Data, methods and formula to bridge the gap for colour differences between threshold differences, the formula CIE DE2000 and large CIELAB colour differences

T03E05.FM

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This paper and similar papers are available by the URL
http://www.ps.bam.de/CIE/index.html

Background to work on colour threshold metric

At the CIE Division 1 meeting in Veszprem (Hungary) in 2002 the CIE decided the following Reportership (Text of the CIE chairman):

CIE R1-31:
Smooth change of color difference metric between large CIELAB color differences and threshold color differences

Terms of reference:
To bridge the gap for color differences between large CIELAB color differences, e.g. DE*ab=20, and threshold differences for office conditions

Reporter:
Klaus Richter (DE)
This Reporter is to investigate the relation between a large color difference and a small one at the threshold level with a possible method to develop a continuous metric to connect them, and to report Division 1 how we work on this issue in the future

The Reporter of CIE R1-31 proposed at the CIE Division 1 meeting 2003 in San Diego (USA) to form a new TC on this topic.
Based on the CIE recomendations of:
CIE DE2000 is for the range between 0 to 5 CIELAB
CIELAB is for large colour differences > 5 CIELAB
there is the question: Can we use CIEDE2000 for the full range?

The CIE Division 1 decided to form the following TC:

CIE TC 1-63: Validity of the range of CIE DE2000

Terms of Reference:
To investigate the application of the CIE DE2000 equation at threshold up to CIELAB colour differences greater than 5

Chairman: K. Richter (DE)
Members: D. Rich (US), M.R. Luo (GB), J. Nobbs (GB), C. Oleari (IT), H. Yaguchi (JP), M. Pointer (GB), ...?

Some application conditions:

Colour sample illumination by the illuminance 500 to 1000 lux equal to the luminance of 150 to 300 cd/m^2 for white paper / monitor

Illuminant CIE daylight D65

CIE 45/0 viewing and measurement geometry

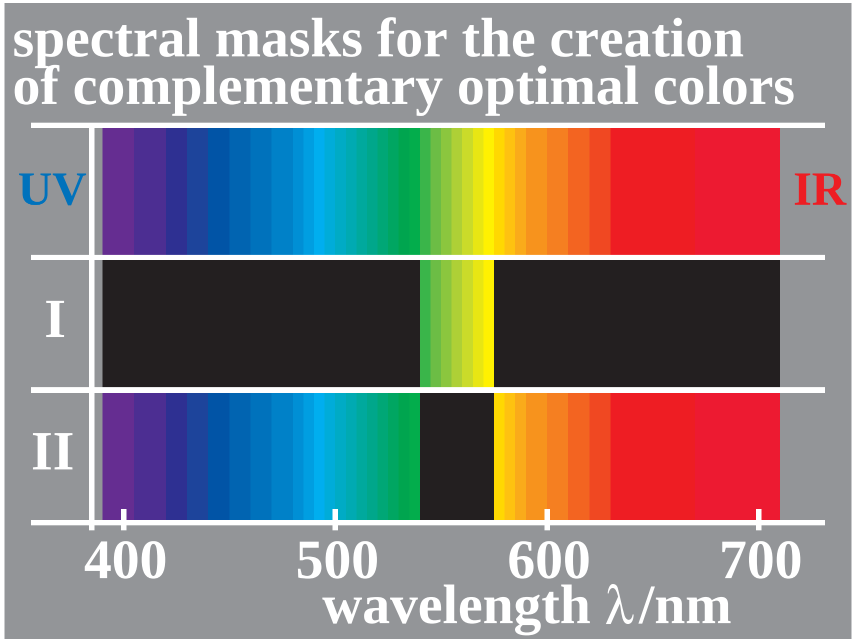
CIE 2 degree observer

normalized CIE data X/Xn, Y/Yn, Z/Zn in the range 0 to 1 instead of the range 0 to 100 for applications in image technology

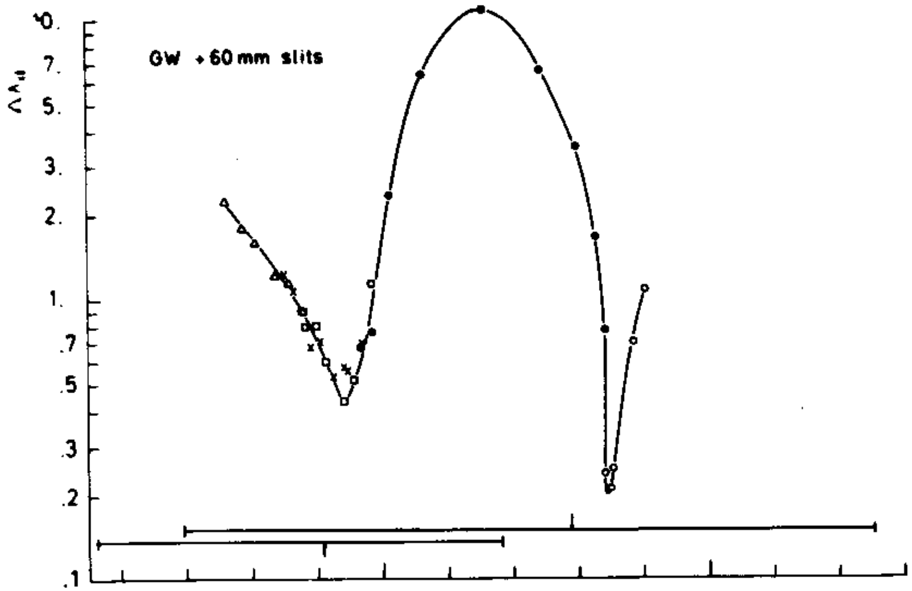
Many experimental data on colour differences may be used to test CIE DE2000 in the full range

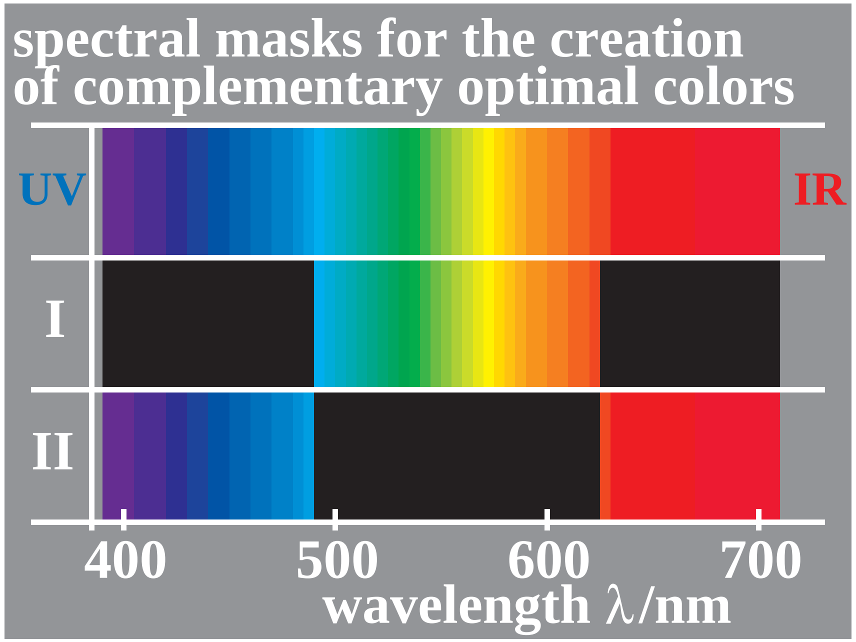
1. **Threshold data: MacAdam, Richter, Holtsmark-Valberg, Yaguchi e. al.**
2. **CIE DE2000 and similar data: Luo, Witt, Nobs and Hirschler data sets**
3. **Large colour difference data: Munsell, OSA, Indow, Richter, e. al.**

Complementary optimal colours and threshold



M8250−1N





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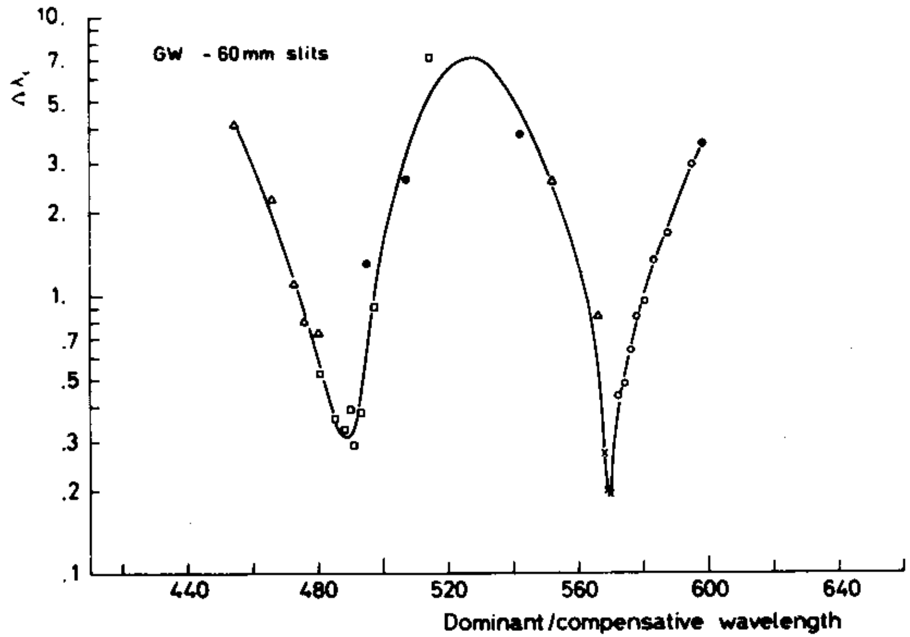

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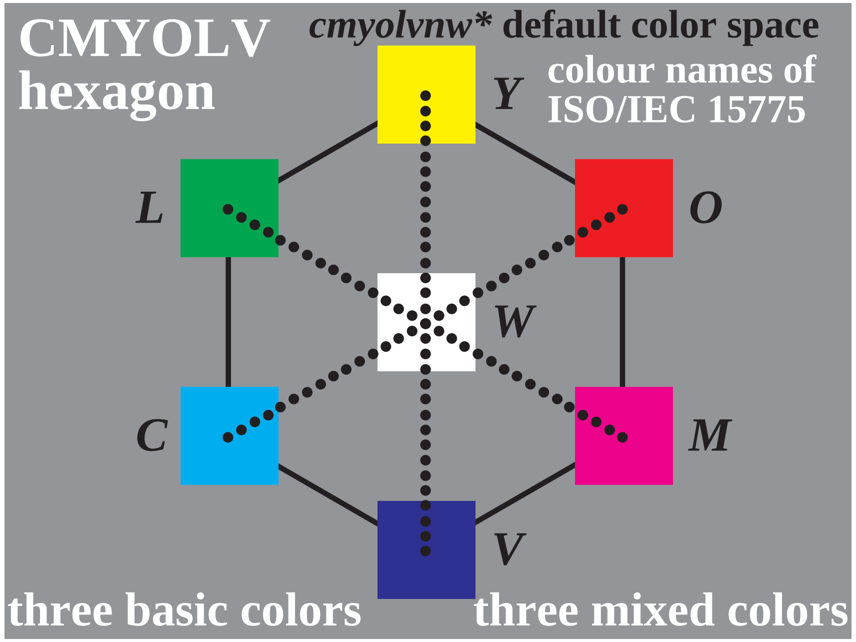
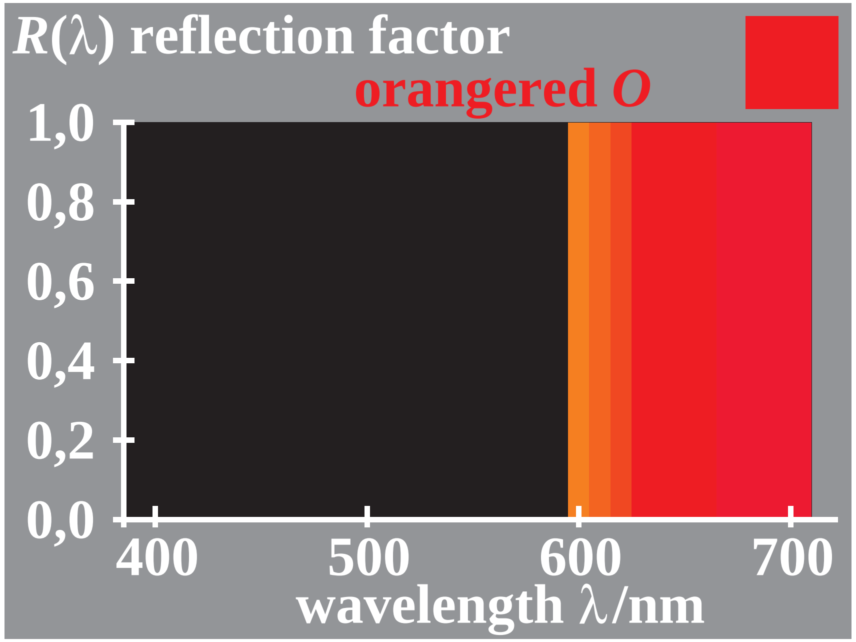
Optimal colours in image technology



H03/E8370-12



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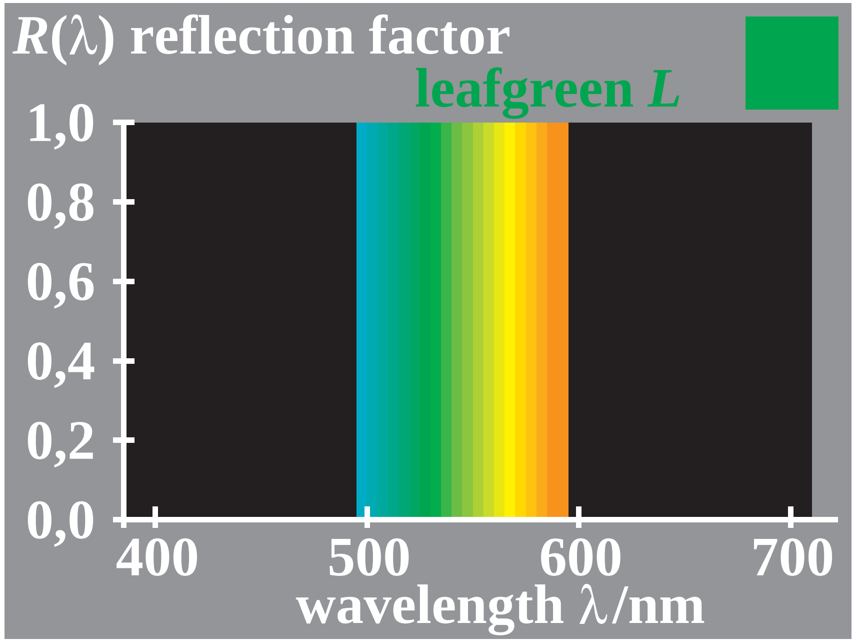

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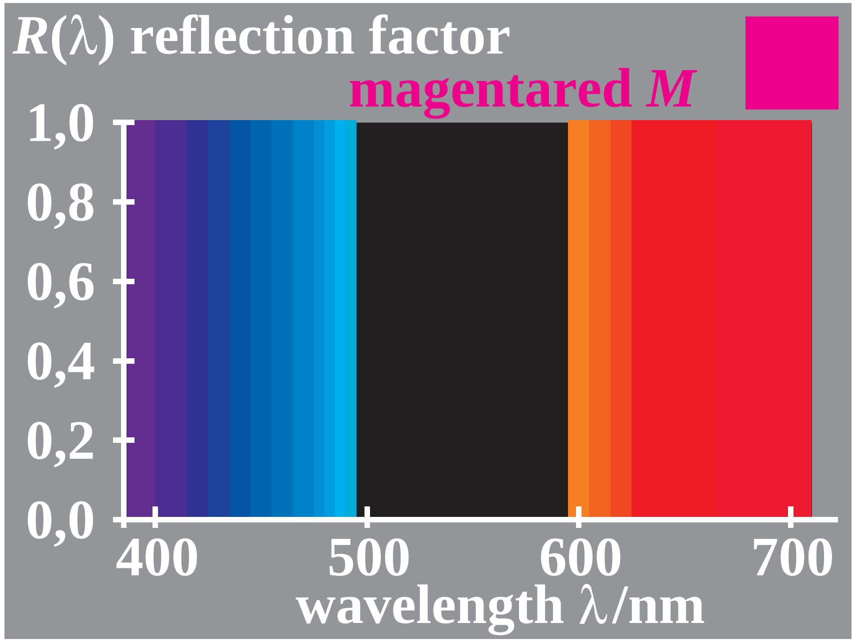

T03/E8161−5N

CIE tristimulus values of optimal colours for Image Technology

basic and mixed additive optimal colors for illuminant D65

basic color or mixed color and name	CIE standard chromaticity *x*	*y*	CIE standard tristimulus value *X*	*Y*	*Z*
three additive basic optimal colors:					
O orangered	0,6695	0,3302	42,65	21,04	0,02
L leafgreen	0,2991	0,6351	34,87	74,04	7,67
V violetblue	0,1445	0,0393	18,06	4,90	102,02
three additive mixed optimal colors:					
C cyanblue	0,2191	0,3268	52,94	78,96	109,70
M magentared	0,3218	0,1375	60,73	25,95	102,04
Y yellow	0,4300	0,5274	77,53	95,09	7,69
D65 (white)	0,3131	0,3275	95,60	100,00	109,71

T03/E8581−7. 2x2

Range 01 normalized CIE tristimulus values in Image Technology

basic and mixed additive optimal colors 01 normalized for illuminant D65

basic color or mixed color and name	Range 01 normalized chromaticity		Range 01 normalized tristimulus value		
	x_{01}	y_{01}	$X_{01}=X/X_n$	$Y_{01}=Y/Y_n$	$Z_{01}=Z/Z_n$
three additive basic optimal colors:					
O orangered	0,6792	0,3304	0,4461	0,2105	0,0002
L leafgreen	0,3102	0,6295	0,3649	0,7405	0,0709
V violetblue	0,1620	0,0420	0,1890	0,0490	0,9289
three additive mixed optimal colors:					
C cyanblue	0,2364	0,3369	0,5539	0,7895	0,9998
M magentared	0,3479	0,1423	0,6351	0,2595	0,9291
Y yellow	0,4424	0,5188	0,8110	0,9510	0,0711
D65 (white)	0,3333	0,3333	1,0000	1,0000	1,0000

H03/E8581−71. 2x2

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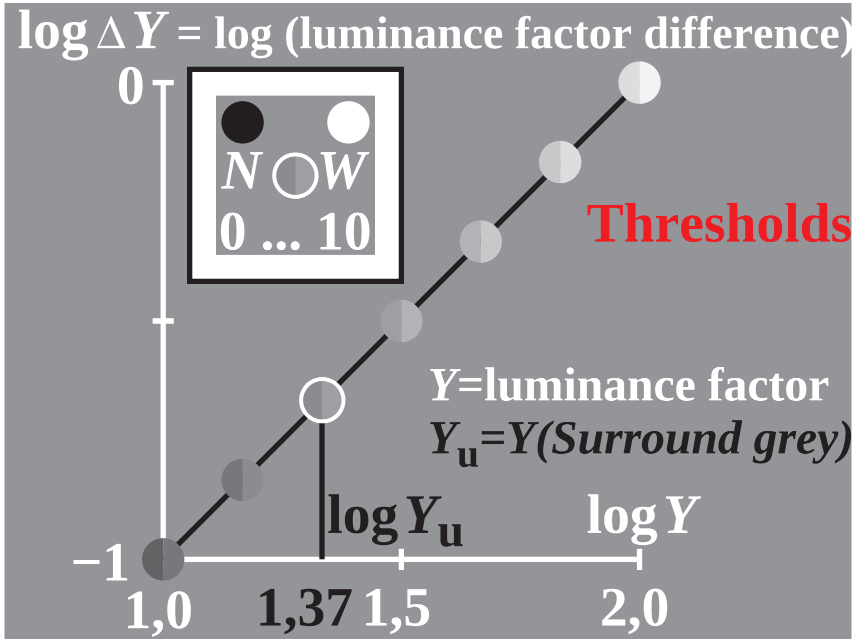
Colour threshold experiments



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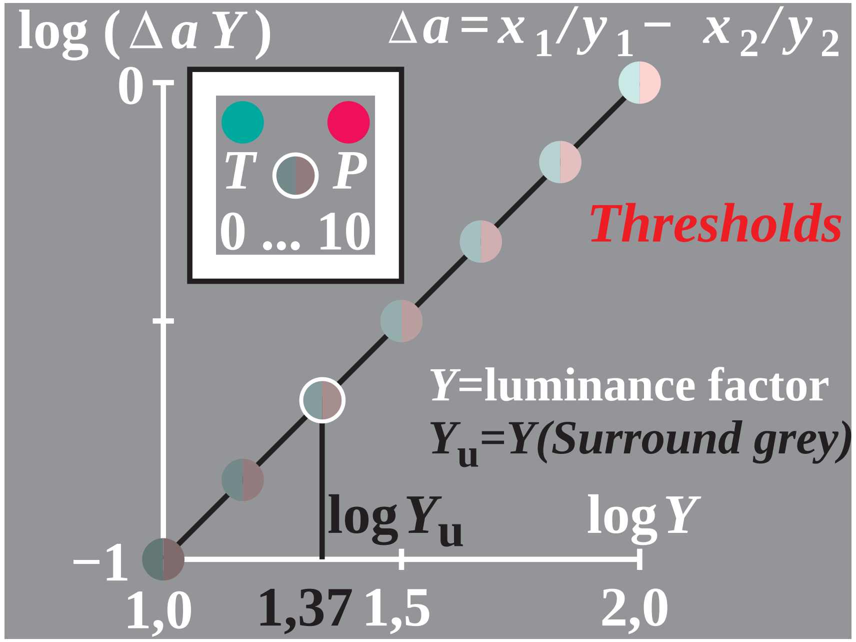
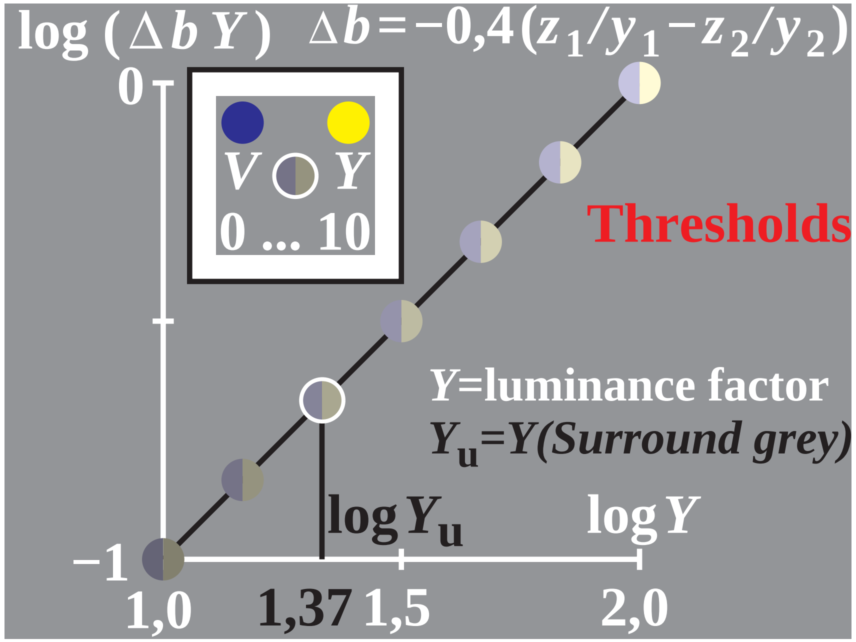


B8761-5N



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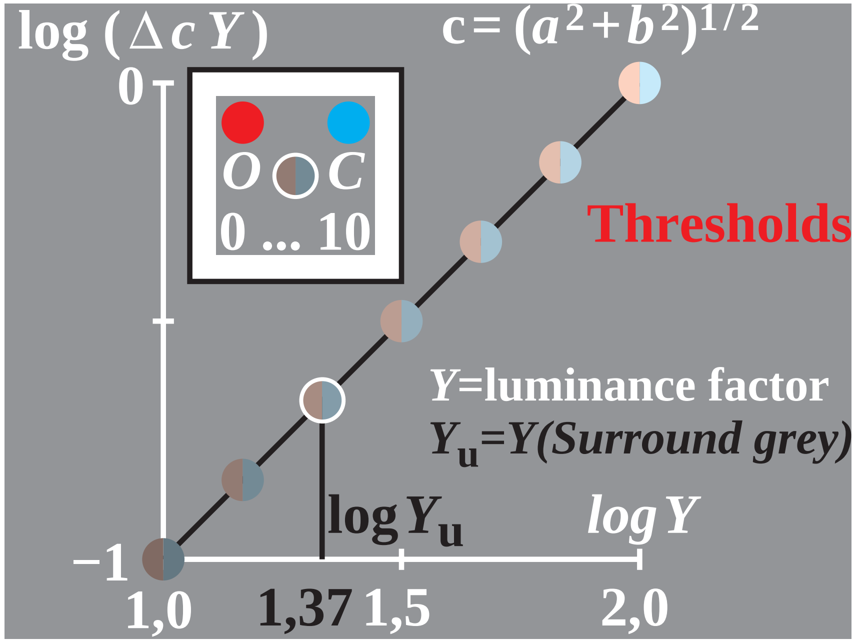

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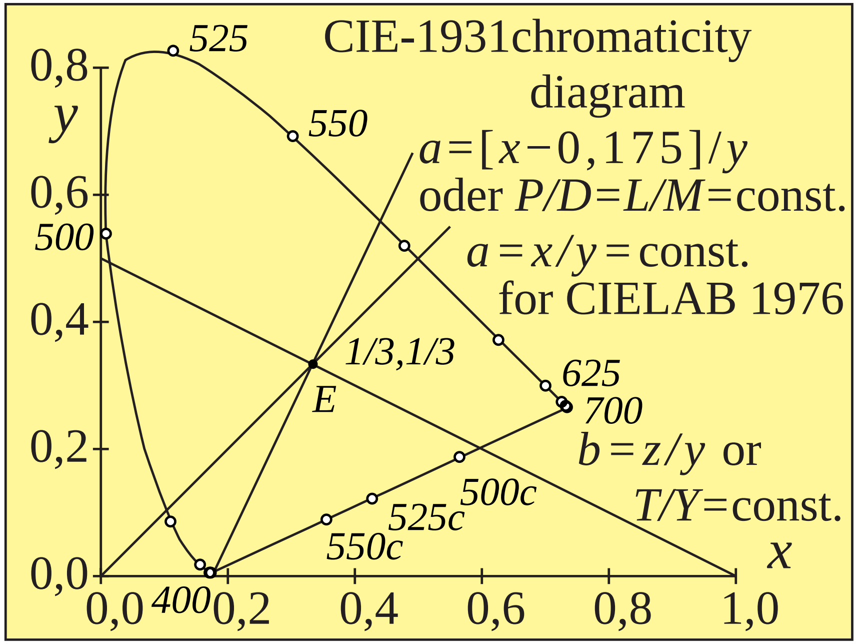
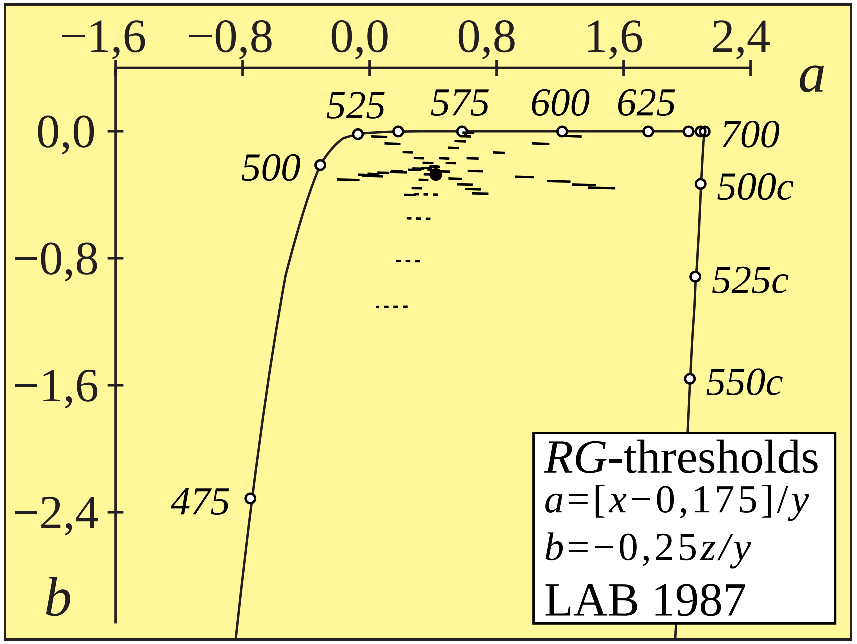
Optimal Colours in Image Technology (IT)



H03/E8281−1N



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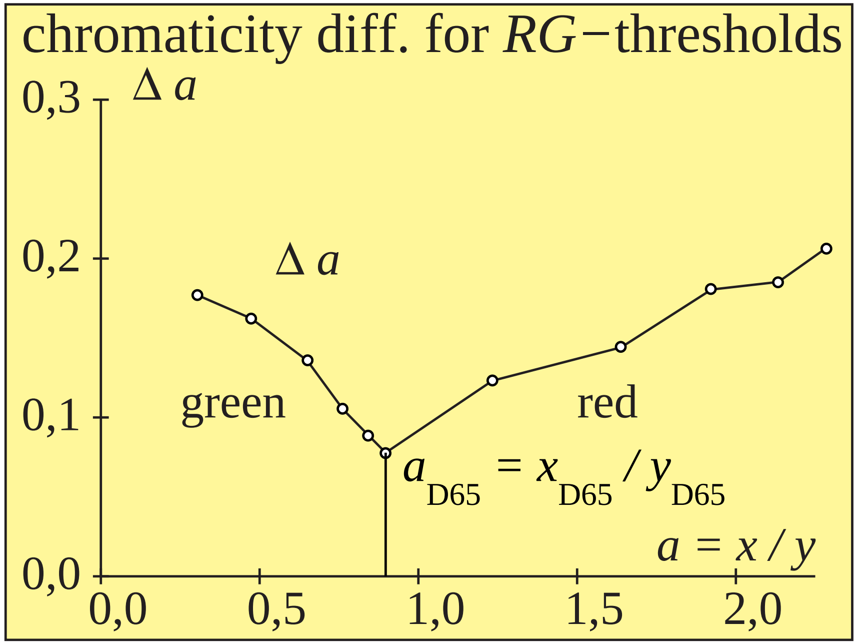
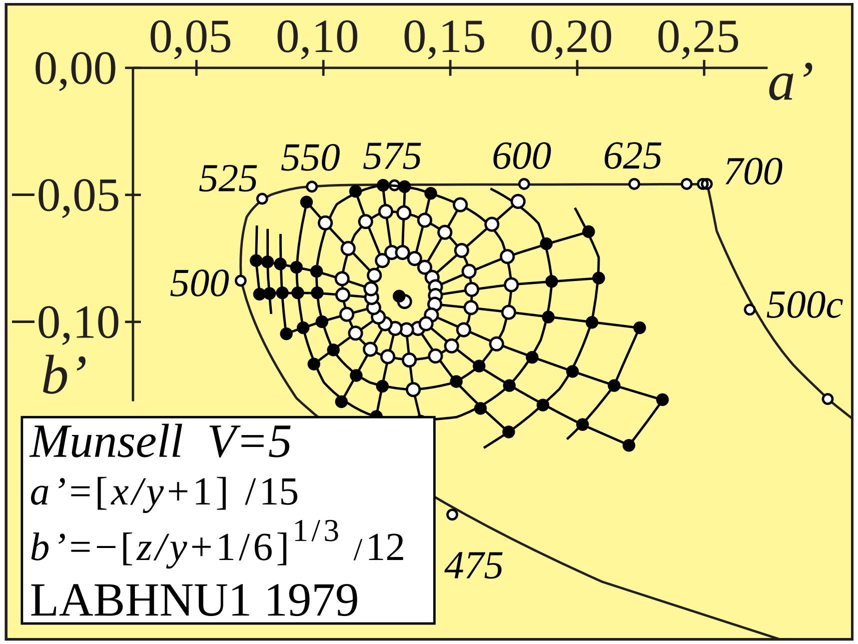


H03/E8311−4N

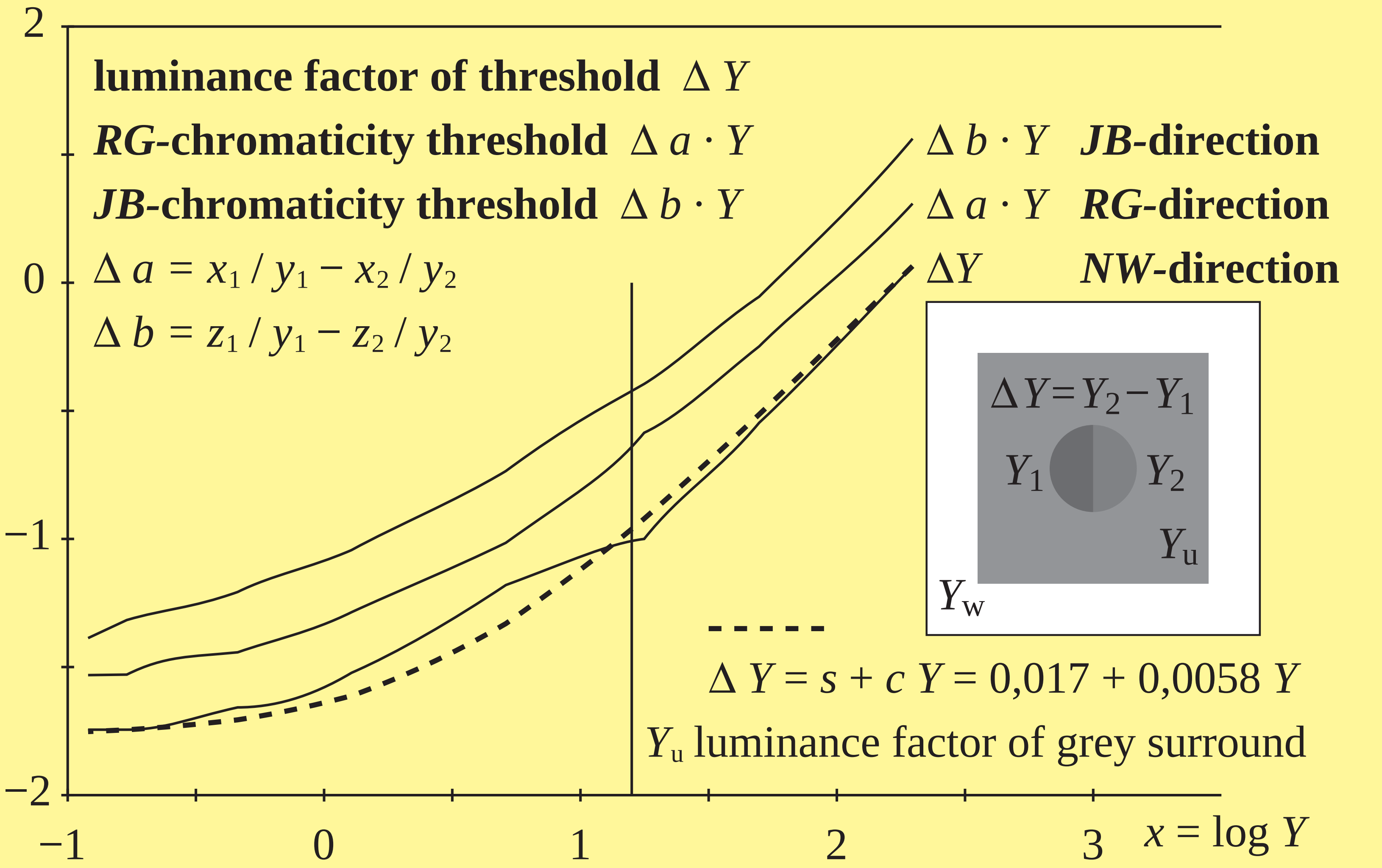


H03/E8280−2N

Plot of colour threshold experiments

NW*-achromatic- as well as *RG*- and *JB*-chrom. thresholds as function of *Y

experiments and data: BAM-research report no. 115 (1985), page 72



Example threshold metric for complementary optimal colours

$$\text{delta } E^*_{ABY,th} = \text{const} \{ [(\text{delta } A_{01}) / A_{01}]^2 + [(\text{delta } B_{01}) / B_{01}]^2 + [(\text{delta } Y_{01}) / Y_{01}]^2 \}^{1/2}$$

We have to show that the threshold difference is equal for complementary optimal colours. For the **complementary** colours it is always valid $X_{01c} = 1 - X_{01}$, $Y_{01c} = 1 - Y_{01}$, $Z_{01c} = 1 - Z_{01}$. Therefore

$$A_{01c} = X_{01c} - Y_{01c} = 1 - X_{01} - (1 - Y_{01}) = Y_{01} - X_{01} = - A_{01}$$

and similar for $B_{01c} = - B_{01}$

According to the **Weber-Fechner law** it is valid at threshold for the luminance factor Y_{01}

$(\text{delta } Y_{01}) / Y_{01} = \text{const}$ **different to CIELAB / CIEDE2000**: $(\text{delta } Y_{01}) / [Y_{01}]^{2/3} = \text{const}$

If the basic colour is dark then the complementary is light and vice versa. The Weber-Fechner law leads to the same constant for complementary optimal colours. Therefore

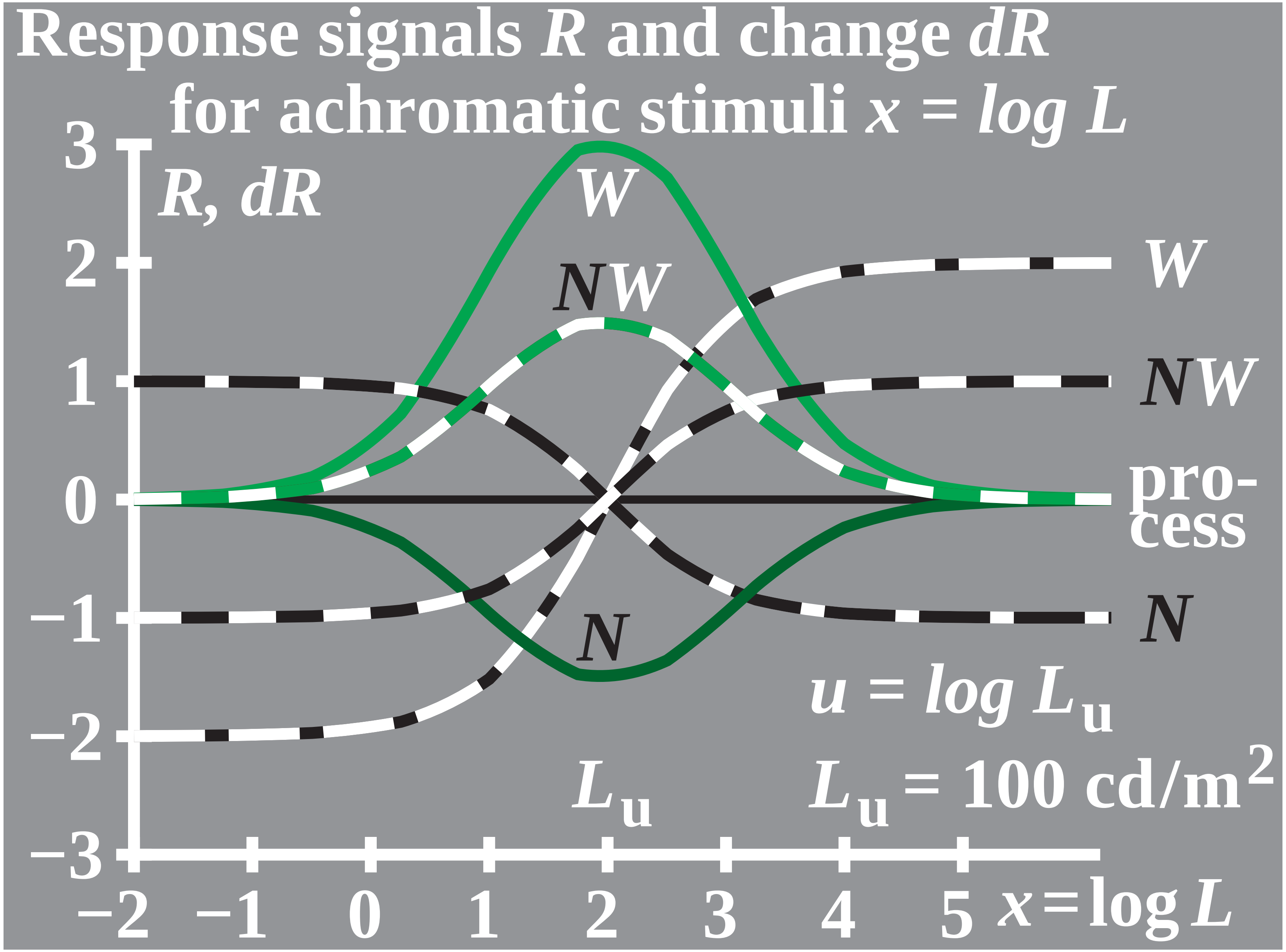
$$(\text{delta } Y_{01}) / Y_{01} = (\text{delta } Y_{01c}) / Y_{01c}$$

Therefore the three components of the first equation are equal for complementary colours or

$$\text{delta } E^*_{ABY,th,basic\ colour} = \text{delta } E^*_{ABY,th,complementary\ colour}$$

Experimental and equation result for the above formula:
The threshold is equal for complementary optimal colours and also equal for all other comlementary colours which mix to "white", e. g. the complementary colours "red" and "cyan" on the monitor.

Change of Signals for two opponent threshold processes



T03/E8241−651. OLMK8931

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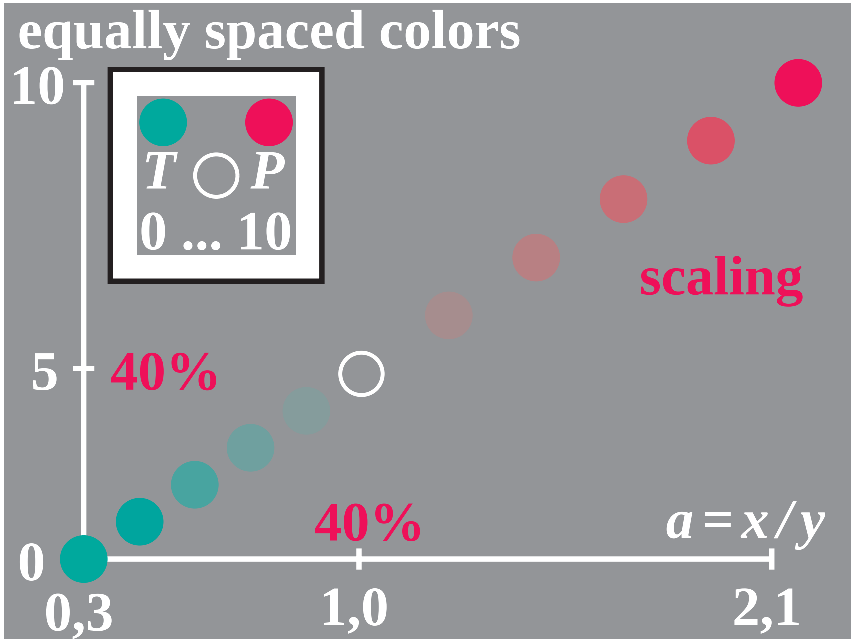
Scaling and threshold experiments



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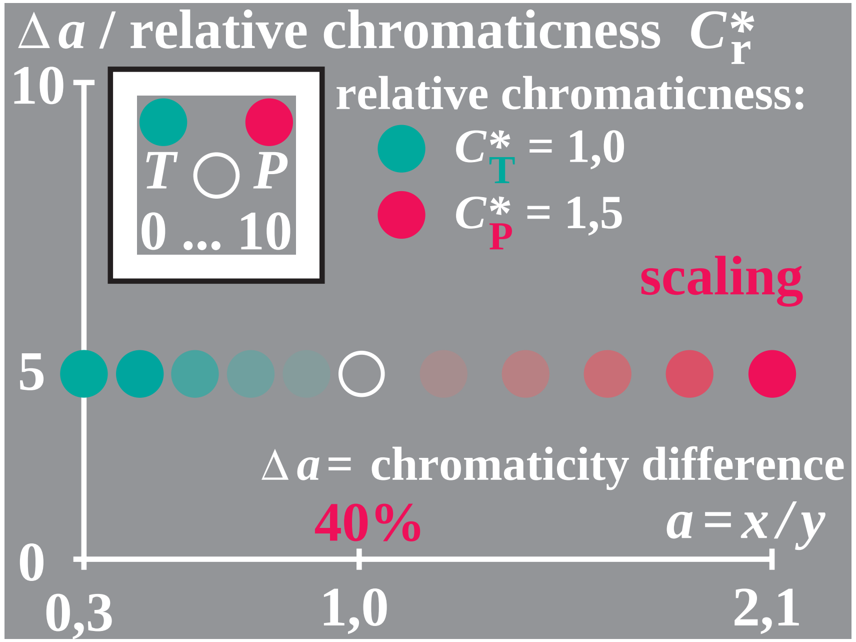

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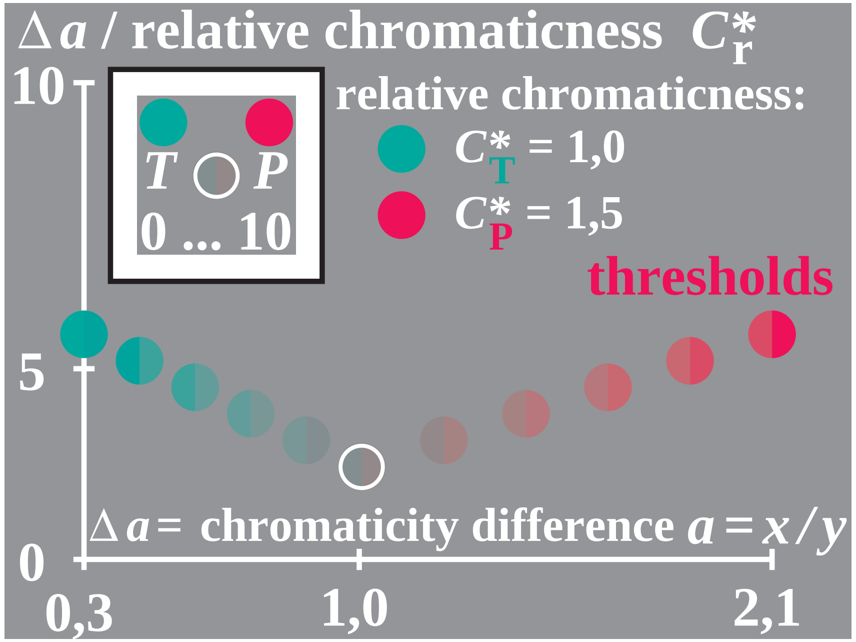

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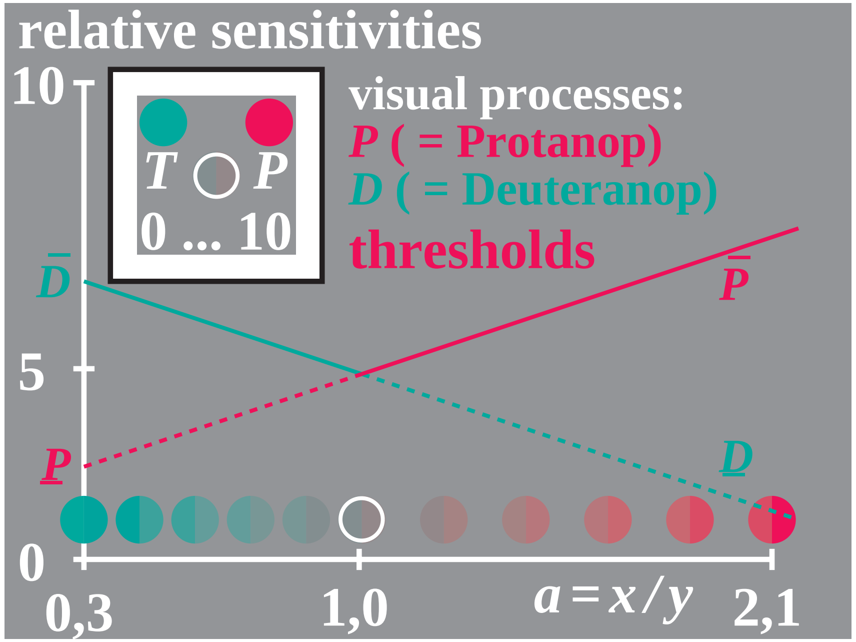
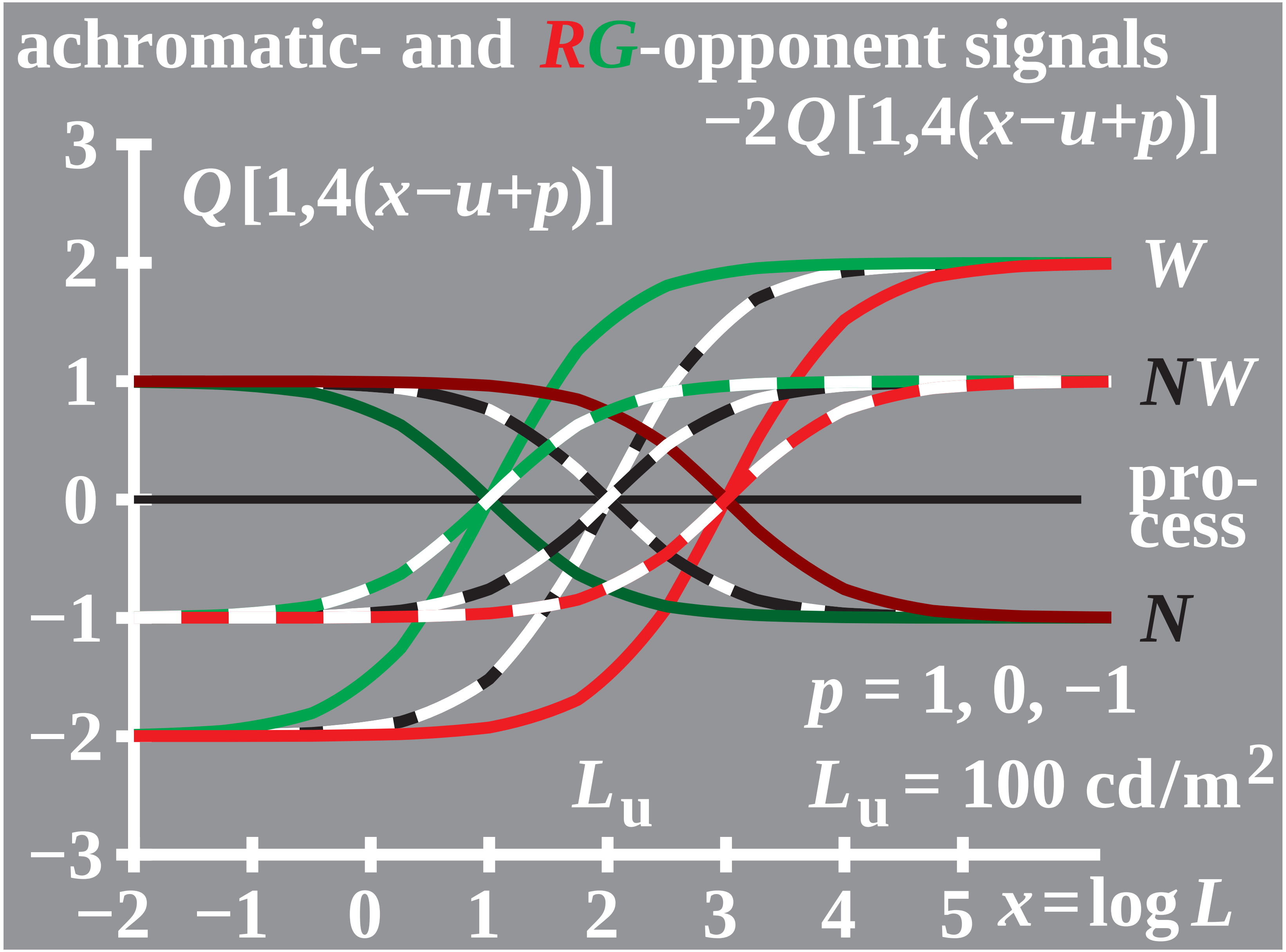


T03/E8210−6N

Signals for two opponent threshold processes and the sum



T03/E8241−549. OLMK8931

Summary

- **Threshold equations describe the threshold as function of chromaticity *a=x/y* in RG direction for equal luminance factor *Y* by**

$$\text{delta } E^*_a \sim \text{delta } a \,/\, [1 + \text{const } |a-a_n|]$$
$$\sim \text{delta } C^*_a \,/\, [1 + \text{const } C^*_a]$$

- **Scaling equations describe the scaling of CIELAB as function of chromaticity *a=x/y* in RG direction for equal luminance factor *Y* by**

$$\text{delta } E^*_a \sim \text{delta } a$$
$$\sim \text{delta } C^*_a$$

- **A threshold equation describes the equal threshold for complementary optimal colours (Holtsmark-Valberg experiments)**

Application conditions:

CIE daylight D65, 45/0 geometry, 2^o observer, 300 cd/m^2 for white

color threshold formula LABJNDS 1985 (JND=just noticeable difference)

$$\Delta E^{*}_{JND} = Y_0 \, [\, (\Delta Y)^2 + (\, a_0 \, \Delta a'' \cdot Y)^2 + (\, b_0 \, \Delta b'' \cdot Y)^2]^{1/2} \, / \, (\, s + d \, Y^{e})$$

$a = x / y \quad a_n = x_n / y_n \quad b = -\,0{,}4 \, z / y \quad b_n = -\,0{,}4 \, z_n / y_n$

$a'' = a_n + (\, a - a_n) / (\, 1 + 0{,}5 \, |a - a_n| \,)$

$b'' = b_n + (\, b - b_n) / (\, 1 + 0{,}5 \, |b - b_n| \,)$

n = D65 or A (surround)

$Y = (\, Y_1 + Y_2 \,) / 2 \quad \Delta Y = Y_1 - Y_2 \quad \Delta a'' = a''_1 - a''_2 \quad \Delta b'' = b''_1 - b''_2$

$s = 0{,}0170 \quad d = 0{,}0058 \quad e = 1{,}0$

$a_0 = 1{,}0 \quad b_0 = 1{,}8 \quad Y_0 = 1{,}5$ *surround D65*

$a_0 = 1{,}0 \quad b_0 = 1{,}7 \quad Y_0 = 1{,}0$ *surround A*

H03/E8560−7N

Equations for colour scaling experimentsq

color space CIELAB 1976, color values, -attributes, -coordinates *(a’, b’)*

tristimulus values X, Y, Z -> color coordinates L^*, a^*, b^*

lightness $L^* = 116\,(Y/Y_n)^{1/3} - 16$

RG−chromaticness $a^* = 500\,[\,(X/X_n)^{1/3} - (Y/Y_n)^{1/3}\,] = 500\,[\,a' - a'_n]\,Y^{1/3}$

JB−chromaticness $b^* = 200\,[\,(Y/Y_n)^{1/3} - (Z/Z_n)^{1/3}\,] = 500\,[\,b' - b'_n]\,Y^{1/3}$

color coordinates L^*, a^*, b^* -> tristimulus values X, Y, Z

tristimulus values

$$X = X_n\,[\,(L^* + 16)\,/\,116 + a^*/500\,]^3$$

$$Y = Y_n\,[\,(L^* + 16)\,/\,116\,]^3$$

$$Z = Z_n\,[\,(L^* + 16)\,/\,116 - b^*/200\,]^3$$

coordinates (a’,b’) for CIELAB 1976, LABHNU 1977, LABHNUx 1979

CIELAB 1976, 2^o	$a' = 0{,}2191\,(x/y)^{1/3}$		$b' = -\,0{,}08376\,(z/y)^{1/3}$
LABHNU 1977	$a' = (x/y + 1/6)^{1/3}\,/\,4$		$b' = -\,(z/y + 1/6)^{1/3}\,/\,12$
LABHNU1 1979	$a' = (x/y + 1)\,/\,15$	*linear!*	$b' = -\,(z/y + 1/6)^{1/3}\,/\,12$
LABHNU2 1979	$a' = (x/y + 1/6)^{2/3}\,/\,15$		$b' = -\,(z/y + 1/6)^{1/3}\,/\,12$
CIELAB 1976, 10^o	$a' = 0{,}2193\,(x_{10}\,/\,y_{10})^{1/3}$		$b' = -\,0{,}08417\,(z_{10}\,/\,y_{10})^{1/3}$
constants for	$a_2 = 500\,(1/X_n)^{1/3} = 0{,}2191$		$b_2 = -\,200\,(1/Z_n)^{1/3} = -\,0{,}08376$
CIELAB, 2^o,10^o	$a_{10} = 500\,(1/X_{n10})^{1/3} = 0{,}2193$		$b_{10} = -\,200\,(1/Z_{n10})^{1/3} = -\,0{,}08417$