Symmetric Colour Vision Model, CIELAB and Colour Information Technology

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http://www.ps.bam.de/FI06.PDF

http://www.ps.bam.de/FI06E.PDF

Abstract

A symmetrical model of colour vision with logarithmic responses of the three cones L, M, and S is described. Within this model the location of the four elementary colours Red (R), Yellow (J), Green (G), and Blue (B) is described. The elementary colours are described by the "neither-nor-criterion", for example yellow J as neither reddish nor greenish. The four elementary colours have the hue angles 25, 92, 162, and 272 degrees in the CIELAB chroma diagram *(a*, b*)*. In Information Technology (IT) these four hue angles are used to define the elementary colours and to output the elementary colours on monitors and printers.

Standard input coordinates *rgb* with 0 <= *r, g, b* <= 1, for example in PS and PDF files, are interpreted a new *rgb** coordinates. For the *PostScript* operator *"0 0 1 setrgbcolor"* these coordinates produce for example the elementary colour Blue B with the maximum chroma in CIELAB for any device. If the digital *rgb*-input coordinates are equally spaced between 0 and 1 then the output spacing is equally spaced in CIELAB, for example between White W and Blue B, Blue B and Black N, and White W and Black N.

Application methods are presented to allow the user to interpret the *rgb* data within the PS and PDF files as *rgb** coordinates. By this method the user can not only output elementary colours but he also can output 16 step equally spaced colour series in CIELAB for every hue and on every device.

1. Introduction

The colour space CIELAB is defined in CIE 15:2004. CIELAB is standard for colour measurement and in colour Information Technology (IT) and is almost used for the CIE standard illuminant D65. The CIELAB colour space has been developed empirically on the basis of data of the Munsell colour order system and independent of the three physiological sensitivities of the three cone receptors.

CIE 170-1:2005 defines for the first time the sensitivities of the three cones $L(\lambda)$, $M(\lambda)$, and $S(\lambda)$. The letters L, M, and S are responsible for the maximum sensitivity in the wavelength ranges long (L), mean (M), and short (S). The maximum sensitivities are near the three wavelength 570 nm, 540 nm, and 445 nm. With this sensitivities $L(\lambda)$, $M(\lambda)$, and $S(\lambda)$ and additionally many physiological and psychophysical data of *Valberg* (2005) one may expect in some years a substitution of the colour space CIELAB.

The workshop serves to show the present status of knowledge and to show trends. Both the extension of these knowledge (contribution of *P. Kittelmann*) as well as the application of CIELAB (contributions of *S. Jaeger, J. Witt* and *H. Wagenknecht*) in Information Technology (IT) are main points in this workshop.

In the field of colour information technology the four elementary colours with the hue angles 25, 92, 162 and 272 degrees in the CIELAB chroma diagram *(a*, b*)* are used to solve the following user requirements:

1. The elementary colours shall be reproduced on any output device (printer, monitor), for example if the digital *rgb*-input coordinates have the standard value (0, 0, 1) for Blue B.

2, All colours with for example the input coordinates *rgb = (x, x, y)* with 0 <= *x, y* <=1 describe colours of the hue elementary blue B and form a colour hue triangle (compare Fig. 5).

3. In any hue triangle the 16 step colour series are equally spaced in CIELAB, for example for the hue Blue B between White W and Blue B, between Blue B and Black N, and betwen White W and Black N, if the *rgb*-input

data are digitally equally spaced.

NOTE For all 16 step *rgb*-input values in a hue triangle Blue B it is valid:

rgb = (x, x, y) with 0 <= x, y <=1; x = i/15 and y = j/15 with only natural positive numbers 0 <= i, j <= 15

4. A uniform method for the calculation of the *rgb* coordinates from the CIELAB-data *L*, a*, b** and vice versa is defined for any device.

2. Symmetric colour vision model and cone sensitivities LMS

The cone sensitivities LMS have been recently defined in CIE 170-1:2005. The maxima of the cone sensitivities are located near the wavelength 570, 540 and 445nm. According to *Valberg* (2005) one can measure the physiological responses in the retina which show logarithmic transformations of the *(linear)* tristimulus values LMS. In a logarithmic plot the responses show approximately parables as function of the wavelength.
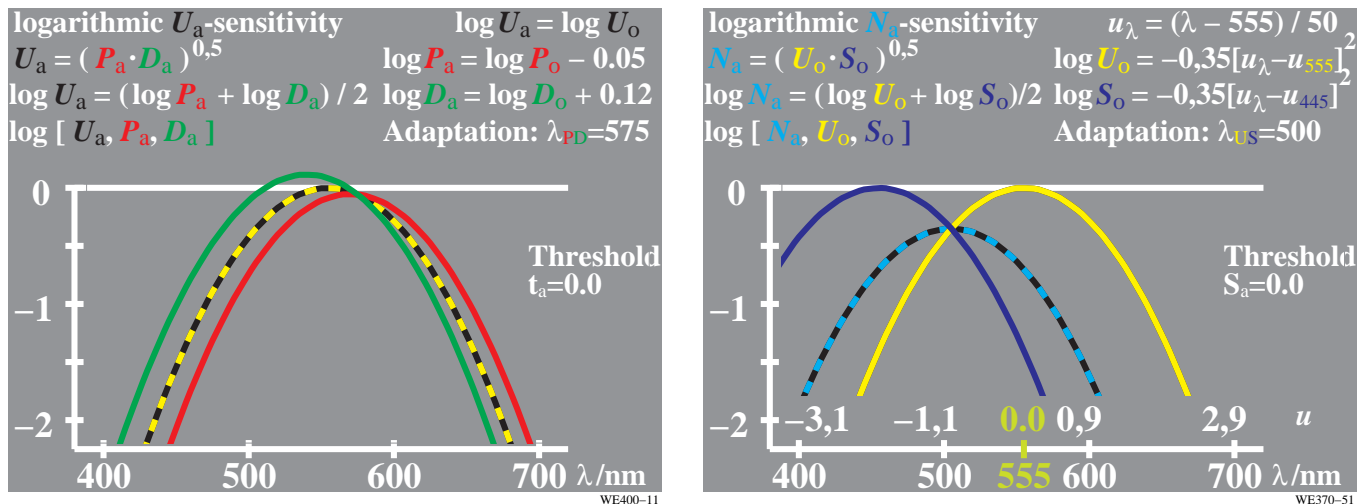

Figure 1: Cone sensitivities L, M, and S with appropriate normalisation and logarithmic sum

On the *left* side Fig. 1 shows the cone sensitivities $L(\lambda)$ and $M(\lambda)$ with a logarithmic y-axis. With an appropriate normalisation $L(\lambda)$ and $M(\lambda)$ cut at 575 nm. This is the dominant wavelength of elementary Yellow J. Half of the logarithmic sum of $L(\lambda)$ and $M(\lambda)$ leads to the function $U_a(\lambda)$ which is approximately the spectral luminous function $V(\lambda)$ with a maximum at 555 nm. The deviations of the *logarithmic* sum compared to the colorimetric *linear* sum are about 1% at both spectral ends near 400 nm and 700 nm, see *Richter* (1996).

On the *right* side Fig. 1 shows the cone sensitivities $S(\lambda)$ and the function $U_a(\lambda)$ with a logarithmic y-axis. For the same normalisation of both to the value one the cut is at 500 nm which is the mean of the two wavelength 445 nm and 555 nm. Half of the logarithmic sum of $S(\lambda)$ and $U_a(\lambda)$ is $N_a(\lambda)$ which is approximately the spectral sensitivity $V'(\lambda)$ of night vision. If identical parables are chosen with only maxima at different wavelength then the differences of the responses, for example log $L(\lambda)$ – log $M(\lambda)$ and $S(\lambda)$ – log $U_a(\lambda)$, are linear functions of the wavelength, see Richter (1996). The physiology of the retina shows that at the same time the complementary responses are created, for example log $M(\lambda)$ – log $L(\lambda)$ and $U_a(\lambda)$ – log $S(\lambda)$. Therefore the colour vision model gets **symmetric properties**. For additional information see the publication after the workshop.

For complementary optimal colours equal colour difference thresholds have been shown experimentally in the usual adjacent viewing situation, see *Holtsmark* and *Valberg* (1969). Therefore to a high degree symmetric properties are necessary to describe colour thresholds of complementary (optimal) colours. In application the three basic colours OLV (RGB) of colour television and the three mixture colours CMY are complementary. If the adjacent viewing situation is changed to view separate samples on a grey background then some deviations from the symmetry are necessary, see Richter (2006b). During the workshop *P. Kittelmann* will present new experimental results for small and large colour differences.

About the results of IT application projects three other staff members will report during the FARBINFO '06 workshop. In section 9 "References" recent publications of these members are listed, see *S. Jaeger* (2005, 2006), *J. Witt* (2005, 2006), and *H. Wagenknecht* (2005).

In the following the colour notations are used which have been defined in different International Standards and Technical Reports. According to ISO/IEC 15775:1999 and ISO/IEC TR 24705:2005 the eight device colours are named OLV, CMY, and NW for White and Black (=french *Noir*). For elementary colours the names RJGB are defined (J=french *jaune* = yellow).

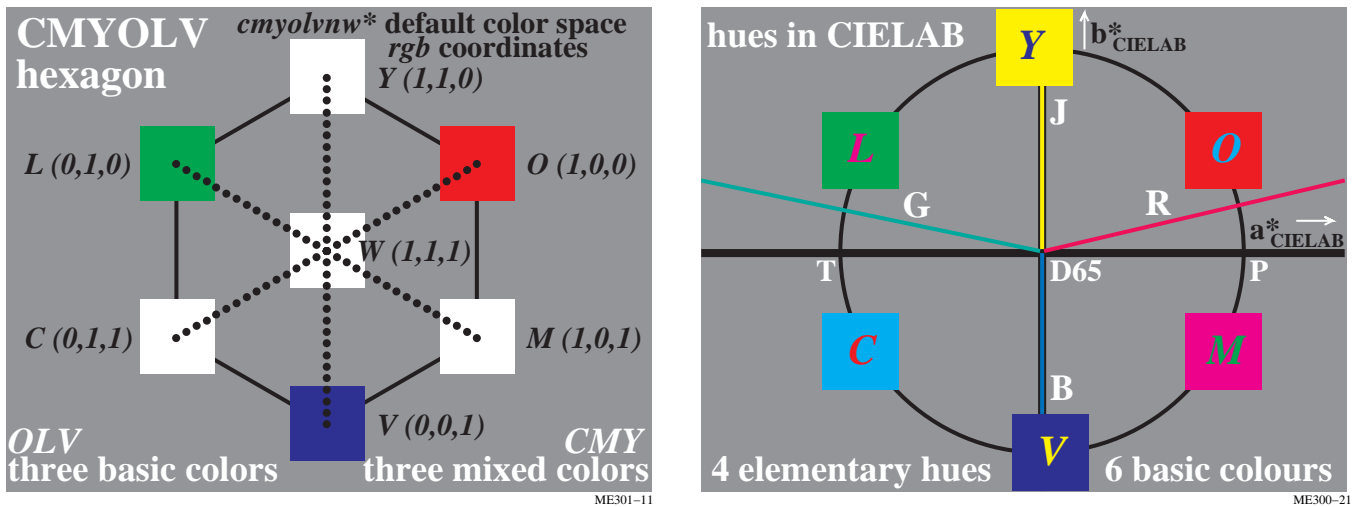# 3. Device and elementary colours in the CIELAB chroma diagram *(a*, b*)*

Figure 2: 7 *rgb* device colours OLVCMYW and 4 elementary colours RJGB in the chroma diagram *(a*, b*)*

Fig. 2 shows 7 *rgb*-device colours OLV, CMY and W *(left)* in the colour hexagon and 4 elementary colours RJGB in the CIELAB chroma diagram *(a*, b*) (right)*, The six chromatic colours are all arranged by a 60 degree shift and starting with O at 30 degrees. This arrangement can be assumed to be the first approximation of most of the devices in the field of information technology. However for Cyan Blue C and Violet Blue V there are deviations of about 40 degree, see Fig. 3. The elementary colours are device independent and have constant CIELAB hue angles h_{ab}.

The *rgb*-data in Fig. 2 (left) include only the values 0 and 1 for the device colours of maximum chroma. The device colours OYLV are for most devices different compared to the four elementary colours RJGB. If the application program interprets the *rgb* data as device colours with the coordinates *olv** then most of the device outputs show a yellowish red (O = Orange Red), a yellowish green (L = Leaf Green), and a reddish blue (V = Violet Blue). The four device hues OYLV are **different on all devices**.

If the application program interprets the *rgb*-data as elementary colours with the coordinates *rgb** then all devices show the elementary colours Red R, Yellow J, Green G, and Blue B. Yellow J is produced for the *rgb* data (1, 1, 0). The four elementary hues are **equal on all devices**. They are located in the CIELAB chroma diagram *(a*, b*)* at the hue angles h_{ab} 25, 92, 162, and 272 degrees.

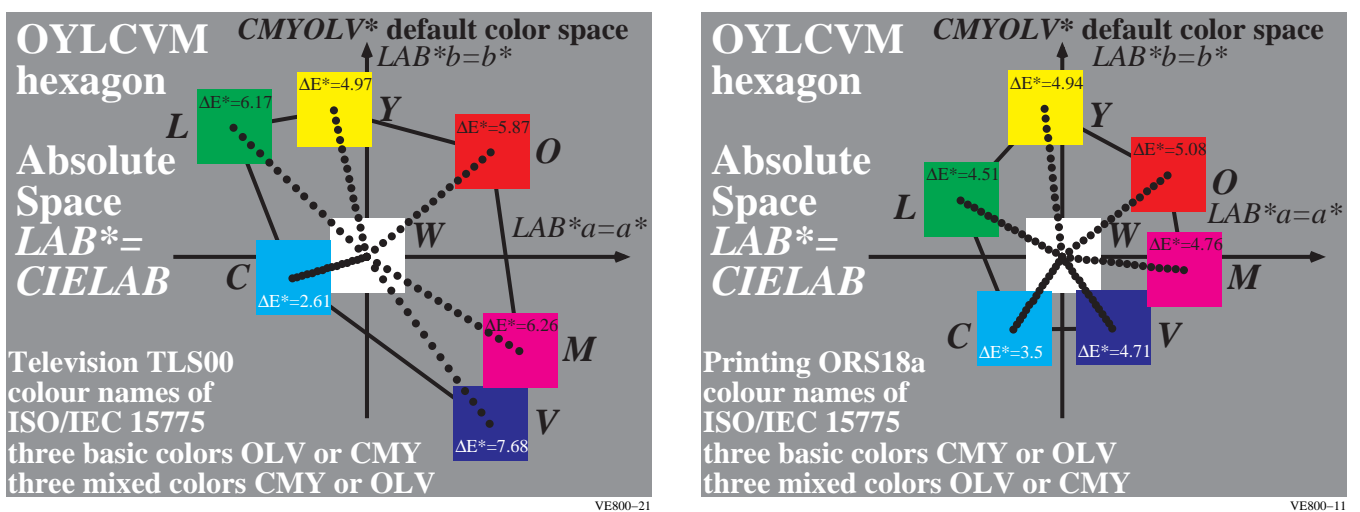# 4. Device colours for standard monitor and offset printing

Figure 3: Chroma of standard colour television and offset printing in the CIELAB chroma diagram *(a*, b*)*

Fig. 3 shows the chroma of the standard monitor (Television Luminous System TLS00) *(left)* and of the standard offset printing (Offset Reflective System ORS18) *(right)*. The numbers 00 and 18 are the CIELAB lightness L*=0 and L*=18 for black N. The hue angles of the device colours are very different, for example Cyan Blue C has the hue angles 196 degree in the System TLS00 *(left)* and 250 degree in the system ORS18 *(right)*.

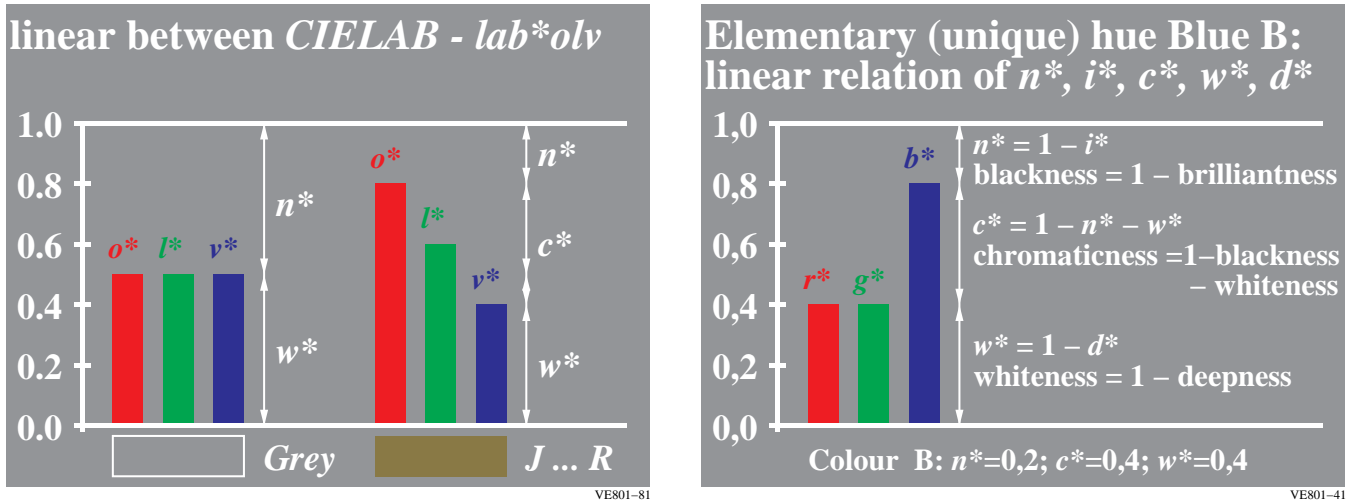# 5. Device coordinates *olv** and elementary coordinates *rgb**

Figure 4: Interpretation of coordinates *rgb* as coordinates *olv and *rgb** for device and elementary colours**

Fig. 4 shows the interpretation of the coordinates *rgb* as coordinates *olv** and *rgb** for device and elementary colour output. The coordinates *olv** and *rgb** have for any hue a **linear** relation to the coordinates *L** and C^*_{ab} of the colour system CIELAB. Therefore equal differences of the coordinates *olv** and *rgb** in the data range 0 to 1 (and additionally for >1) correspond to equal differences in the CIELAB colour space. The series from Black to Blue is for example described by the coordinates *rgb** = (0, 0, 0) for Black N and *rgb** = (0, 0, 1) for Blue B. The coordinate *rgb** = (0, 0, 0.5) describes a blue which is visually and in the CIELAB colour space in the middle between Black N and Blue B. Additionally Fig. 4 shows the very simple linear relations between *c*, n*, w*, i*, d** and *olv** or *rgb**.

For the coordinates *olv** and *rgb** there is a well defined **linear** relationship to the coordinates *L*a*b** of CIELAB and vice versa. The relationship between the coordinates *rgb* and *L*a*b** is often not defined or **non linear**, see for example in *sRGB* (see IEC 61966-2-1:2004) and *AdobeRGB* (2005).

The coordinates of the colour spaces *sRGB* and *AdobeRGB* include therefore **no** corresponding **linear** relations between the digital differences of there coordinates and the CIELAB coordinates but in a first step linear relations to CIEXYZ. Therefore in the application they are hard to interpret for users and show less efficiency for the colour coding compared to *olv** and *rgb**. For example the digital differences in the colour space *sRGB* are by the **factor 6 different** for a 16 step equally spaced colour series in CIELAB between White W and Cyan Blue C, which is described in *olv** by the equal digital spacing of the red component. For a calculation example see section 7.

6. Creation of 16 step elementary hue colours in a hue triangle

The 16 step outputs in a colour hue triangle (compare Fig. 5) depend at first on the CIELAB data of the eight device colours OLV, CMY and NW. For the output of elementary colours additionally the four elementary hue angle 25, 92, 162, and 272 of the four elementary colours RJGB in CIELAB are necessary.

The CIELAB chroma is shown in Fig. 3 for the standard monitor and for offset printing. Therefore for both the lightness *L** and the hue angle h_{ab} in CIELAB are known. For the production of colours with the hue angles of the elementary colours the device colours must be mixed in a appropriate manner.

In Fig. 5 the CIELAB device colours of the standard monitor TLS00 are given in the table on the top right. For example Violet Blue V has the hue angle 306 degree. For example to mix Blue B with the hue angle 272 degree a green component must be added. Therefore for the coordinates *rgb** = (0, 0, 1) which define the output of Blue B then finally the device coordinates *olv** = (0, 0.61, 1) are calculated, compare the *olv** coordinates in Fig. 5.

The device coordinates *olv** are different for every device, the coordinates *rgb** for Blue B are always equal. For the elementary colour Blue B the output hue is visually and additionally in CIELAB always equal. The CIELAB hue angle h_{ab} is always 272 degree for Blue B. Both the device colour V (306 degree in CIELAB) and the elementary hue B (272 degree in CIELAB) are created with the following PDF file on page 10:
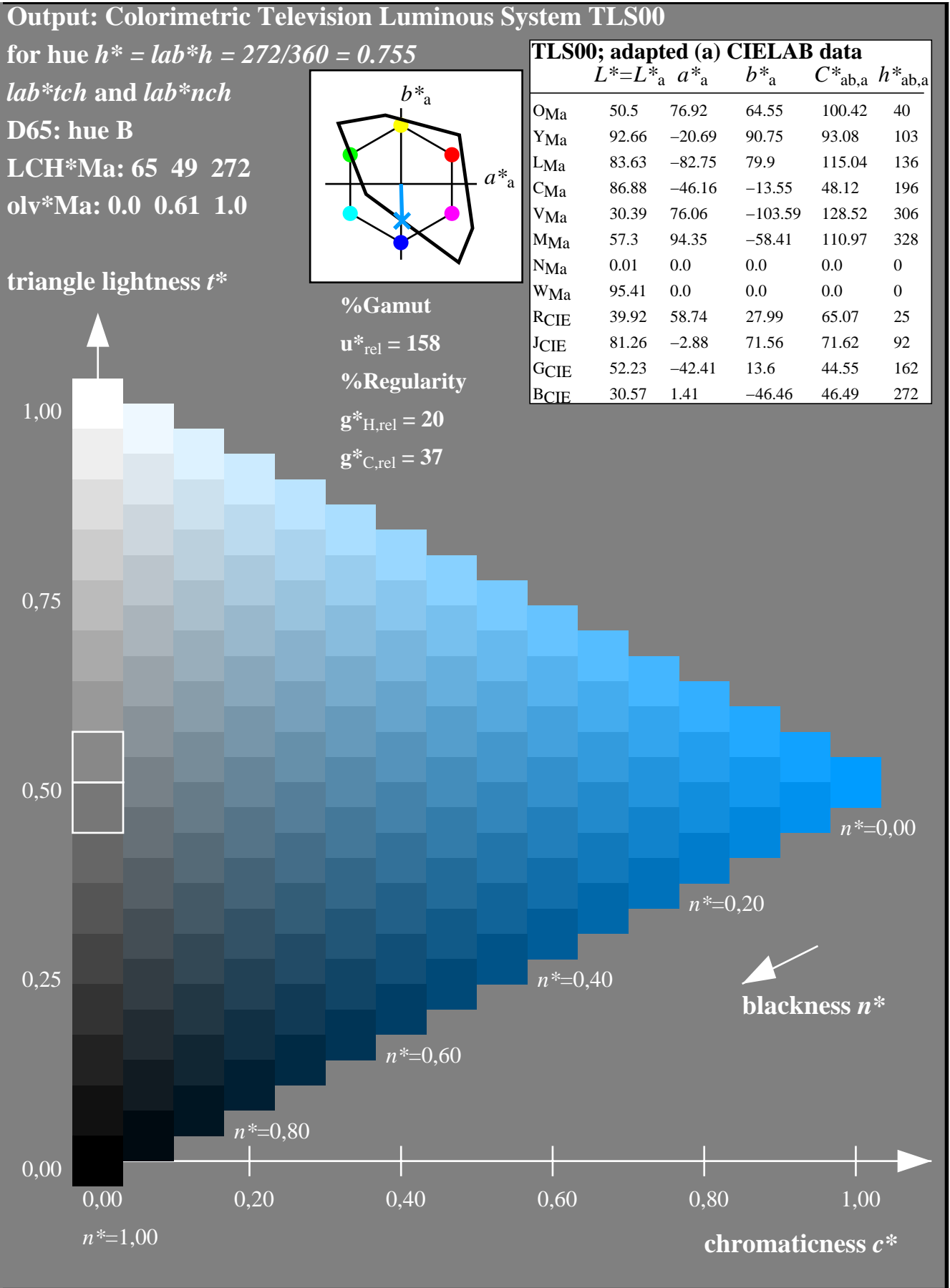
http://www.ps.bam.de/ME59/L59E00NP.PDF

Output: Colorimetric Television Luminous System TLS00

for hue $h^* = lab^*h = 272/360 = 0.755$

lab*tch and *lab*nch*

D65: hue B

LCH*Ma: 65 49 272

olv*Ma: 0.0 0.61 1.0

triangle lightness *t**

%Gamut

u*rel = 158

%Regularity

g*H,rel = 20

g*C,rel = 37

TLS00; adapted (a) CIELAB data				
	$L^*=L^*_a$	a^*_a	b^*_a	$C^*_{ab,a}$ $h^*_{ab,a}$
O_{Ma}	50.5	76.92	64.55	100.42	40
Y_{Ma}	92.66	−20.69	90.75	93.08	103
L_{Ma}	83.63	−82.75	79.9	115.04	136
C_{Ma}	86.88	−46.16	−13.55	48.12	196
V_{Ma}	30.39	76.06	−103.59	128.52	306
M_{Ma}	57.3	94.35	−58.41	110.97	328
N_{Ma}	0.01	0.0	0.0	0.0	0
W_{Ma}	95.41	0.0	0.0	0.0	0
R_{CIE}	39.92	58.74	27.99	65.07	25
J_{CIE}	81.26	−2.88	71.56	71.62	92
G_{CIE}	52.23	−42.41	13.6	44.55	162
B_{CIE}	30.57	1.41	−46.46	46.49	272

1,00

0,75

0,50

0,25

0,00

n^*=0,00

n^*=0,20

n^*=0,40

blackness *n**

n^*=0,60

n^*=0,80

n^*=1,00

0,00   0,20   0,40   0,60   0,80   1,00

chromaticness *c**

Figure 5: 16 step equidistant colour series for elementary hue B with the standard monitor TLS00

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Fig. 5 shows the hue triangle with 16 step equally spaced colour series for the elementary hue Blue B with the standard monitor TLS00. For the standard monitor the input *rgb* data are interpreted the coordinates *rgb** = (0, 0, 1) and are transferred to the coordinates *olv** = (0, 0.61, 1) by the *PostScript* programming code in the PS or PDF file.

Fig. 5 shows the standard colour hexagon with the 60 degree hue shifts. Aditionally the standard monitor colours, see Fig. 3, are compared with this standard colour hexagon. The device colour Violet Blue V has the hue angle 306 degree and differs much compared to the hue angle 272 degree of the elementary colour Blue B. The CIE-test colours no. 9 to 12 which are defined in CIE 13.3 for colour rendering, define the four elementary colours RJGB.

The *relative* chroma **c*** and the *relative* triangle lightness **t*** which always has the value **t*** = 0.5 for the device colour of maximum CIELAB chroma serve as coordinates in the hue triangle. A similar coordinate compared to **t*** is known from the colour order systems of *Ostwald* (1920) and the *Natural Colour System (NCS)*. Additionally the relative coordinate blackness **n*** is shown which is used together with **c*** in the NCS colour order system. The very simple **linear** relation of **c*** and **n*** to *olv** or *rgb** is shown in Fig. 4.

To get an equidistant output spacing on the monitor for Blue B for example a linearizing method according to ISO/IEC 19797:2004 may be used. A more new method has been developed by J. Witt (2006). This method works with a colour table, for example of the 9x9x9 *rgb* colours and the corresponding *L*a*b** colours. With this method 16 step equally spaced colour series can be produced for any hue triangle, for example for the device hue angles OLV, CMY and the elementary hue angles RJGB and additionally for any other hue angle.

In the application the measured device table is added to any PS or PDF file together with additional appropriate *PostScript* code, see ISO/IEC TR 19797:200. Then the *rgb* data in this file are interpreted as either *olv** data or *rgb** data. In a first step an interpretation and output method is realized for *PostScript* vector code, for example created with *Adobe Illustrator*.

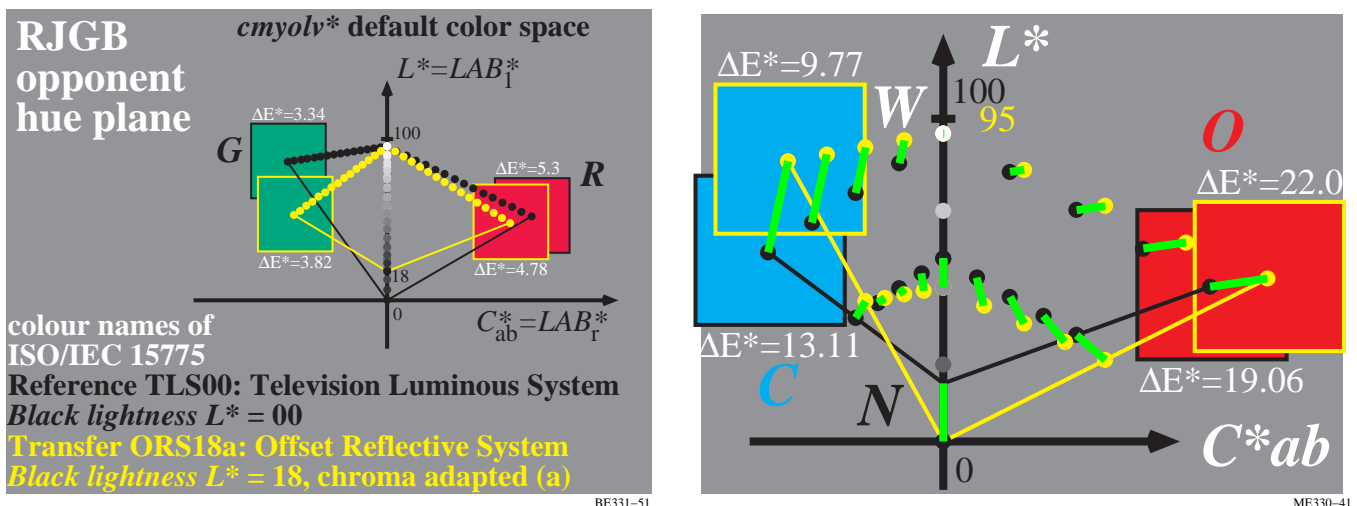# 7. User Coordinates and Colour Management

Figure 6: Opponent hue triangles for TLS00 and ORS18 *(left)* and colour management *(right)*

Fig. 6 shows opponent hue triangles for the Television Luminous System TLS00 and the Offset Reflective System ORS18a *(left)* and corresponding colour management *(right)*. Mathematically Fig. 5 shows the *affine* transformation (right) of the 5 step colour series on the surface and within the triangle. Only this affine transformation maintains the relative distances between the 5 or 16 step colour series in TLS00 and ORS18a. This transformation is unique in both directions and the only "secure" transformation which maintains any detail in the area of colour management.

The CIELAB lightness $L*$ and chroma $C*_{ab}$ for the elementary colour Blue B differ for any device. This is considered if for example the following user requirements are realized in the colorimetric reproduction:

There are **three user requirements** for the **colour reproduction** in the information technology:

1. Maintain the hue on any device, compare Fig. 5.
2. Use the complete available colour gamut in any hue triangle, compare Fig. 6
3. Produce equally spaced CIELAB output in any hue triangle for equidistant digital values, compare Fig. 5

All user requirements are reached if for any device the device colour with maximum chroma is defined as colour with the relative triangle lightness **t*** = 0.5 and the relative chroma **c*** = 1.0. Equations to calculate **t*** and **c*** from the CIELAB data **L*a*b*** and vice versa have been developed, see *Richter* (2005a and b). Based on this equations for any *rgb** data one can calculate not only CIELAB data but additionally the coordinates relative blackness **n***, relative chroma **c***, relative whiteness **w***, relative brilliantness **i*** (= 1 − **n***), relative deepness **d*** (= 1 − **w***), and relative

triangle lightness *t**. Fig. 5 uses on the x-axis the relative chroma *c** and on the y-axis the relative triangle lightness *t**. Additionally the relative blackness *n** is shown. Modern application programs for graphic design shall offer the input of relative chroma *c**, the relative blackness *n** and the elementary hue *e**, which have for the four elementary hues the hue angles 0, 90, 180 and 270 degrees and the elementary hue data *e** = 0, 0.25, 0.50, and 0.75.

If one compares the user requirements with the results of ICC colour management (ISO 15076-1:2005) then the ICC output of different Colour Management Modules (CMMs) varies by up to 30 CIELAB for the standard case of Fig. 6 and for the same ICC profile data. This large deviation compared to the tolerance of 3 CIELAB according to ISO/IEC 15775 is possible because the output tone functions are not defined in ISO 15076-1 and can be freely chosen within the CMM. Therefore the CMMs of for example the companies *Adobe, Apple, Heidelberg, and Windows* lead to very different results.

The different CMMs of ICC-Colour Management use up to now neither the elementary colours RJGB nor the visual coordinates relative chroma *c**, relative blackness *n** and relative elementary hue *e**. Therefore in comparison to this primary visual properties at present there is neither a possibility for input and output nor a meaningful and a less effective coding method for the colours. In applications the defined **linear** relationships between *cne**, *olv**, and *rgb** and the CIELAB data *L*a*b** shall be used for an approvement. In section 5 we mention the less efficiency of *rgb* coordinates of the colour spaces *sRGB* and *AdobeRGB* compared to *olv** and *rgb**. For an example calculation with *olv*, sRGB* and corresponding *L*a*b** data see the file

http://www.ps.bam.de/VE74/L74E00NP.PDF

For the 16 step series C – W, see the colours on page 1 or 2, the table on page 3 shows the corresponding *olv**, *sRGB*, and *L*a*b** data in the columns J, K, L. The red coordinate *o** of *olv** changes equally by the value 0,063 for the 16 steps. The coordinate *r* of *sRGB* changes near Cyan Blue C by the value 0.25 and near White W by the value 0.04. For the 16 step series C – W which is equally spaced in CIELAB therefore the digital differences of the *o** coordinate are **equal** and the *r* coordinate in *sRGB* are **different by the factor 6**. This shows the less efficiency of the colour space *sRGB* compared to the visual properties of colour vision.

8. Future trends

The colour information technology shall use in future more the visual properties of colour vision to increase the acceptability of the users. For this the location of the elementary hues in CIELAB and an efficient and meaningful coding with linear relations between the coordinates *rgb** and *L*a*b** of CIELAB play an important role. Probably CIELAB will be replaced in future by a colour space CIELMS which describes both colour thresholds and large colour steps for both adjacent and separate viewing situations.

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, D50**
colour order system: name and coordinates	**Device system name and coordinates:**
RAL Design System (CIELAB) *L*C*h*, lightness, chroma, hue	**Printer system (illuminants D65, D50):** *cmy*, content of "cyan", "magenta", "yellow"
Munsell Colour System *VCH*, lightness (Value), Chroma, Hue	**Display system (standard illuminant D65):** *rgb/sRGB*, content of "red", "green", "blue"
Natural Colour System (NCS) *nce**: blackness, chromaticness, elementary hue	*IT colour coordinates confuse the users! Nearly no connection to colour order systems!*

New: Application connection by coordinates *olv*, rgb*, tce*, ...* und linear relation to *L*a*b**

CIELAB: *L*C*h* : lightness, red-green and jellow-blue chroma; *L*C*h* : lightness, chroma, hue

Definition of *relative* device coordinates similar to (absolute) coordinates of colour order systems

lch*: relative lightness, relative chromaticness, hue

tch*, tce*: relative triangle lightness, relative chromaticness, hue or elementary hue

nce*: relative blackness, relative chromaticness, elementary hue

LE430–31

Figure 7: Application of colour in daily life and in colour information technology

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Fig. 7 shows the application of colour in daily life and in the colour information technology. There is nearly no connection between the coordinates *rgb* and *cmy* of the colour information technology and the coordinates of the colour order systems *RAL* (CIELAB), *Munsell* and *NCS*. Now there is a new definition of new coordinates **olv*** and **rgb*** with linear relations to CIELAB, for example of *lch** (relative CIELAB lightness *l**, relative CIELAB chroma *c**, and CIELAB hue h_{ab}). For example if the application program allows the input **nce*** (relative blackness **n***, relative chroma **c***, relative elementary hue **e***) then there is an improved connection between the field of colour information technology and the meaningful and user friendly colour coordinates used in design, art, and architectur.

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