PostScript Frame File code with output linearization method (FF_LM)

Table 7 - Frame File Postscript code (FF_PS) with three loops

<p>Frame File PostScript Code (FF_PS) with three loops (important parts) <i>and line 05 (%line 139) to include different transfer PS codes and line 20 (%line 239) to include the PS code of an ISO or DIN test file</i></p> <pre> 01 %!PS-Adobe-3.0 EPSF-3.0 SE34LMFF.PS 20110801 02 %%BoundingBox: 0 0 842 595 03 04 %line169 %BEG INCLUDE TRANSFER PS CODES 05 06 %END INCLUDE TRANSFERS PS CODES 07 %%EndProlog 08 gsave 09 10 colorm10f 1 colorm20f {/colormf exch def %colorm10f,colorm20f 11 gsave 12 13 xcolor10f 1 xcolor20f {/xcolorf exch def %xcolor10f,xcolor20f 14 gsave 15 16 xchart10f 1 xchart20f {/xchartf exch def %xchart10f,xchart20f 17 gsave 18 19 %line 239 %BEG INCLUDE TEST FILE PS CODE 20 21 %END INCLUDE TEST FILE PS CODE 22 23 68 MM 1.5 MM moveto 24 (http://130.149.60.45/~farbmetrik/SE34/SE34LMFF.PDF) showde 25 26 showpage 27 grestore 28 29 } for %end for xchartf=xchart10f,xchart20f 30 grestore 31 } for %end for xcolorf=xcolor10f,xcolor20f 32 grestore 34 } for %end for colormf=colorm10f,colorm20f 35 %%Trailer </pre> <p>Remarks:</p> <p>The outer loop 10 to 34 is without and with a Linearization Method <i>colormf=0 or 1 without and with Frame File Linearization Method (FF_LM)</i></p> <p>The middle loop 13 to 31 is for the amount of Room Reflections <i>xcolorf=0 to 7 for 8 display luminance reflections</i></p> <p>The inner loop 16 to 29 is for the amount of ISO test pages <i>xchartf=0 to 11 for 1 to 12 ISO and DIN test file pages</i></p> <p>Inclusion of TRANSFER PS CODE, for example 1MR, DEH, at line 05 Inclusion of TEST FILE PS CODE, for example ME16 of ISO 9241-306</p>

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Table 7 shows an example PS code with three loops. A similar code is used to produce for example the output of many pages, see the file PS text (9 300 lines!)
<http://farbe.li.tu-berlin.de/RE69/RE69L0FP.TXT>

If one changes the extension from ".TXT" to ".PS" then for example the software *Mac Preview* produces a PDF file with 64 pages within a minute. This file includes according to line 5 of Fig. 23 the 1-Minus-Relation and calculates 1080 measurement data from the *rgb* data according to IEC 61966-2-1. This produces a table with a cloud of 729 rgb_d and corresponding $(L^*a^*b^*C^*_{ab}h_{ab})_d$ data. The CIELAB data fill a double cone with the $L^*C^*_{ab}$ data of a 48 step colour circle as basis.

On the pages 20 to 32 (first series) for the 1080 colours of the standard display the above file shows the tables $rgb^*_d - LCh^*_d$ (intended relation) and the tables $rgb^*_d - LCh^*_d$ (relation with dash-star coordinates for output linearization). The following two coordinates are identical: $rgb^*_d = rgb_{dd}$ (device to device output). The colour difference $\Delta E^*_{ab,d}$ between intended and real output is the difference between LCh^*_d and $LCh^*_{d'}$.

On the pages 42 to 64 (second series) for the 1080 colours of the standard display the above file shows the tables $rgb^*_e - LCh^*_e$ (intended relation) and the tables $rgb^*_e - LCh^*_e$ (relation with dash-star coordinates for output linearization). The following two coordinates are identical: $rgb^*_e = rgb_{de}$ (device to elementary output). The colour difference $\Delta E^*_{ab,e}$ between intended and real output is the difference between LCh^*_e and $LCh^*_{e'}$.

Both tables are listed in Fig. 30 on page 32 (device output) and Fig. 31 on page 32 (elementary output).

8.4 Hue and colour output and accuracy for the sRGB display colours

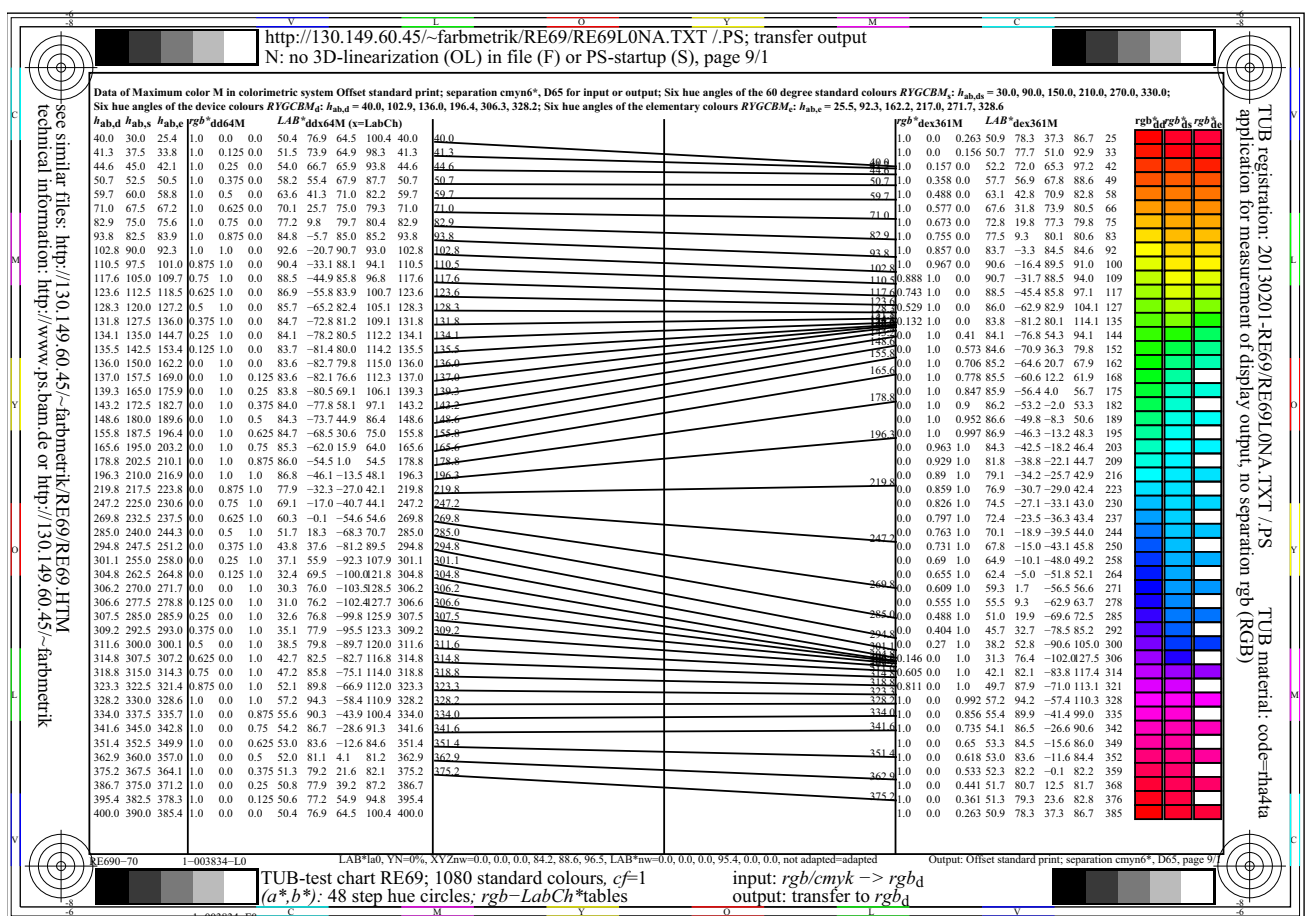


Fig. 39 - *rgb* and CIELAB data of a 48 step hue circle for the device and elementary sRGB colours

Fig. 39 shows *rgb* and CIELAB data of a 48 step hue circle for the device and elementary colours. For the *sRGB* display colours near the hue angle $h_{ab,e}=306$ a large range of rgb_d data with a hue angle range of 30 degree ($h_{ab,d}=300$ to $h_{ab,d}=330$) produce only a small change of the visual rgb_e data with a hue angle range of only 10 degree ($h_{ab,e}=300$ to $h_{ab,e}=310$).

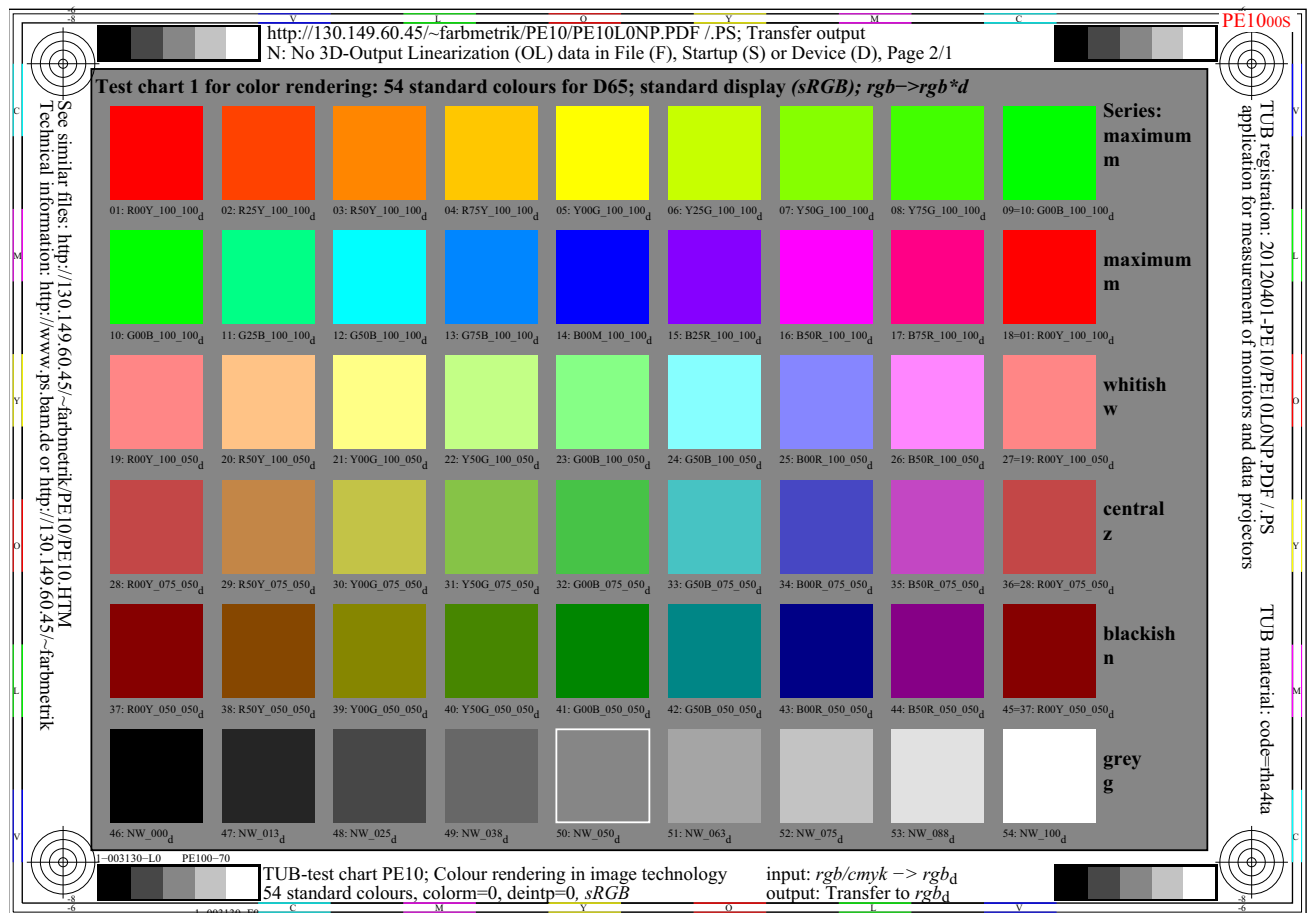


Fig. 40 - HIC^*_d data of the TUB test chart PE10 for colour rendering with a 16 step device hue circle

Fig. 40 shows the HIC^*_d data of the TUB test chart PE10 for colour rendering with a **16 step device hue circle**. In addition there are three 8 step colour circles: whitish, central (greyish), and blackish. Finally there is a 9 step grey scale. The first and last colour of the 16 and 8 step colour circles are the same. This reduces difficulties for visual evaluations of the colour differences between the first and last step.

The following Fig. 41 shows the HIC^*_e data of the TUB test chart PE10 for colour rendering with a **16 step elementary hue circle**. The colour samples in the first two lines have maximum chroma and create a 16 step colour circle. The colour samples in the following three lines have half of the maximum chroma and create three 8 step colour circles (with high lightness, mean lightness, and low lightness) and a 9 step equally spaced grey scale. With this property the TUB test chart PE10 may be more appropriate for colour rendering applications compared to other test charts with a similar amount of samples.

There are several reasons for this assumption:

1. The hue circle is visually spaced and based on the elementary hues. Any hue change may be evaluated visually without any reference colours.
2. Three additional 8 step hue circles fill the natural colour space.
3. The four hue circle cover the natural lightness of the colours, for example a light yellow and a dark blue.
4. The TUB test chart PE10 for colour rendering includes a 9 step grey scale which is important for images.

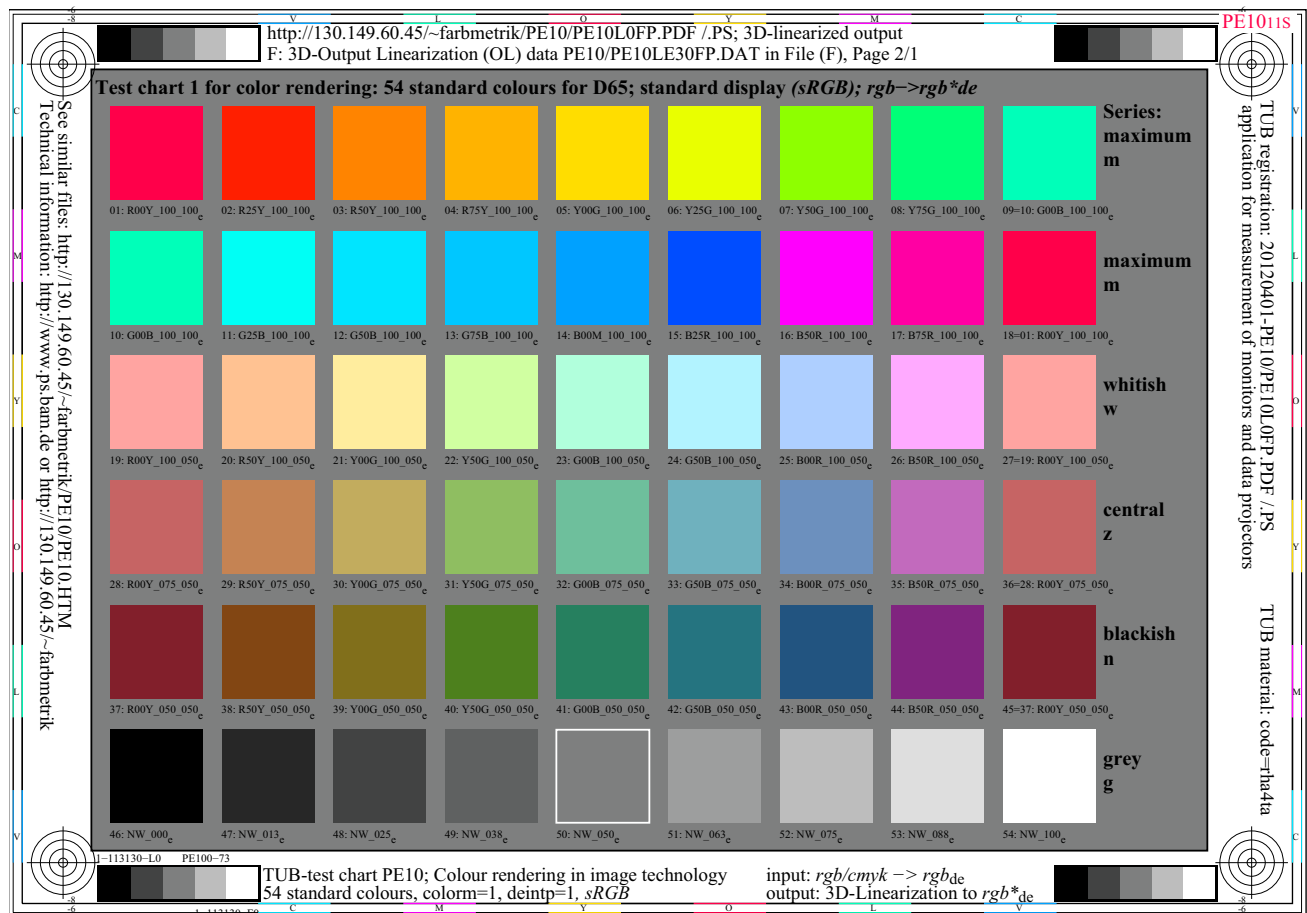


Fig. 41 - HIC^*_e data of the TUB test chart PE10 for colour rendering with a 16 step elementary hue circle
 Fig. 41 shows the HIC^*_e data of the TUB test chart PE10 for colour rendering with a 16 step elementary hue circle.

Table 8 - CIELAB colour differences ΔE^*_{ab} of start and linearized output of the standard sRGB display

Calculation of display output by files and series			Display output transfer and linearization of sRGB display according to IEC 61966-2-1				
files, colour amount, page, and serie			test colours	colour difference ΔE^*_{ab} (real-intended)			
file and output code (d, e, dd, de)	colours	page, serie	content	hue transfer		3D-linearization	
				d (de=0)	e (de=1)	dd (de=0)	de (de=1)
RE69L0NP.PDF (output of d, e) and	57	18, 1 and 2	hue circle	0,9	26,3	0,1	0,4
	53	19, 1 and 2	test chart 1	6,5	21,3	0,8	0,8
	81	28, 1 and 2	plane $R-C$	7,3	11,2	0,8	0,7
RE69L0FP.PDF (output of dd, de)	81	29, 1 and 2	plane $Y-B$	8,7	27,1	0,7	0,6
	81	30, 1 and 2	plane $G-M$	11,4	22,0	0,6	0,6

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Table 8 shows the CIELAB colour differences between real and intended colours on a sRGB display for no room light reflection on the display ($L_r=0$). For the 48 steps of a hue circle and the 9 grey steps (57 colours) the CIELAB colour difference is $\Delta E^*_{ab,d} = 0,9$. However, the colour difference is $\Delta E^*_{ab,e} = 26,3$ for the start output of the sRGB elementary colours. These differences are reduced to $\Delta E^*_{ab,dd} = 0,1$ and $\Delta E^*_{ab,de} = 0,4$ by output linearization. The remaining difference is therefore below threshold ($\Delta E^*_{ab}=1$). This is similar for the colours of the test chart PE10 for colour rendering. This test chart is shown in Fig. 40 on page 44 for the intended device

colour output and in Fig. 41 for the intended elementary colour output. Again the mean difference is below threshold and similar for the 81 colours in the hue planes *R-C*, *Y-B*, and *G-M* for the two intentions device colour and elementary colour output.

Compared to other output methods the accuracy is by a factor 10 higher, for example compared to ICC colour management according to ISO 15076-1. This difference occurs if the triangle encoding of this paper is compared with the usual 8 bit CIELAB encoding of ICC-colour management, compare the encoding space in a hue triangle in Fig. 14 on page 18.

According to CIE 168 the *sRGB* colour space fills only 20% of the CIELAB coding space.

The standard *sRGB* space according to ISO 9241-306 with 2,5% room light reflection fills half of the space defined by no room light reflection.

Therefore the coding of the for example 729 measurement data between -128 to 127 (8 bit) for CIELAB a^* and b^* and between 0 and 100 for L^* produces at least coding errors of $\Delta E^*_{ab}=1$. These errors are here avoided, because only the $L^*a^*b^*$ data of a 48 step colour circle are used with for example two digits after the comma for the three CIELAB data $L^*a^*b^*$.

Similar tables compared to Table 8 on page 45 with the colour differences ΔE^*_{ab} are available

- for different room light reflections on the screen or
- for different *CMY* and *CMYK* printers with only *rgb* input or
- for different *CMY* and *CMYK* printers with the additional *cmk* input or
- for *CMYK* offset print with *rgb* or *cymk* input.

In these cases the standard deviation of the general colour output plays a larger role and increases the colour differences ΔE^*_{ab} between the intended and the real output.

For example the 6 basic colours *RYGCBM* are 3fold on the test chart with the 1080 colours (Fig. 3 on page 10).

A digital photo printer with *rgb* or *cmk0* input data has shown a standard deviation near $\Delta E^*_{ab}=0,5$.

For two laser printers no. 1 and 2, and offset print, all with *cmk* input data in the file, the output colour depends often on the colours of the neighborhood and is between $\Delta E^*_{ab}=2$ and 5.

In addition for the laser printer no. 2 with only *rgb* data in the file the very irregular start output produces problems and irregular output, see Fig. 49 on page 54.

Therefore, and in addition, the colour differences ΔE^*_{ab} are dependent on device specific properties of printers and offset print.

The accuracy of the proposed method OLM16 for output linearization of this paper is given in Table 8 and is below

$\Delta E^*_{ab} \leq 1$. This is in the range of the visual threshold.

9.2 Definition for minimum colour difference reproduction between displays and printers

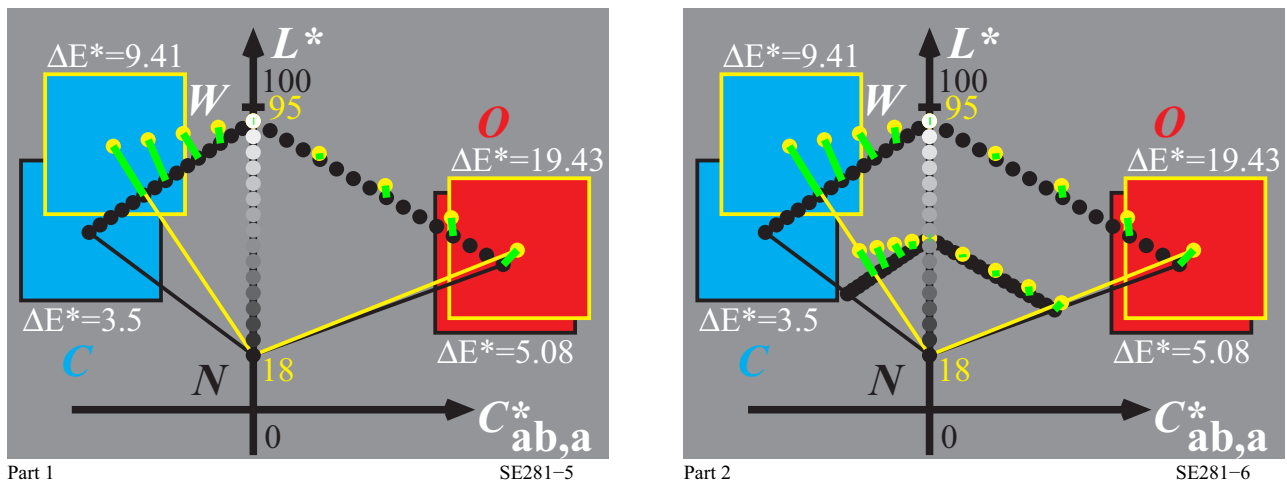


Fig. 43 - “Minimum colour difference” transfer between linearized display and printer output

Fig. 43 shows the “Minimum colour difference” transfer between linearized display and printer output. Again the 16 steps of the display (yellow balls) and printer (black balls) are shown. Both transfers (left and right) show a shift of the light colours. In addition the darker colour series is shifted on the right side. The minimum colour difference ΔE^*_{ab} according to CIELAB is only reached on the left side. However, the “standard” ISO 15076-1 (ICC colour management) allows many proprietary solutions, which many companies use to a high degree. They are all called colour management according to ISO 15076-1.

In Fig. 43 for both cases of the colour transfer any colour of the yellow triangle is shifted to a colour of the black triangle. Therefore any colour on the display transfers to a reproducible colour on the printer.

However, the whole triangle gamut of the printer is **not** used, only about 70% for the cyan hue. Many colours which differ on the display are equal on the printer. There is loss of colour information for about 20% of the light display colours for the cyan hue. However, up to now many printer companies seem to favor this kind of reproduction. This method is especially used for the so called *RGB* printers with the usual *rgb* input. These printers need *rgb* data in the files. In the case that *cmymk* data are in the file, there at first a device-dependent and software-dependent change to *rgb* values is used. However within the printer or the driver again a change to *cmymk* values is necessary.

In addition some companies produce the output according to company specific *user wishes or preferences*. Usually companies produce lighter colours compared to the *colorimetric affine match*. An example of an *RGB* printer will be shown later in Fig. 48 on page 53.

The different device colours, the “Minimum colour difference” criteria, and the company specific consider of user wishes produce colours which are not distinguishable on the printer output for many very different colours on the screen. This may be called a colour chaos in the colour reproduction area. Some colour differences of the 16 step series on the display with a value $\Delta E^*_{ab} = 5$ are in this case reduced below the colour threshold with $\Delta E^*_{ab} = 1$ and are not distinguishable. There is a large variety of outputs on the market.

However, for the *affine* transfer there is only one solution. The output properties can be evaluated visually for the display or printer output without any measurement equipment, for example with the test charts of DIN 33872-2 to -6, see

<http://farbe.li.tu-berlin.de/33872E.html>

For the 16 step series the value $\Delta E^*_{ab} = 5$ may vary depending on the display or the printer. Fig. 42 on page 47 shows for the series between white and cyan and between white and red differences between $\Delta E^*_{ab} = 2,51$ and 5,18. (right). Therefore all the steps are visible ($\Delta E^*_{ab} > 1$) on both devices and there is no loss of colour difference information.

10 Start and linearized output of printers with *CMY* and *CMYK* device colours

10.1 Linearization of a *CMY* photo printer with *rgb* data in the file

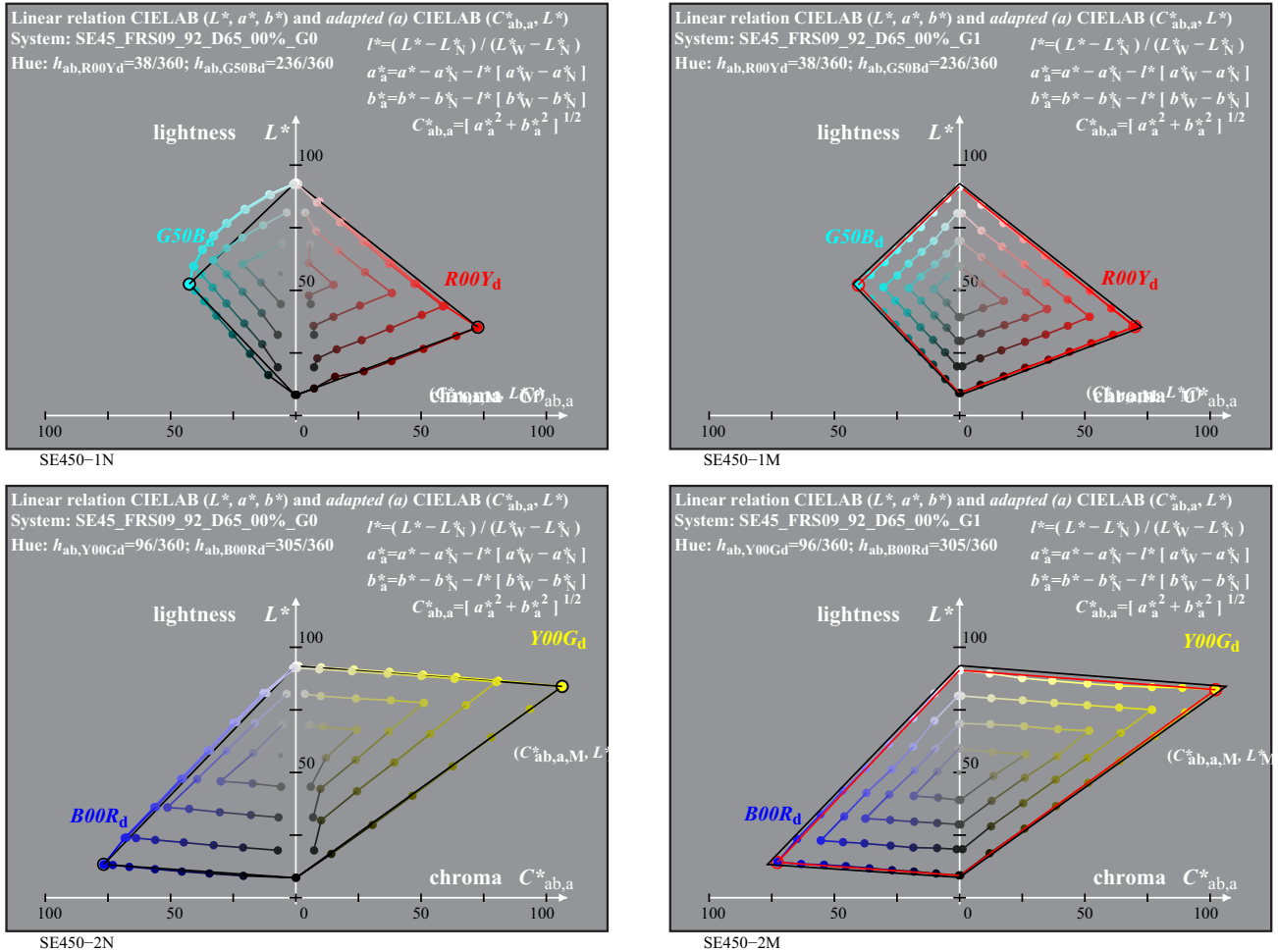


Fig. 44 - Start and linearized output in CIELAB hue planes $R_d - C_d$, and $Y_d - B_d$

Fig. 44 and many of the following figures show the start output on the left side and the linearized output on the right side. The examples in Fig. 44 and Fig. 45 on page 50 are for a photo printer which holds the 1-Minus-Relation. Both PS operator *rgb setrgbcolor* and *1-r 1-g 1-b 0 setcmykcolor* produce the same output.

The 1-Minus-Relation is for example valid for *Adobe FrameMaker 8 on Windows*. It is for example usually valid for the operating system *Unix*. All the PS figures on the server

<http://farbe.li.tu-berlin.de>

have been developed with the software *Decwrite* on the operating system *Compac VMS* which holds the colorimetric 1-Minus-Relation. The 1-Minus-Relation was valid for the software *Preview* on the operating system *Mac OSX* until version 10.2 (about 2004). At that time the colour output switched to a colour output which is similar to the output of the software *Adobe Reader*. The output of this software differs according to the version. A larger change in the gamma function appeared between *Adobe Reader*, Version 3 and 4 (about 2004).

In Fig. 44 the start output (*left*) of the photo printer produces a colorimetric tint (ΔE^*_{ab} about 5) for many grey steps. The grey axis is defined by the CIELAB data (a^*_W, b^*_W) of white and (a^*_N, b^*_N) of black and differs only slightly from the intended zero values for all these data.

In Fig. 44 the linearized output of the photo printer produces a regular spacing within the hue planes $R_d - C_d$ and $Y_d - B_d$. The grey scale is now equally spaced in L^* . The grey scale is now achromatic and in that

case printed by the CMY photo colorants. All the plots of Fig. 27 are based on real measurements of the start and linearized output. The colour difference between the intended and real colour is near the value $\Delta E^*_{ab}=0,5$.

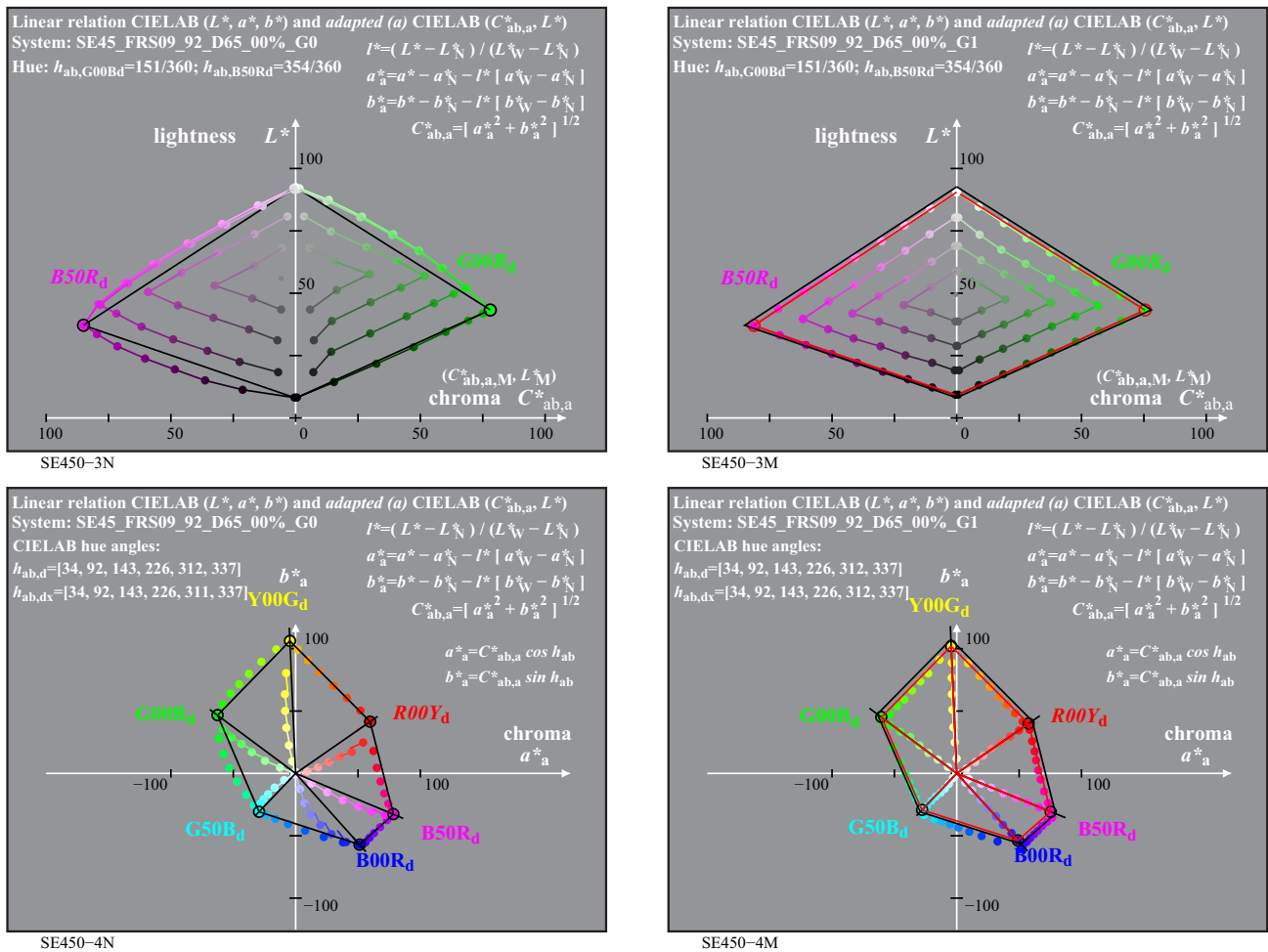


Fig. 45 - Start and linearized output in CIELAB hue planes $G_d - M_d$, and for hue circle

Fig. 45 shows again the start output on the left side and the linearized output on the right side for the photo printer. The two top figures for the hue plane $G_d - M_d$ show similar properties compared to Fig. 44 on page 49.

The two bottom figures show the six series between white and the most chromatic colours in a CIELAB (a^* , b^*) diagram. The start output shows some change of the CIELAB hue angle h_{ab} . The linearized output shows the samples on straight lines as intended.

NOTE: In Fig. 45 it was intended to produce the colours on a hexagon, for examples on a line between Y_d and G_d in the diagram (a^* , b^*). The present software version OLM16 uses the maximum chroma for 48 hue angles. The older software version OLM04 of ISO/IEC TR 19797:2004 uses the maximum chroma for 06 hue angles. In this case the 6 device colours and the colours on the black connection lines are used as reference for the colours of maximum chroma. For the OLM16 the chroma is between Y_d and G_d larger compared to the black connecting line between Y_d and G_d .

10.2 Linearization of a *CYMK* laser printer no. 1 with two transfers *rgb* - *cmlyk* in the file

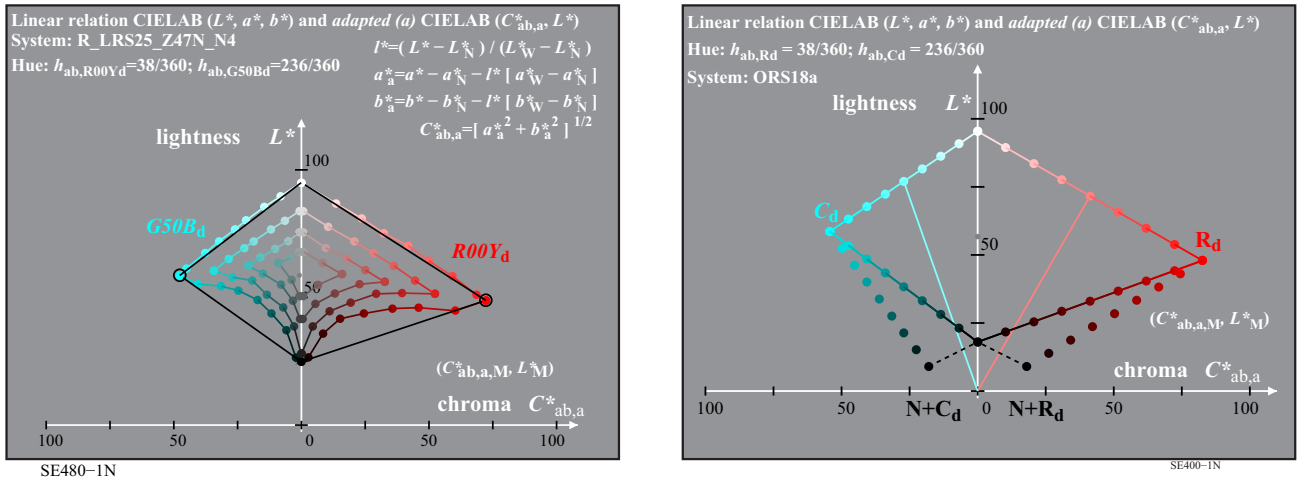


Fig. 46 - Two start outputs with the separations *cmyn4 and *cmyn5** on a *CMYK* laser printer**

Fig. 46 shows start outputs with the separation methods *cmyn4** and *cmyn5** for a *CMYK* laser printer with *cmlyk* data in the file. There are many method to transfer *rgb* data in the file to *cmlyk* data in the file. CIE colorimetry and PostScript define the 1-Minus-Relation which transfers the PS operator *r g b setrgbcolor* to the PS operator *c m y k setcmlykcolor*.

For the most chromatic colours it is valid $c = 1-r$, $m = 1-g$, $y = 1-b$, and $k=0$.

For all colours it is valid $w = \min(r g b)$, $c = 1-r-w$, $m = 1-g-w$, $y = 1-b-w$, and $k = w$.

The value w is subtracted from the original three values *cmly*. This method is called undercolor removal and has the property that for all grey colours with $r=g=b$ only black is used for the print. Therefore the printed black (for example in colour figures) is always printed only by the black colorant. This reduces the printing costs compared to the *overprint* of three colorants to produce black.

However, Fig. 29 (*left*) shows that many dark chromatic colours can not be not printed. This unwanted case is avoided in Fig. 29 (*right*). Here different amounts of black between 0 and 100% are printed on top of R_d or C_d . However this output produces a black with a reddish tint or cyan tint. Both colours have a lightness lower compared to the lightness of the black colorant and in addition there is a gap near black N produced by only the black colorant.

For the intention to produce all the colours up to the triangle line between black N (only) and R_d or C_d , there is the following solution. For example if 50% cyan and 50% black are overprinted the result is a whitish cyan. The explanation is as follows. If 50% cyan is printed then 50% of the white paper is now cyan. If in addition 50% of black is printed, then 25% is cyan, 25% is black, 25% is the overprint cyan and black, and 25% is still white. The result is a shift of the output colour $0,5(C_d+N_d)$ towards the white point, compare Fig. 46 (*left*).

For example this shift towards white can be avoided if for example 50% cyan and 75% black are overprinted which reduces the shift towards white. According to Fig. 46 some shift towards white is allowed because the colours are below the line R_d-N or C_d-N for complete overprint.

Instead of the colour separation *cmyn4** defined by the 1-Minus-Relation the colour separations called *cmyn5** and *cmyn6** have been used for output separation in this report. The lines R_d-N and C_d-N are reached by the start output of the fixed transfer *rgb* -> *cmyn5** of this laser printer with a *cmlyk* input channel.

The start and linearized output properties of such a printer will be discussed in the following.

10.3 Linearization of a *CYMK* laser printer no. 1 with a special transfer *rgb - cmyk* in the file

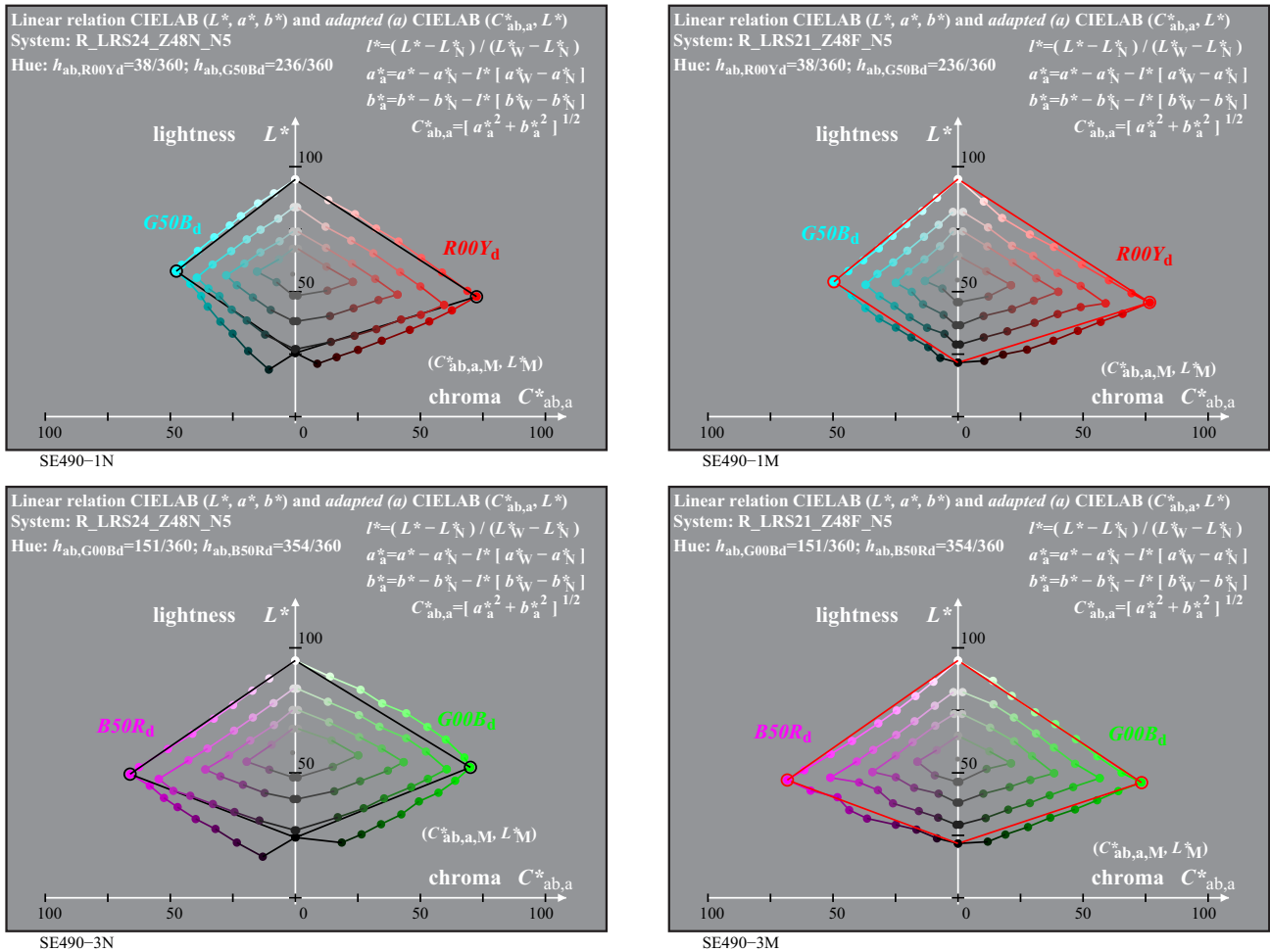


Fig. 47 - Two start and linearized outputs $R_d - C_d$ and $G_d - M_d$ with the separation *cmyk5**

Fig. 47 shows two start and linearized outputs in the hue planes $R_d - C_d$ and $G_d - M_d$ on a *CMYK* laser printer with *cmyk* data in the file.

The *cmyk* data in the file are computed by a fixed separation equation called *cmyk5**. This equation transfers the *rgb* data in the file to *cmyk* data, and for example all data with $r = g = b$ to only a $k = w = 1 - k$ value.

This equation *cmyk5** is different compared to the separation *cmyk4** which can not produce the output colours on the line $R_d - N$ and $C_d - N$, compare Fig. 46 on page 51 (left).

The output shows a reasonable spacing. However there is some more scatter of the results (right) compared to the photo printer in Fig. 44 on page 49 and Fig. 45 on page 50.

In addition the lightness L^* of black is near $L^*=24$ instead of $L^*=9$ for the photo printer.

10.4 Linearization of a CMYK laser printer no. 2 with only rgb data in the file

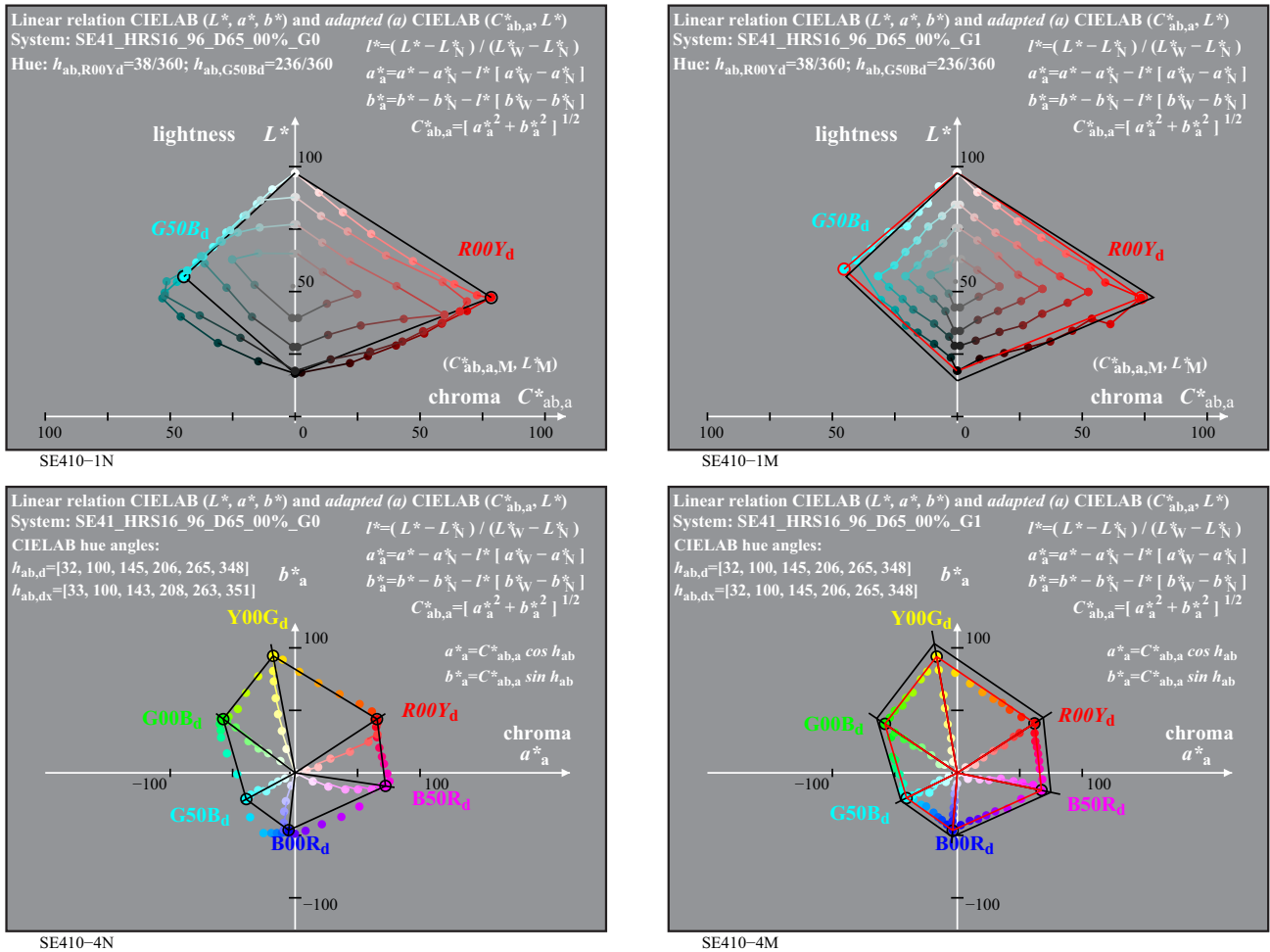


Fig. 48 - Start and linearized output in hue plane $R_d - C_d$ and in CIELAB diagram (a_a^*, b_a^*)

Fig. 48 shows the start and linearized output of a low cost *PostScript* laser printer of a leading printer company. This *Postscript* printer has two input channels for *rgb* and *cmymk* data in the file.

For equivalent *rgb* and *cmymk* data in the file the output on this PS printer is very different. This is similar for the output of the TUB test chart RE69 with 1080 colours in Fig. 37 on page 39.

Fig. 48 (left) shows an example output, similar to the output of many RGB printers on the market. For many different *rgb* data in the TUB file RE69 with the 1080 colours many output colours appear equal, for example many light cyan colours.

This result may be based on the usual ICC-colour management method which often produce clipping in some colour areas. This property is expected by the *Minimum Colour Difference Method* of Fig. 43 on page 48.

10.5 Hue transfer of a CMYK laser printer no. 2 with only *rgb* data in the file

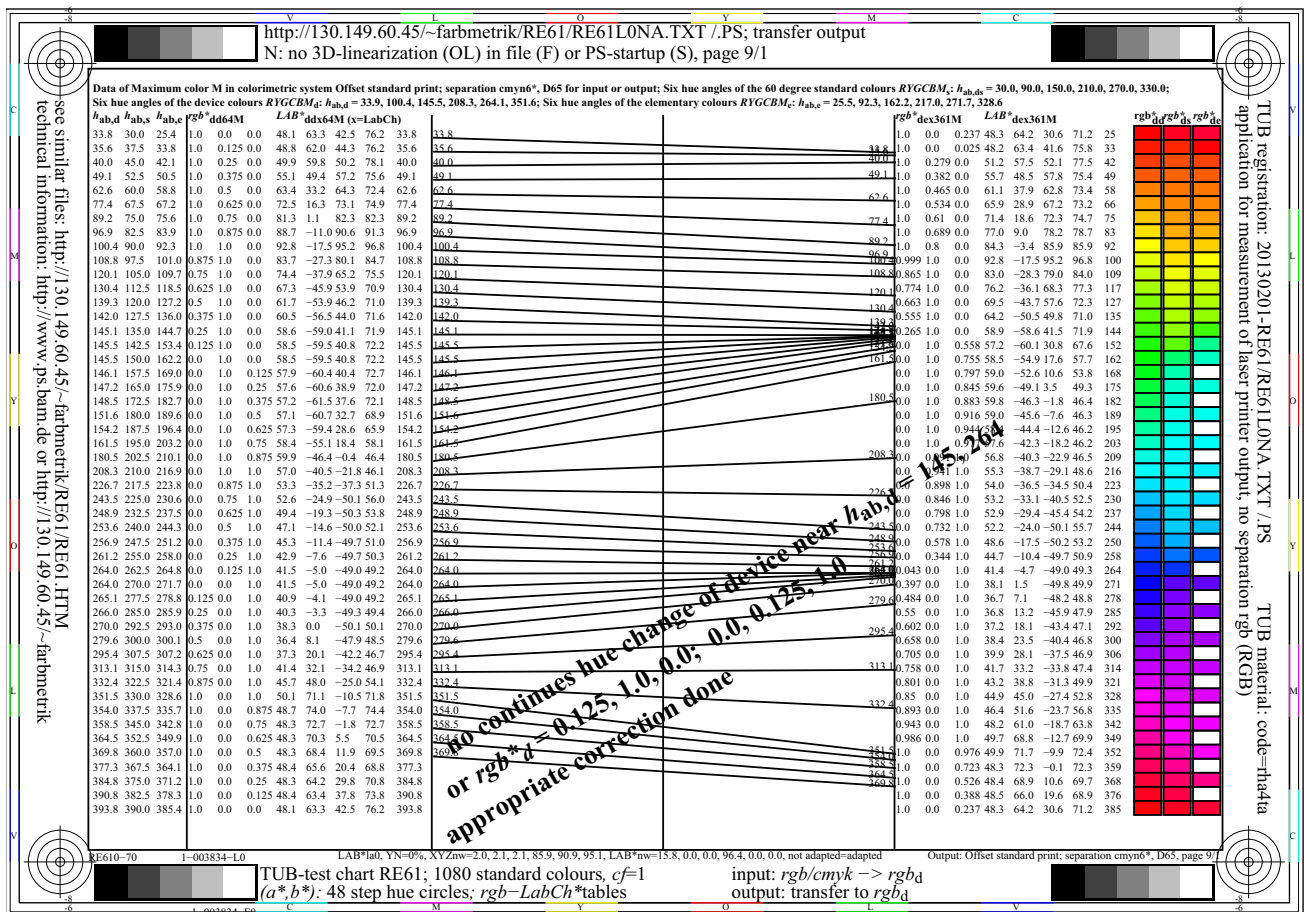


Fig. 49 - *rgb* and CIELAB data of a 48 step hue circle of a laser printer with only *rgb* data in the file

Fig. 49 shows the *rgb*- and CIELAB data for the standard 48 step hue circle of a CMYK laser printer no. 2. Only *rgb* data are used in the file. This is now the common method to describe colours in files, on the desktop, and in the internet. Column 2 includes 48 different *rgb* input values in the file with a continues spacing of eight steps, for example between $rgb_{d,R} = (1\ 0\ 0)_d$ and $rgb_{d,Y} = (1\ 1\ 0)_d$. The 48 steps are distributed in the standard file with the 1080 colours. For the position see for example the page 18 of the file <http://farbe.li.tu-berlin.de/RE69/RE69L0FP.PDF>

In column 2 for any *rgb* data set one of the three *rgb* data has the value 0 and another the value 1. This indicates that the 48 steps produce the maximum (M) chroma which is possible with this printer. Real measurement data in CIELAB of the output are included in column 2. Usually there is a continues change of the CIELAB hue angle for a continues change of the *rgb* data. However, the laser printer 2 shows some hue changes backwards near $rgb_d = (0, 125\ 1\ 0)_d$ and $rgb_d = (0\ 0, 125\ 1)_d$. In addition a large range of *rgb* input values produce nearly the same hue output colours near $h_{ab} = 152$ (roughly near G_e with $h_{ab,e} = 162$), and near $h_{ab} = 264$ (roughly near B_e with $h_{ab,e} = 271$), and near $h_{ab} = 33$ (roughly near R_e with $h_{ab,e} = 26$). Therefore many steps of the output circle look very similar, and especially near the elementary colours R_e , G_e , and B_e .

It is the intention of the OLM16 to produce an equally spaced colour circle output between the four elementary colours *RYGB_e*. The hue angles $h_{ab,e}$ of this circle are known, see the values in third column between $h_{ab,e} = 25$ towards $h_{ab,e} = 385$ ($=25$). The data in column 2 include a continues hue change $h_{ab,d}$ of the device colours and the corresponding rgb_d and $(L^*C^*_{ab})_d$ data. For the $h_{ab,e}$ data listed in column 3 the corresponding rgb_e and $(L^*C^*_{ab})_e$ data are calculated by linear interpolation. Pages 7 to 16 of the file

<http://farbe.li.tu-berlin.de/RE69/RE69L0FP.PDF>

include the corresponding data for $h_{ab,e}$ in the range between 0 and 360 degree, and in steps of 1 degree. This

table allows a fast calculation for any hue angle of any rgb data. The indices dd (= device to device hue) and de (=device to elementary hue) and M (maximum chroma) are used for the rgb and $L^*a^*b^*C^*_{ab}h_{ab}$ data of the two colour circles in column 2 and 3.

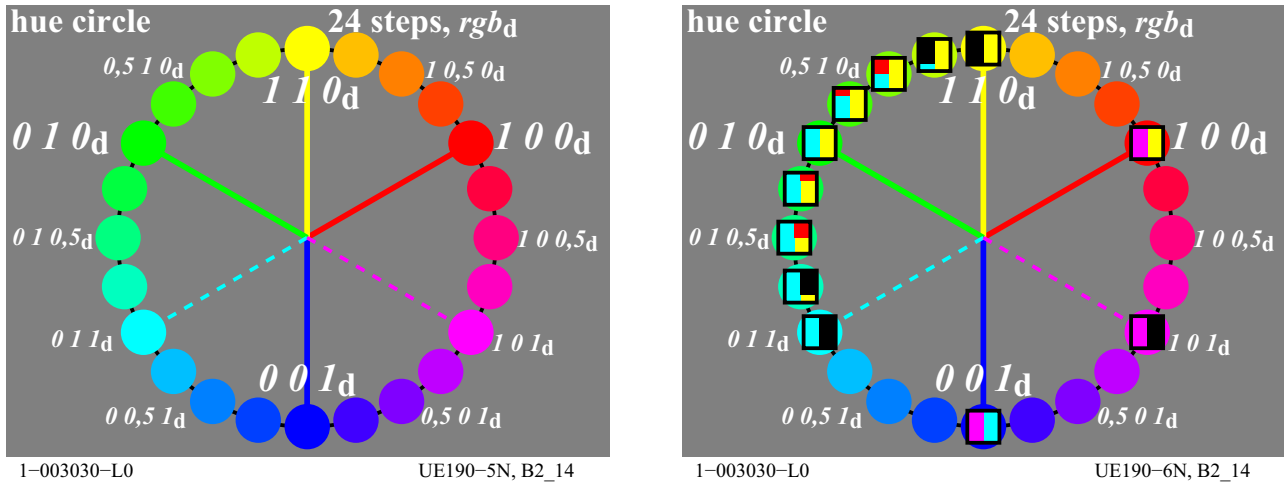


Fig. 50 - Amount of three device colorants CMY for the output of a hue circle

Fig. 50 (left) shows a hue circle produced with rgb_d device data. If the output is steered according to the rgb_d device data, then the three device colorants CMY will be printed directly for the cm_y_d values $(1, 0, 0)_d$, $(0, 1, 0)_d$, and $(0, 0, 1)_d$. According to the 1-Minus-Relation this corresponds to the rgb_d data $(0, 1, 1)_d$, $(1, 0, 1)_d$, and $(1, 1, 0)_d$.

Fig. 50 (right) shows the amount of colorants to produce the different hue steps. For the colours cyan, magenta, and yellow only one colorant is printed on the paper. For the colours red, green and blue two colorants on top of each other are printed on the paper.

According to Fig. 5 on page 12 (hue agreement according to DIN 33872-5) the example printer produces the elementary hues according to an rgb^* device, for example R_e with a hue angle within the range $h_{ab}=272\pm 8$ and not near $h_{ab}=305$ defined by the sRGB standard IEC 61966-2-1.

However, both Fig. 6 on page 12 and Fig. 49 on page 54 shows that three neighbouring hue steps near R_e , G_e , and B_e are not distinguishable.

If in a worse case for example 5 steps are not distinguishable near G_d with $rgb_d = (0, 1, 0)_d$, then the red part within the figure shows the additional amount of colorant needed in the print.

So a user may be disappointed that *three steps are not distinguishable*. In addition the *cost per page will increase*, because the printer produces more overprint colours as visually needed. Both cases happen for the example printer.

The visual output evaluation of the test chart DIN 33872-5 produces this result without any measuring equipment.

If for the same printer an rgb^* device is made according to the OLM16, then the following Fig. 51 on page 56 shows both the intended hue spacing in the output which in addition reduces the cost per page.

Therefore this study shows an example case where an RGB printer of the market, which may disappoint the user by the test result according to DIN 33872-5, is changed to an **rgb^* printer** with the OLM16. Then this and most of the other tests of DIN 33872-X will pass.

10.6 Hue transfer of CMYK laser printer no. 2 with a transfer $rgb \rightarrow cmyk$ data in the file

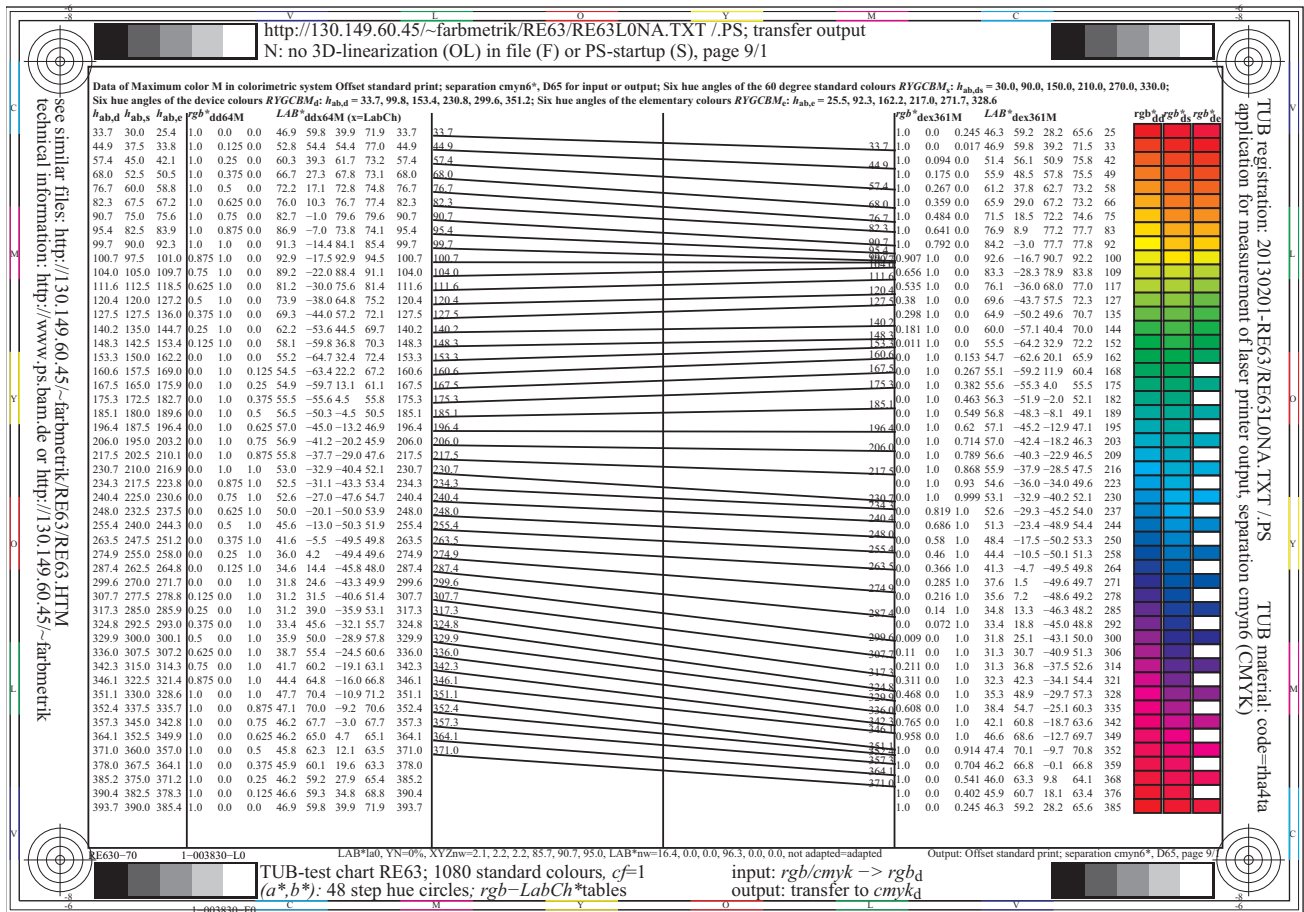


Fig. 51 - rgb and CIELAB data of a 48 step hue circle with $cmyk6^*$ separation

Fig. 51 shows the rgb - and CIELAB data of the CMYK laser printer no. 2 for the standard 48 step hue circle. Now the rgb data in the file have been changed by the separation method $cmyk6^*$ to $cmyk$ data. This method uses complete undercolor removal and therefore the grey scale is only printed by the black colorant.

Fig. 49 on page 54 and Fig. 51 shows the hue circle output of the same laser printer no. 2 which look very different. Fig. 49 on page 54 is based on only rgb data in the file and Fig. 51 is based on a fixed transfer of rgb to $cmyk$ data within the file or by the *Frame File Linearization Method* (FF_LM), see Table 7 on page 42. The hue output is much more regular except near $h_{ab,e}=100$ (roughly near Y_e with $h_{ab,e}=92$). The interpolation methods for the calculation of the rgb_{de} and $(L^*a^*b^*C^*)_{de}$ data as function of $h_{ab,e}$ are the same in Fig. 49 on page 54 and Fig. 51. A higher accuracy of the intended hue is expected because of the much more regular spacing of the start output as function of $h_{ab,e}$.

The intended larger hue angle differences Δh_{ab} for the dark output area between green via blue towards red is indicated by producing only every second step in colour in this region, see the last vertical colour circle. The lines in Fig. 51 show a trend for the intended larger hue angle difference of the dark output area between green via blue towards red. This already helps to produce a colour circle similar to an elementary colour circle which is visually equally spaced.

10.7 Summary for start and linearized printer output

There are printers on the market with the same output for rgb and $cmyk$ data according to the 1-Minus-Relation. It is hard to linearize at least some of the printers on the market with only rgb input data in the file and no transfer to $cmyk$ data within the file. However, this is the common use of many of the printers which usually have no $cmyk$ input channel.

11 Start and linearized output for *CMYK* offset print

http://130.149.60.45/~farbmatrik/RE83/RE83L0NA.TXT /PS; transfer output N: no 3D-linearization (OL) in file (F) or PS-startup (S), page 9/1									
Data of Maximum color M in colorimetric system Offset standard print; separation cmyk ⁶ , D65 for input or output; Six hue angles of the 60 degree standard colours RYGBCM _a ; h _{ab} _{ab} = 30.0, 90.0, 150.0, 210.0, 270.0, 330.0; h _{ab} _{ab} hues of the device colours RYGBCM _a ; h _{ab} _{ab} = 31.7, 100.0, 153.0, 232.9, 299.7, 350.8; Six hue angles of the elementary colours RYGBCM _a ; h _{ab} _{ab} = 25.5, 92.3, 162.2, 217.0, 271.7, 328.6									
LAB									
L	a	b	L	a	b	L	a	b	L
31.7	30.0	25.4	100.0	0.0	0.0	47.0	60.1	37.1	70.6
44.0	37.5	33.8	10.125	0.0	0.0	52.7	54.6	29.9	76.0
56.4	45.0	42.1	1.0	0.25	0.0	60.4	69.3	39.3	71.2
65.6	52.5	50.5	1.0	0.375	0.0	65.9	28.9	63.9	70.1
76.8	60.0	58.8	1.0	0.5	0.0	72.6	16.6	70.9	72.8
83.0	67.5	67.2	1.0	0.625	0.0	76.7	9.2	75.9	76.4
91.9	75.0	75.6	1.0	0.75	0.0	83.8	-2.6	77.2	77.2
96.0	82.5	83.9	1.0	0.875	0.0	87.4	-7.6	71.1	71.5
100.0	90.0	92.2	1.0	1.0	0.0	91.3	-14.5	82.1	83.4
100.9	97.5	101.0	0.075	1.0	0.0	93.0	-17.6	91.1	92.8
102.6	105.0	109.7	0.75	1.0	0.0	90.8	-20.3	90.7	102.6
111.0	112.5	118.5	0.625	1.0	0.0	82.0	-28.9	75.1	80.5
119.4	120.0	127.2	0.5	1.0	0.0	74.8	-36.6	64.9	74.5
126.6	127.5	136.0	0.375	1.0	0.0	70.0	-42.3	57.0	71.0
140.3	135.0	144.7	0.25	1.0	0.0	62.0	-53.9	44.6	70.0
147.2	142.5	153.0	0.125	1.0	0.0	58.5	-59.6	38.3	70.9
152.9	150.0	162.2	0.0	1.0	0.0	55.7	-64.0	32.6	71.8
160.0	157.5	169.0	0.0	1.0	0.125	55.1	-62.4	22.6	66.4
167.4	165.0	175.9	0.0	1.0	0.25	55.5	-58.1	12.9	59.6
176.9	172.5	182.7	0.0	1.0	0.375	55.8	-54.2	2.9	54.3
187.2	180.0	188.6	0.0	1.0	0.5	57.5	-47.9	-6.0	48.3
200.7	187.5	196.4	0.0	1.0	0.625	57.3	-42.5	-16.1	45.4
210.1	195.0	203.5	0.0	1.0	0.75	57.3	-38.9	-22.6	45.0
219.2	202.5	210.1	0.0	1.0	0.875	57.3	-36.7	-30.0	47.4
232.8	210.0	216.9	0.0	1.0	1.0	53.0	-31.0	-40.9	51.4
237.2	217.5	225.0	0.0	0.875	1.0	52.4	-28.3	-44.0	52.4
243.2	225.0	230.6	0.0	0.75	1.0	52.3	-24.1	-47.7	53.5
249.6	232.5	237.5	0.0	0.625	1.0	50.4	-18.4	-49.7	53.0
257.0	240.0	244.3	0.0	0.5	1.0	46.1	-11.3	-49.4	50.6
265.4	247.5	251.2	0.0	0.375	1.0	41.1	-3.8	-49.0	49.2
277.0	255.0	258.0	0.0	0.25	1.0	35.4	6.9	-48.6	48.9
289.0	262.5	264.8	0.0	0.125	1.0	34.8	15.5	-45.0	47.6
299.6	270.0	271.7	0.0	0.0	1.0	32.3	24.2	-42.5	48.9
308.0	277.5	278.8	0.125	0.0	1.0	31.8	31.1	-39.8	50.5
317.3	285.0	285.9	0.25	0.0	1.0	32.2	38.1	-35.0	51.8
325.5	292.5								

Fig. 52 shows the *rgb*- and CIELAB data of the *CMYK* offset print for the standard 48 step hue circle. Similar as in Fig. 51 on page 56 the *rgb* data in the file have been changed by the separation method *cmyn6** to *cmyk* data. This method uses complete undercolor removal and therefore the grey scale is only printed by the black colorant.

The accuracy of the printer output, and of the standard offset output depends on different factors. Any output of the standard offset process is usually proofed at least by four 5 step colour scales. This visual evaluation or colorimetric specification uses equally spaced *cmYK* data between white and *CMYK_d* in the test file. If there are

visual differences for the offset print output, then the offset machine is usually adjusted to reach this goal. Therefore to a high degree the start offset output of the 16 step series is already visually equally spaced. Fig. 40 on page 44 shows the 54 colours of the test chart 1 for colour rendering. For this test chart the colour differences between the intended and measured colours are $\Delta E^*_{ab,dd}=2,0$ and $\Delta E^*_{ab,de}=2,4$, see page 19 (series 1 and 2) of the file <http://farbe.li.tu-berlin.de/RE83/RE83L0FA.PDF>

12 Future device-independent visual RGB^* colour space

This last part considers the recent report CIE R1-57:2013 *Border between luminous and blackish colours*.

Table 9 - The colorimetric coordinates of the *Ostwald* colours for CIE standard illuminant D65

<i>rgb</i> [*] _e and CIE data of a elementary hue circle according to CIE R1-47 for <i>Ostwald</i> colours XYZ, xy, YAB, and Lab* data for relative spacing of elementary hue <i>h</i> _{ab} of CIELAB 16 step elementary hue circle with intended elementary hues: <i>h</i> _{ab} = 25.4, 92.3, 162.2, 271.7 of CIELAB															
	X	Y	Z	x	y	A	B	C _{AB}	<i>h</i> _{AB}	<i>L</i> [*]	<i>a</i> [*]	<i>b</i> [*]	<i>C</i> [*] _{ab}	<i>h</i> _{ab}	<i>rgb</i> → <i>rgb</i> [*] _{oe}
<i>R00Y</i>=<i>R</i>_{oe}	66.0	41.1	20.9	0.515	0.321	26.9	9.5	28.5	19.5	70.3	70.9	33.4	78.4	25.2	1.00 0.00 0.00
<i>R25Y</i>_{oe}	64.0	41.5	6.4	0.571	0.371	24.5	15.5	29.0	32.3	70.5	65.1	71.4	96.6	47.6	1.00 0.25 0.00
<i>R50Y</i>_{oe}	62.6	41.7	1.0	0.593	0.396	22.8	17.7	28.9	37.8	70.7	61.2	106.3	122.7	60.0	1.00 0.50 0.00
<i>R75Y</i>_{oe}	71.1	58.7	0.1	0.546	0.451	15.3	25.5	29.7	59.0	81.1	35.2	137.3	141.7	75.6	1.00 0.75 0.00
<i>Y00G</i>=<i>Y</i>_{oe}	76.8	83.9	1.3	0.473	0.517	-2.9	36.0	36.1	94.7	93.4	-5.9	141.9	142.0	92.3	1.00 1.00 0.00
<i>Y25G</i>_{oe}	65.9	89.6	6.7	0.406	0.552	-19.2	36.3	41.1	117.8	95.8	-39.4	113.6	120.3	109.1	0.75 1.00 0.00
<i>Y50G</i>_{oe}	43.7	79.6	8.1	0.332	0.605	-31.9	31.4	44.7	135.4	91.5	-77.3	101.2	127.3	127.3	0.50 1.00 0.00
<i>Y75G</i>_{oe}	26.4	67.7	12.4	0.247	0.635	-38.0	24.5	45.2	147.1	85.9	-113.0	78.6	137.7	145.1	0.25 1.00 0.00
<i>G00B</i>=<i>G</i>_{oe}	21.8	61.8	31.6	0.189	0.536	-36.9	14.2	39.5	158.8	82.8	-119.5	37.9	125.4	162.3	0.00 1.00 0.00
<i>G25B</i>_{oe}	27.8	58.9	81.5	0.165	0.349	-28.1	-6.9	28.9	193.9	81.2	-86.9	-13.9	88.0	189.1	0.00 1.00 0.50
<i>G50B</i>_{oe}	25.6	45.4	108.7	0.142	0.252	-17.5	-23.7	29.5	233.5	73.1	-61.3	-46.1	76.7	216.9	0.00 1.00 1.00
<i>G75B</i>_{oe}	20.2	29.3	108.4	0.128	0.185	-7.6	-30.6	31.5	256.0	61.0	-33.4	-66.8	74.7	243.4	0.00 0.50 1.00
<i>B00R</i>=<i>B</i>_{oe}	18.4	18.7	107.7	0.127	0.129	0.6	-34.9	34.9	271.0	50.4	3.3	-84.8	84.9	272.2	0.00 0.00 1.00
<i>B25R</i>_{oe}	18.0	8.8	105.2	0.136	0.067	9.5	-38.2	39.4	284.0	35.7	64.2	-108.5	126.1	300.6	0.50 0.00 1.00
<i>B50R</i>_{oe}	61.7	26.3	99.4	0.329	0.14	36.7	-28.3	46.3	322.3	58.3	112.5	-65.8	130.3	329.6	1.00 0.00 1.00
<i>B75R</i>_{oe}	71.2	40.6	51.0	0.437	0.249	32.5	-2.6	32.6	355.2	69.9	83.6	-7.1	83.9	355.1	1.00 0.00 0.50
5 step equidistant grey scale with intended lightness: <i>L</i>[*] = 0.0, 25.0, 50.0, 75.0, 100.0															
<i>N000W</i>=<i>N</i>0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00 0.00 0.00
<i>N025W</i>	4.1	4.4	4.8	0.312	0.329	0.0	0.0	0.0	77.5	25.0	0.0	0.0	0.0	0.0	0.25 0.25 0.25
<i>N050W</i>	17.5	18.4	20.0	0.312	0.329	0.0	0.0	0.0	55.3	50.0	0.0	0.0	0.0	0.0	0.50 0.50 0.50
<i>N075W</i>	45.8	48.2	52.5	0.312	0.329	0.0	0.0	0.0	21.0	75.0	0.0	0.0	0.0	0.0	0.75 0.75 0.75
<i>N100W</i>=<i>W</i>95.0	100.0	100.0	108.8	0.312	0.329	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0	1.00 1.00 1.00

TE090-3N Lab*, page 1/2

Table 9 shows the colorimetric coordinates of the *Ostwald* colours for a 16 step elementary hue circle and a 5 step grey scale, compare Table 1 of CIE R1-57:2013.

In Table 9 in general the CIELAB chroma $C^*_{ab,e}$ is much larger compared to the data in Table 4 on page 33 for the *sRGB* colour space. For the red colour *R00Y*_e the chroma is $C^*_{ab,oe}=78,4$ and $C^*_{ab,sRGBe}=80,4$.

One can expect that the sum of the chroma of the opponent colours Red *R*_e and Cyan *C*_e in the *sRGB* colour space (80,4+40,8=121,1) is less compared to the sum of the chroma of the opponent colours in the *Ostwald* colour space (78,4+76,7=155,1). For highest colour contrast the display manufacturers and printer companies may try to fill the *Ostwald* colour gamut to reach the highest chromatic image contrast.

Table 9 uses special *rgb*^{*}_{oe} data (Index oe for the *Ostwald* (o) elementary (e) colours). Again a linear relation between any CIELAB data and these *rgb*^{*}_{oe} data may be used in both directions, compare Table 4 on page 33 (left and right) and Fig. 23 on page 26. However, in Fig. 25 on page 27 the *rgb*^{*}_{oe} data have now a *visual* definition and the values are related to *visual appearance*.

For example, if one of the three rgb^*_{oe} data has the value 1, then the colour appears neither luminous nor blackish according to CIE R1-57. Therefore any of the colours in Table 9 has the relative blackness $n^*_o=0$, (or brilliance $i^*_o=1$), and the relative chroma $c^*_o=1$.

The relative elementary hue e^* (an Index o is not necessary) changes by the value $\Delta e^*=0,0625$ for one step of the 16 step colour circle. It is for example $e^*=0,00$ for R_{oe} , $e^*=0,25$ for Y_{oe} , $e^*=0,50$ for G_{oe} , and $e^*=0,75$ for B_{oe} .

If one compares the colour triangles based on Table 9 with the triangles in Fig. 42 on page 47 or Fig. 20 on page 24 or Fig. 21 on page 25 then in general any device triangle (of the *sRGB* display, of the offset print, or of a laser printer) is smaller compared to the triangle of the *Ostwald* colours.

For applications it may be appropriate to adapt the tristimulus values of the *Ostwald* colours to the tristimulus values $Y=88,6$ for white and $Y=2,5$ for black of both standard offset and displays according ISO/IEC 15775 and ISO 9241-306. In general the *Ostwald* triangles are much larger compared to the application triangles. Therefore one can expect that any surface colour will have rgb^*_{oe} data between zero and 1, and in addition with a *linear relation* to the CIELAB data for all surface colours in both directions.

If the CIELAB data are outside the *Ostwald* gamut then still there is a *linear relation* in both directions, However, in this case for example one of three rgb^*_{oe} data has a value larger one, and this may happen for fluorescent red colours. In applications a larger colour gamut can be used as reference, if for example wide gamut rgb^*_{oe} data with values between -0,5 and 1,5 are possible in a CIE document. This agreement seems to be useful for highlight and/or fluorescent colours.

An example for the calculation of the rgb^*_{oe} data for the given data $(L^*, C^*_{ab}, h_{ab})_{o,Y_e}$ and $(L^*, C^*_{ab}, h_{ab})_{sRGB,Y_e}$ of yellow Y_e is given in Annex E of the paper http://farbe.li.tu-berlin.de/OUTLIN13_02.PDF

The following three set of colour coordinates are equivalent:

$$(L^*, C^*_{ab}, h_{ab})_{sRGB,Y_e} = (83,6 \ 84,3 \ 92,3), \quad nce^*_{o,Y_e} = (0,25 \ 0,59 \ 0,25), \quad \text{and} \quad rgb^*_{o,Y_e} = (0,75 \ 0,75 \ 0,16)$$

The colour coordinates nce^*_{oe} are the mostly used colour coordinates in the area of art, design, and architecture, compare the *Swedish Natural Colour System NCS*.

The coordinates rgb^*_{oe} , which are now applied for the area of image technology, are connected by linear equations to nce^*_{oe} .

By *affine* colorimetric equations the coordinate systems used in the areas of *art/design* and of *image technology* are connected with the CIELAB coordinates of colorimetry

In addition the example shows a weak point of the *sRGB* display colour system. The blackness $n^*_{o,Y_e} = 0,25$ of the elementary yellow Y_e on *sRGB* displays is too high (elementary yellow appears too dark) for many users in the area of art, design and architecture. For example the *Company Sharp* produces in addition to the usual *RGB* displays *RGBY* displays with a fourth primary near the elementary yellow which produces less relative blackness.

13 Normative and other references

CIE 15:2018, Colorimetry, 4th Edition

CIE S 017:2011, ILV, International lighting vocabulary (see also e/LV online at CIE Web site)

CIE 168:2005: Criteria for the Evaluation of Extended-Gamut Colour Encoding

CIE 170-1:2006 and 170-2:2015 Fundamental chromaticity diagram with physiological axis – Part 2: Spectral Luminous Efficiency Functions and Chromaticity Diagrams

CIE R1-47:2009, Hue angles of elementary colours, see for download in the MLA format (two options)

[<http://files.cie.co.at/526.pdf>]._Internet Archive_.

[<http://web.archive.org/web/20160304130704/http://files.cie.co.at/526.pdf>].

CIE R1-57:2013, Border between luminous and blackish colours, see download in MLA format (two options)

[http://files.cie.co.at/716_CIE%20R1-57%20Report%20Jul-13%20v.2.pdf]._Internet Archive_.

[http://web.archive.org/web/20150413002133/http://files.cie.co.at/716_CIE%20R1-57%20Report%20Jul-13%20v.2.pdf].

DIN 33872-1 to 6:2010, Information technology - Office machines - Method of specifying relative colour reproduction with YES/NO criteria, see for download of test charts <http://farbe.li.tu-berlin.de/33872E.html>

For DIN-test charts for 8 viewing conditions, see <http://farbe.li.tu-berlin.de/OE.HTM> see pages OE70_OE99

ISO EN DIN 9241-306:2008, Ergonomics of human system interaction – Part 306: Field Assessment methods for electronic visual displays, For TUB-test charts for a revision, see <http://130.149.60.45/~farbmetrik/AE.HTM>

ISO 8995; CIE S 008:2002-05, Lighting of indoor work places

ISO 11664-4:2008(E)/CIE S 014-4/E:2007: Joint ISO/CIE Standard: CIE Colorimetry — Part 4: 1976 $L^*a^*b^*$ Colour Space (CIELAB)

ISO 15076-1:2010, Image technology colour management -- Architecture, profile format and data structure -- Part 1: Based on ICC.1:2010

ISO/IEC 15775:1999, Information Technology – Office machines – Method of specifying image reproduction of colour copying machines by analog test charts – Realization and application

ISO/IEC 15775/Amd.1, Information technology – Office machines – Machines for colour image reproduction – Method of specifying image reproduction of colour copying machines by analog test charts – Realization and application – Amendment 1, see a public draft version

<https://web.archive.org/web/20060116221659/http://www.jbmia.or.jp/sc28/sc28docs/j28n648.zip>

For the Asian ISO-test charts of JIS X 6933 (approximately equal to ISO/IEC 15775:1999 and Amd1: 2005) from JBMIA in Japan, see

https://iso.jbmia.or.jp/test_c.html

ISO/IEC TR 19797:2004, Information technology – Office machines – Machines for colour image reproduction – Device output for 16-step colour scales, output linearization method (LM) and specification of the reproduction properties, see a public draft version

<https://web.archive.org/web/20060116212434/http://www.jbmia.or.jp/sc28/sc28docs/j28n687.zip>

ISO/IEC TR 24705:2005, Information technology – Office machines – Machines for colour image reproduction – Method of specifying image reproduction of colour devices by digital and analog test charts, see a public draft version

<https://web.archive.org/web/20060104024850/http://www.jbmia.or.jp/sc28/sc28docs/j28n689.zip>

see for download of test charts according to ISO/IEC TR 24705

<http://farbe.li.tu-berlin.de/24705TE.html>

SS 019100:1997, Colour notation system, and SS 019102:2004, NCS ATLAS (NCS Colour atlas)

Author publications

Hurvich and Jameson (1955), JOSA 45, 546-552 and 602-616.

Richter, K. (2012), Colour and Colour Vision, Elementary Colours in Colour Image Technology, TU Berlin, see <http://farbe.li.tu-berlin.de/color> and <http://standards.iso.org/iso/9241/306/ed-2/ES15.PDF>

Richter, K. (2014), Trends for CIE-ISO-colour standards for input and output of all colour devices with relative CIELAB colour coordinates *rgb**, see http://farbe.li.tu-berlin.de/CIE_TC42_DFWG_14.PDF

Valberg, A and T. Seim (2008), Neural mechanisms of chromatic and achromatic vision, CR&A 33, 433-443.

J. Witt (2006) Colorimetric methods for the production of test charts for colour copiers, colour scanners and colour monitors, PhD thesis, TU Berlin (8 MB, in German, see *linearization accuracy* in Table 6.3, page 138) <http://opus4.kobv.de/opus4-tuberlin/frontdoor/index/index/docId/1320>

For more information on output linearization, see the web site <http://farbe.li.tu-berlin.de/outlin>

Text added at 2019-06-07 together with working links

The development of ISO/IEC TR 24705 (see last page) was decided by a Ballot Resolution Meeting (BRM) of SC28 members on DIS ISO/IEC 19839-1 to 4. This DIS failed because 45% of P-members instead of 66% voted "Yes". See the BRM report in a public version

<https://web.archive.org/web/20030325083431/http://www.actech.com.br/sc28docs/j28n547.doc>

DIS ISO/IEC 19839-1 to 4 was based on DIN 33866-1, and 3 to 5. ISO/IEC 15775 is based on DIN 33866-2.

The different parts of DIS ISO/IEC 19839-1 to 4 are listed in the following. The following links show a free download possibility of these SC28 documents from the WBM server. The technical content of ISO/IEC TR 24705 or/and the four parts of DIS ISO/IEC 19839-1 to 4 may be a starting point for further work in SC28, other interested standard groups, or also for use in different applications.

ISO 9241-306:2018 for displays covers the technical content of DIS ISO/IEC 19839-4 for monitors. ISO 9241-306:2018 uses three of the test charts of ISO/IEC 15775 for copiers. ISO/IEC 15775 is under revision, and this revision may not change the ISO standard illuminant D65. Only then it is in line with ISO 9241-306 and IEC 61966-2-1 and the former parts of DIS ISO/IEC 19839-1 to 4.

DIS ISO/IEC 19839-1: Method of specifying image reproduction of colour devices by digital and analog test charts - Classification and principles, see a public draft version

<https://web.archive.org/web/20030325005802/http://www.actech.com.br:80/sc28docs/j28n512.pdf>

DIS ISO/IEC 19839-2: Method of specifying image reproduction of colour devices by digital input and analog output as hardcopy for colour image reproduction devices: "digital - analog" (Printers) - Application and realization., see a public draft version

<https://web.archive.org/web/20030325050829/http://www.actech.com.br/sc28docs/j28n513.pdf>

DIS ISO/IEC 19839-3: Method of specifying image reproduction of colour devices by analog input and digital output for colour image reproduction devices: "analog - digital" (Scanners) - Application and realization, see a public draft version

<https://web.archive.org/web/20030325100829/http://www.actech.com.br/sc28docs/j28n514.pdf>

DIS ISO/IEC 19839-4: Method of specifying image reproduction of colour devices by digital input and analog output as softcopy for colour image reproduction devices: "digital - analog" (Monitors) - Application and realization., see a public draft version

<https://web.archive.org/web/20030426234527/http://www.actech.com.br/sc28docs/j28n515.pdf>

ISO/IEC TR 24705 includes on the first 25 pages (of 42) the content and the purpose of the digital and analog ISO/IEC-test charts. This technical part is to a high degree not included in ISO/IEC 15775 and ISO 9241-306. If SC28 decides to delete TR 24705, then a lot information is missing for example for ISO 9241-306 which refers to both ISO/IEC 15775 and ISO/IEC TR 24705.