Part 7: Color Differences

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7.1. Introduction

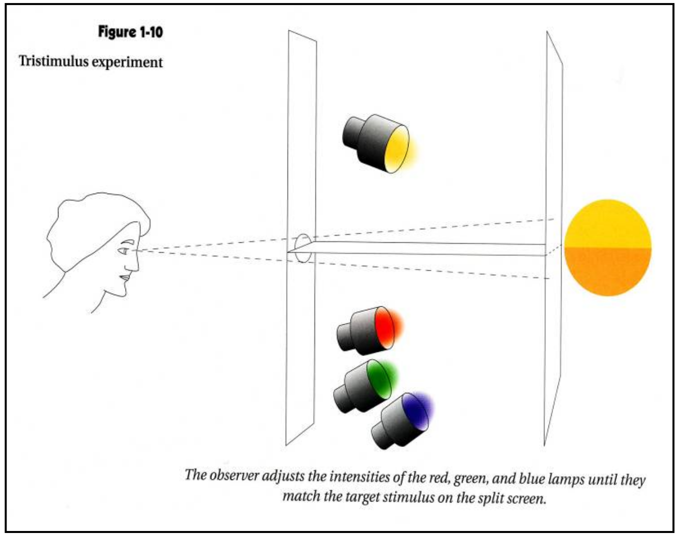
Basic and advanced colorimetry

Wyszecki's description of basic colorimetry is as follows:

'Colorimetry, in its strict sense, is a tool used to making a prediction on whether two lights (visual stimuli) of different spectral power distributions will match in colour for certain given conditions of observation. The prediction is made by determining the tristimulus values of the two visual stimuli. If the tristimulus values of a stimulus are identical to those of the other stimulus, a colour match will be observed by an average observer with normal colour vision.'

Basic colorimetry:

- CIE systems: the basis for numerical color specification.
- Specify stimuli in terms of their sensory potential for an average human observer.
- Foundation for color appearance models.



7.1. Introduction

Basic and advanced colorimetry

Wyszecki describes the domain of advanced colorimetry as follow:

'Colorimetry in its broader sense includes methods of assessing the appearance of colour stimuli presented to the observer in complicated surroundings as they may occur in everyday life. This is considered the ultimate goal of colorimetry, but because of its enormous complexity, this goal is far from being reached. On the other hand, certain more restricted aspects of the overall problem of predicting colour appearance of stimuli seem somewhat less elusive. The outstanding examples are the measurement of colour differences, whiteness, and chromatic adaptation. Though these problems are still essentially unresolved, the developments in these areas are of considerable interest and practical importance.'

Advanced colorimetry:

- Specification of color difference perceptions and color appearance.

7.1. Introduction

Advanced Colorimetry

Color differences: "Color difference (perceived): The magnitude and character of the difference between two colors described by such terms as redder, bluer, lighter, darker, grayer or cleaner. Color difference (computed) the magnitude and direction of the difference between two psychophysical color stimuli and their components computed from tristimulus values, or chromaticity coordinates and luminance factor, by means of a specific set of color-difference equations" (ASTM, E284, 1995).

Color Appearance Models: "A color appearance model provides a viewing condition specific method for transforming tristimulus values to and/or from perceptual attribute correlates" (CIE Pub. 159-2004).

Industrial colorimetry: Colorimetry applied to solve industrial problems.

Color management: Management of the transfer of color information between image capture devices and image production devices.

7.1. Introduction

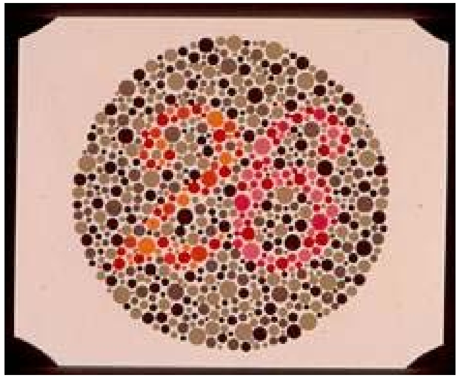
Phase 1. The CIE XYZ space is not uniform; it was not designed for color-difference measurements but just for color-matching.

Phase 2. Two color stimuli, of the same size and shape, which are observed under the same experimental conditions (enough restrictive: an specific aspect of appearance).

Phase 3. Color Appearance (not global): color, gloss, translucency, texture…

7.1. Introduction

Why to study color differences?

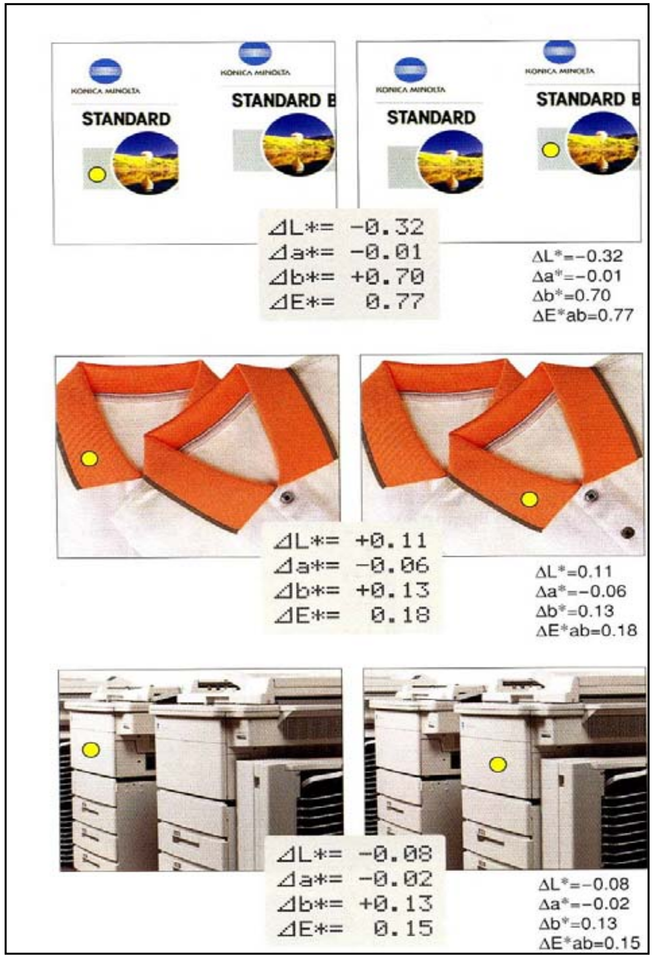


- Scientific knowledge
  - Color vision mechanisms
  - Color spaces …
- Industrial control
  - Color reproduction
  - Color tolerances
  - Color fastness …
- Applications
  - Food colorimetry
  - Fine Arts & restoration
  - Metamerism…

In usual practice color differences (threshold, tolerances, etc.) are much more interesting than simple color specification…

7.1. Introduction

Color control: cars, printed material, textiles, plastic products, etc.



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7.2. Threshold, suprathreshold and large color differences

The size of color differences

The performance of the human visual system (HVS) depends on color-difference size.

What is the size of a just noticeable difference (jnd)?

- ✓ The just noticeable color-difference is normally accepted as 1.0 MacAdam's unit (that is, 1.0 unit from the FMC-2 formula). We can conclude that 1 jnd = 0.56 CIELAB units. (R.D. Lozano, "El color y su medición", pp. 276-277)
- ✓ A rigorous tolerance is from 2 to 5 MacAdam's units, that is, 1.1 to 2.8 CIELAB units.
- ✓ A normal requirement in industry may be from 5 to 10 MacAdam's units, that is, 2.8 to 5.6 CIELAB units. More than 10 MacAdam's units (5.6 CIELAB units) is a loose tolerance.
- ✓ 0.38 CIELAB units for Witt's (1990) ellipses, around 1.0 CIELAB unit for Wyszecki-Fielder's (1971) ellipses, and 1.75 CIELAB units for suprathreshold RIT-DuPont (1991) ellipses (JOSA A, 9, 1247-1254, 1992).

Threshold color differences

Threshold differences (just noticeable differences: jnd's). Approximately $\Delta E^*_{ab}<1$

7.2. Threshold, suprathreshold and large color differences

Threshold color differences

Threshold differences (just noticeable differences: jnd).

Approximately $\Delta E^*_{ab}<1$

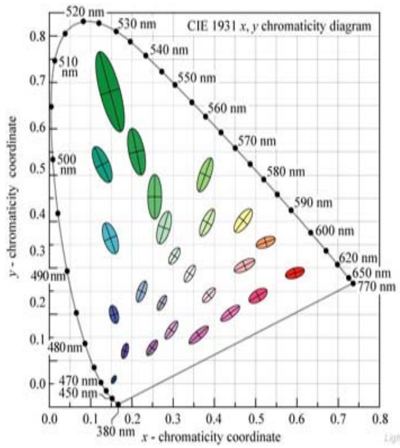


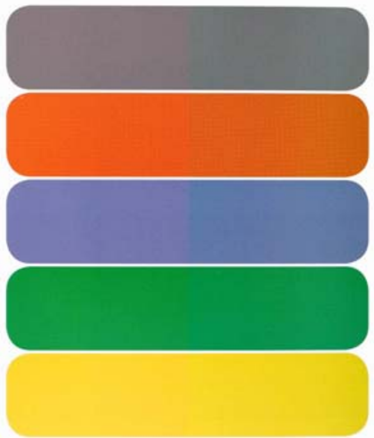
Fig. 17.5. MacAdam ellipses plotted in the CIE 1931 (x, y) chromaticity diagram. The axes of the ellipses are ten times their actual lengths (after MacAdam, 1943; Wright, 1943; MacAdam, 1993).

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

Small-medium color differences. Suprathreshold color differences

They use to be the most important color differences in industrial practice.

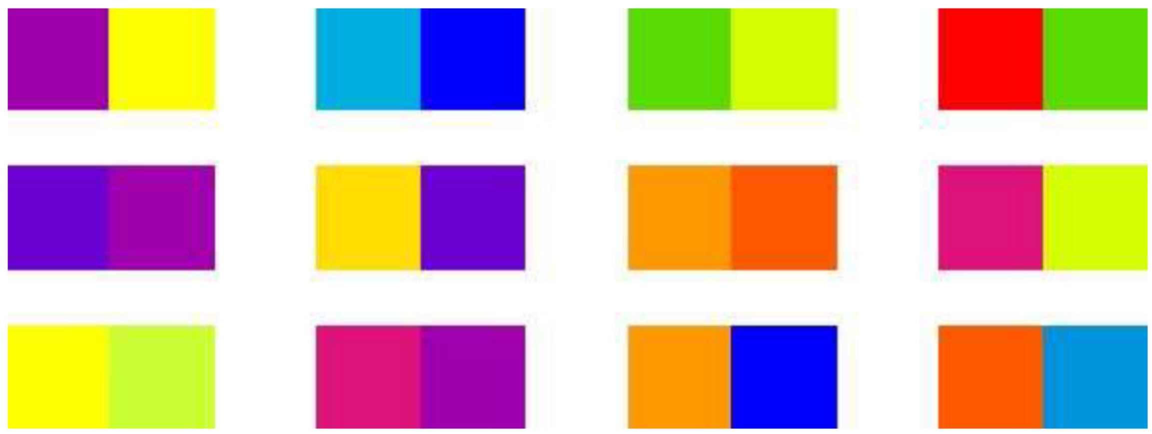
Approximately $1\leq\Delta E^*_{ab}\leq 5$

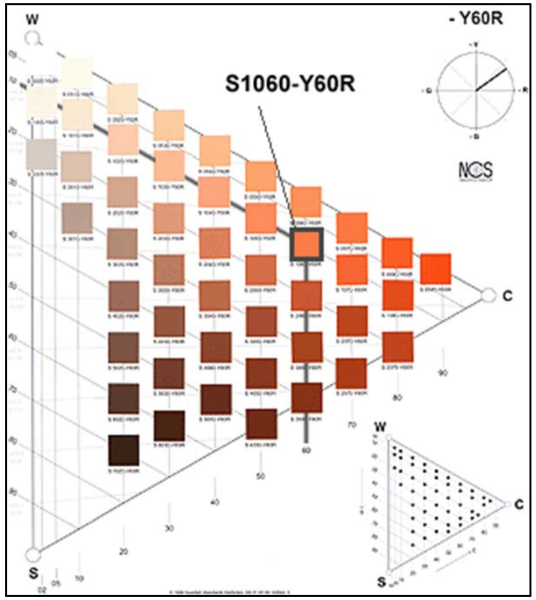


7.2. Threshold, suprathreshold and large color differences

Large color differences

Those in most color order systems. Approximately $\Delta E^*_{ab}>5$





7.2. Threshold, suprathreshold and large color differences

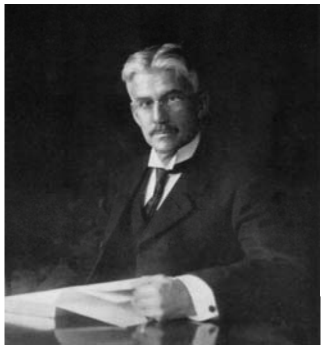
Large color differences: Munsell Color System

The Munsell system denotes a color appearance through its Munsell hue, value, and chroma:

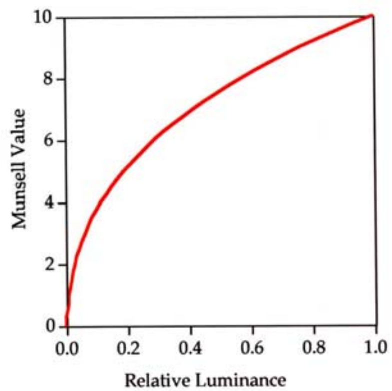
(**HUE VALUE/CHROMA**).

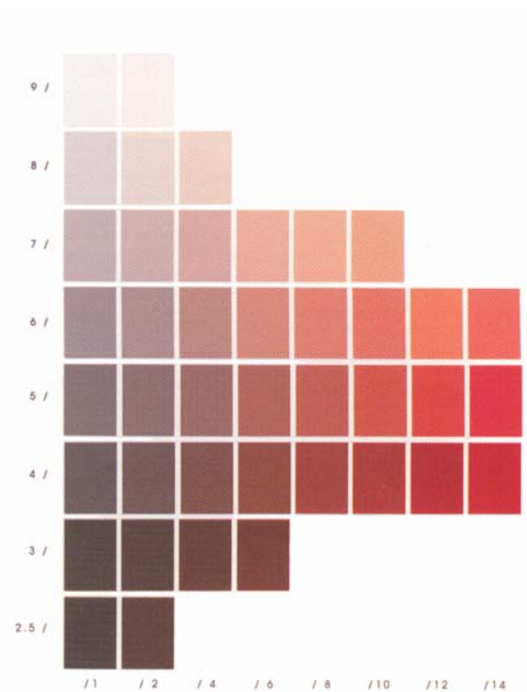
Munsell's objective was to specify colors with equal visual increments along each of the three perceptual dimensions.

Samples (chips) in the "Munsell Book of Color" are designed to be seen under illuminant C, 2 degree observer, Y=20 neutral background.



Albert Henry Munsell

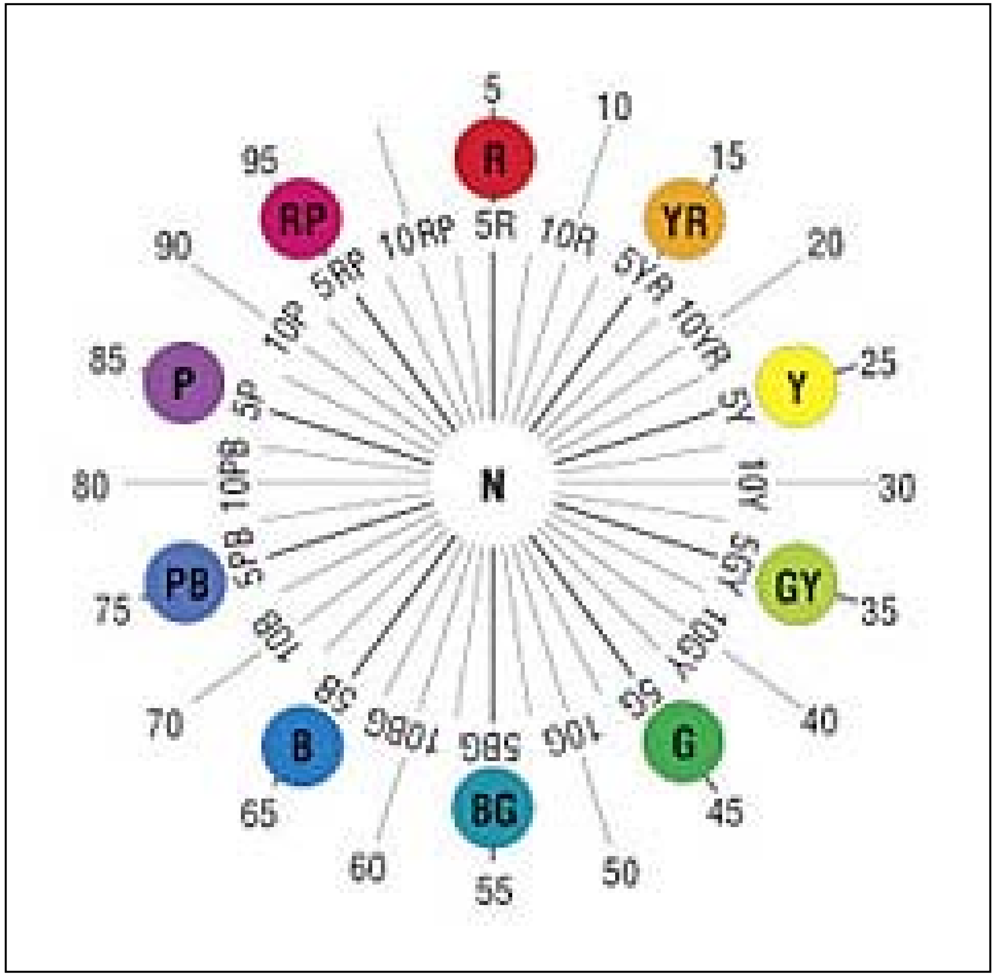




$$Y = 1.2219V - 0.23111V^2 + 0.23951V^3 - 0.021009V^4 + 0.0008404V^5$$

7.2. Threshold, suprathreshold and large color differences

Large color differences: Munsell Color System



Munsell Hue

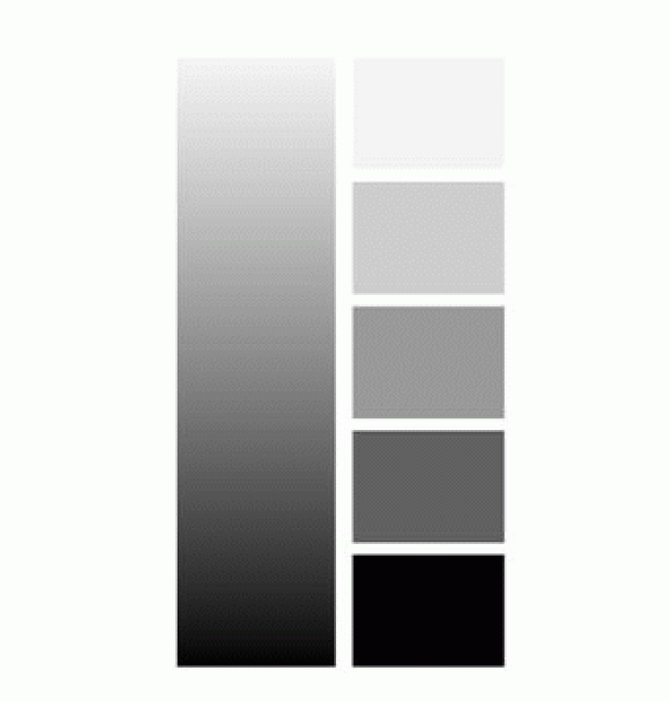
Major Hues:

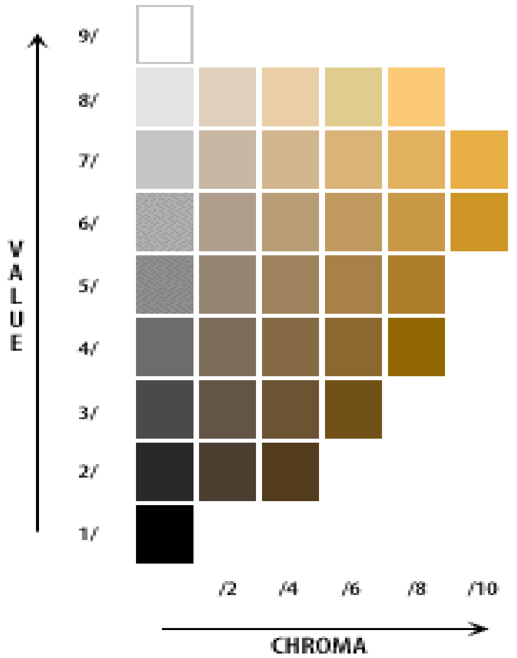
- **Red (5R)**
- Yellow-Red (5YR)
- **Yellow (5Y)**
- Green-Yellow (5GY)
- **Green (5G)**
- Blue-Green (5BG)
- **Blue (5B)**
- Purple-Blue (5PB)
- **Purple (5P)**
- Red-Purple (5RP)

7.2. Threshold, suprathreshold and large color differences

Large color differences: Munsell Color System

Munsell Value





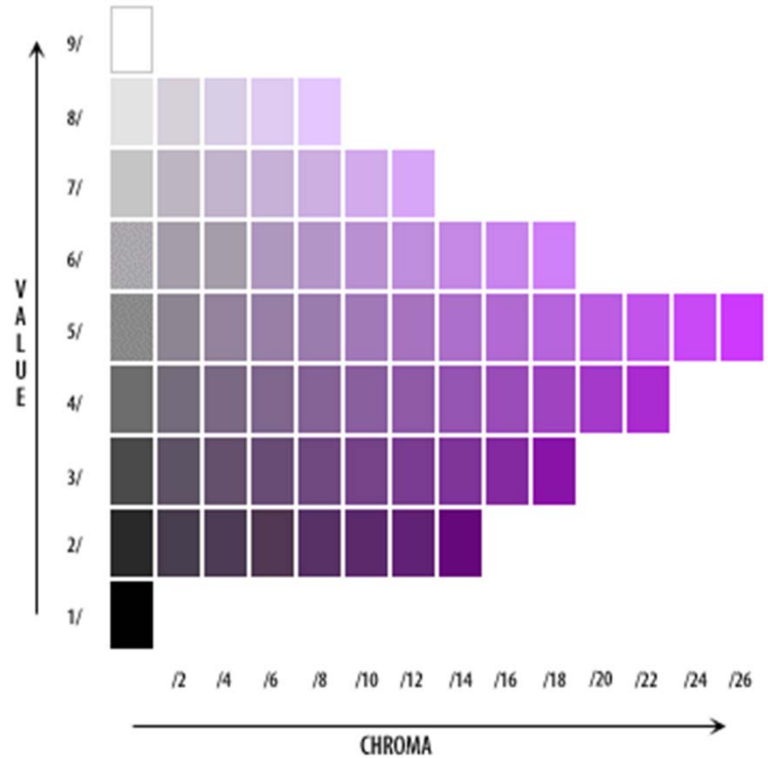
The lightness scale is represented by the Munsell Value scale with black denoted by 0/ and white by 10/. There are nine grays placed uniformly in between. V ≈ L*/10

7.2. Threshold, suprathreshold and large color differences

Large color differences: Munsell Color System

Munsell Chroma

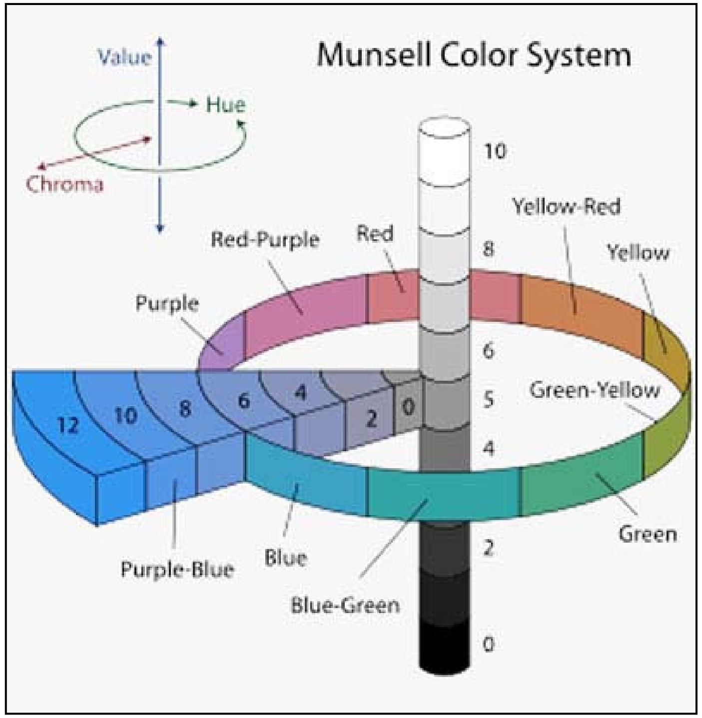
A Color Notation, 1916: “The degree of departure of a color sensation from that of white or gray; the intensity of distinctive hue, color intensity”.

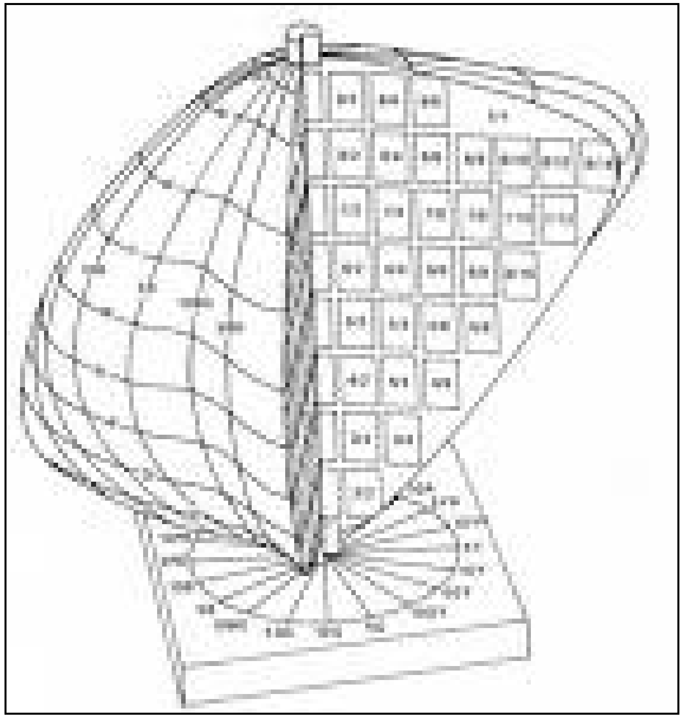


Munsell Chroma increases in steps of two (/2, /4,…,/10, /12…).

7.2. Threshold, suprathreshold and large color differences

Large color differences: Munsell Color System



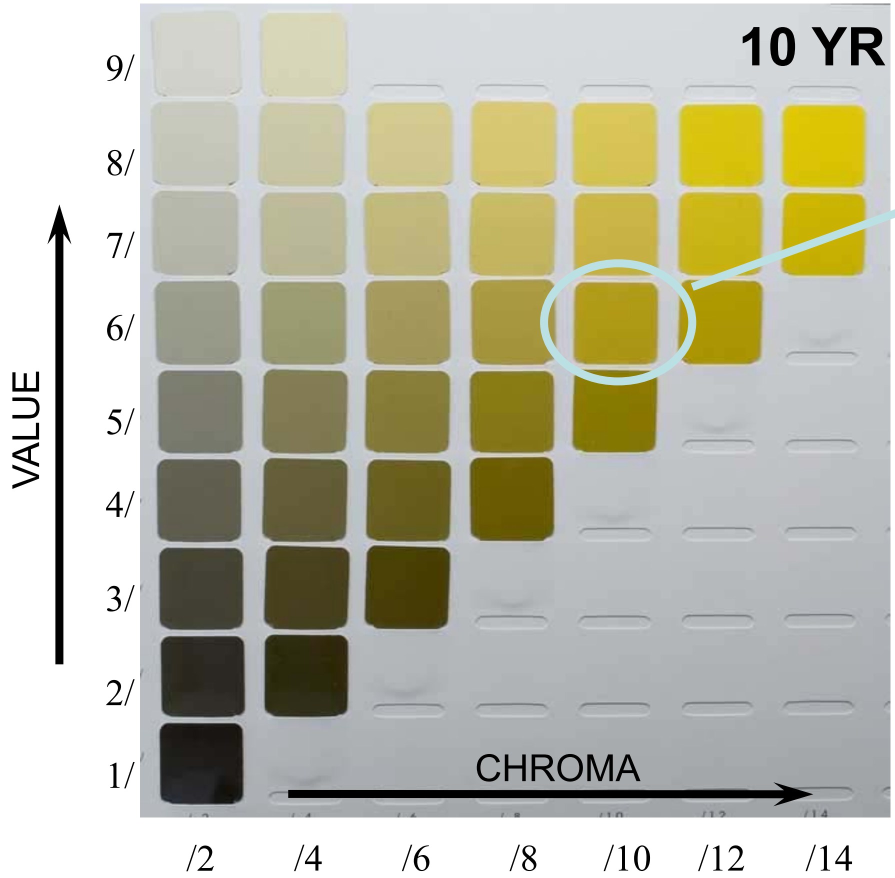


Maximum available Chroma values change with Value and Hue, because pigments employed yield a specific color gamut.

7.2. Threshold, suprathreshold and large color differences

Large color differences: Munsell Color System

Munsell Notation



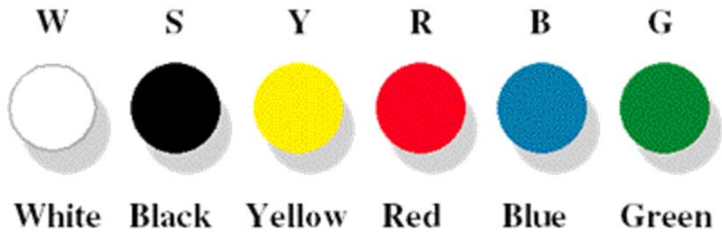
10YR 6/10

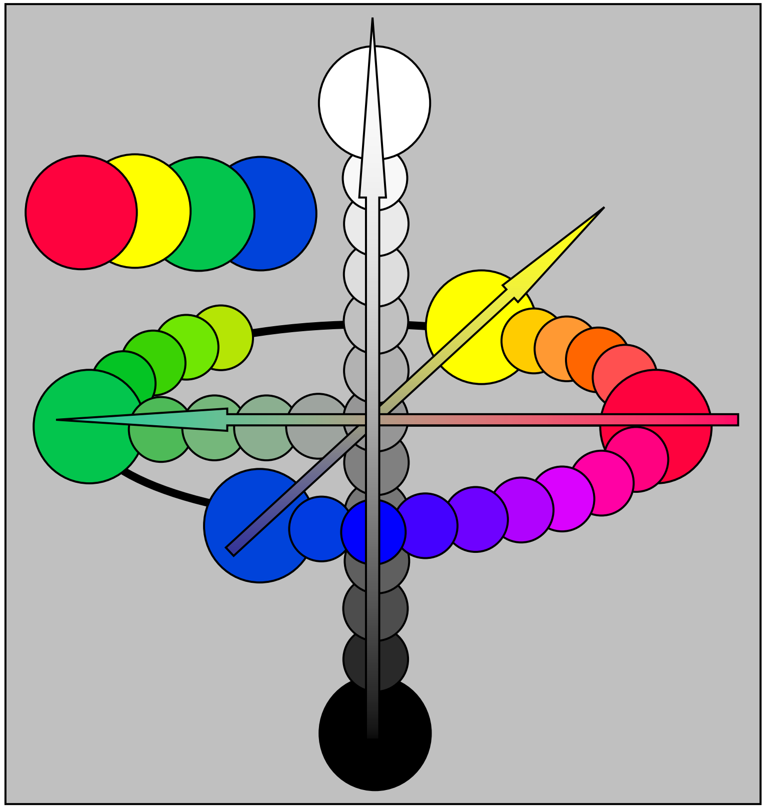
7.2. Threshold, suprathreshold and large color differences

Large color differences: The Swedish Natural Color System (NCS)

Based on the opponent colors theory of Hering.

Six elementary colors: W, S, Y, R, B, G.





The hue circle four quadrants with the unique hues: red, yellow, green, blue. Hues are given representing the relative perceptual composition of the two neighboring unique hues: Y70R.

Blackness (s), whiteness (w), and chromaticness (c) must sum to 100.

BLACKNESS CHROMATICNESS - HUE

7.2. Threshold, suprathreshold and large color differences

Chromaticity differences

Just noticeable chromaticity differences (line thresholds) measured by Wright in 1941 at constant illuminance (100 td), using a 2° visual field, dark surround, and 4 observers.

Note the lack of uniformity of the CIE 1931 chromaticity diagram: the "green" region is spaced out, compared with the "bluish-purple" region.

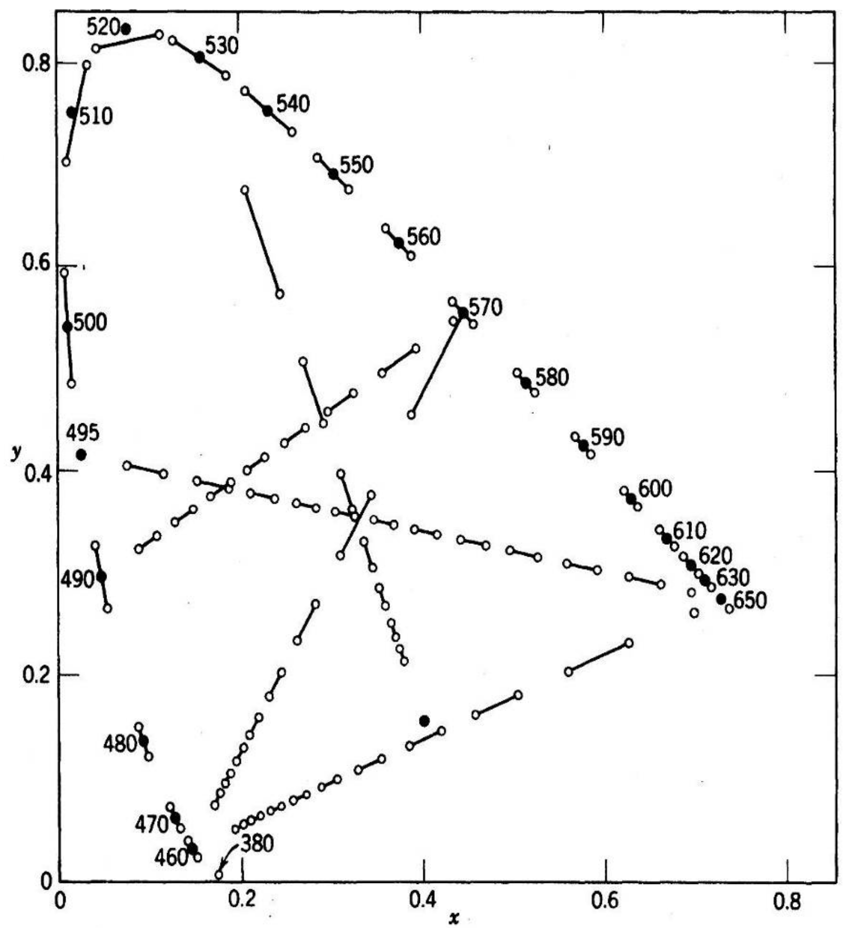


Fig. 1(7.10.5). CIE 1931 chromaticity diagram showing chromaticity differences of perceptually equal size; Wright's dashes (from Judd and Wyszecki, 1975).

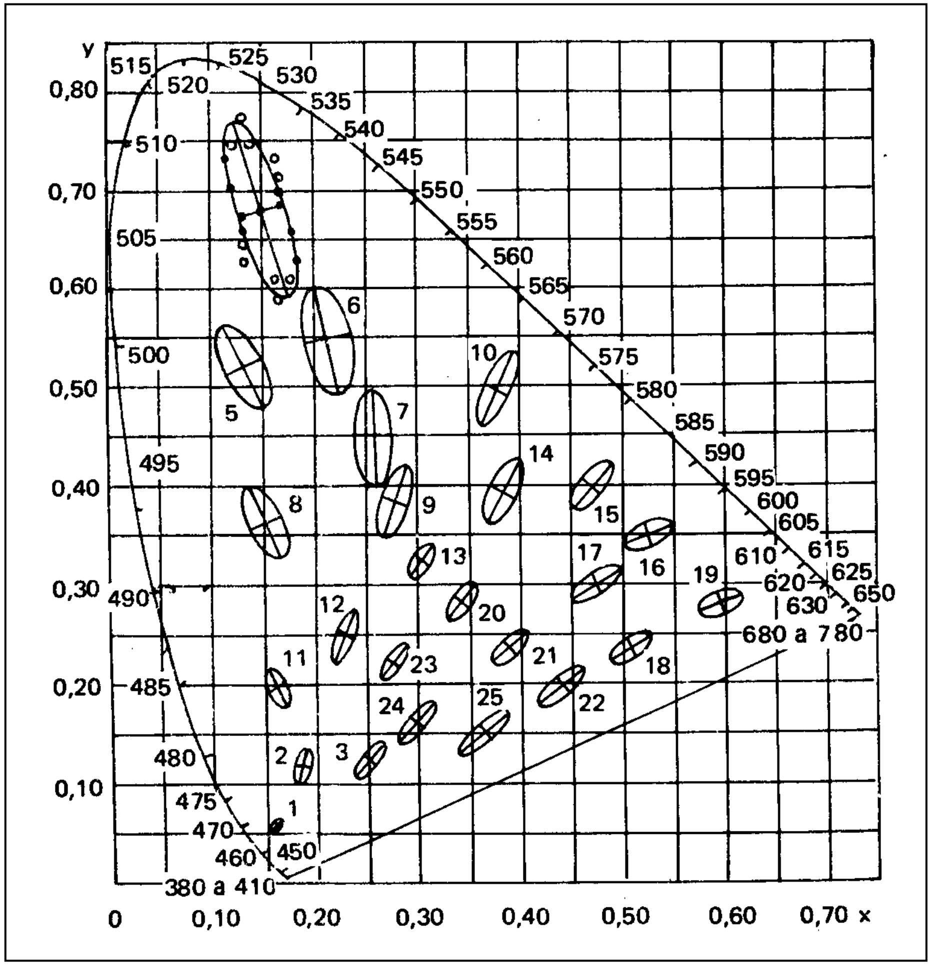
7.2. Threshold, suprathreshold and large color differences

Chromaticity differences: MacAdam's ellipses (1942)

- ✓ Aperture (light) colors.
- ✓ Color-matching ellipses.
- ✓ Only 1 observer (PGN).
- ✓ Visual field: 2º.
- ✓ Background: 42º diameter, illuminant C, 24 cd/m^2.
- ✓ 1 jnd ≈ 3 times larger than Standard Deviation in color matching, but more often is taken as 2 times (CIE 101-1993, p. 4)

7.2. Threshold, suprathreshold and large color differences

Chromaticity differences: MacAdam's ellipses (1942)

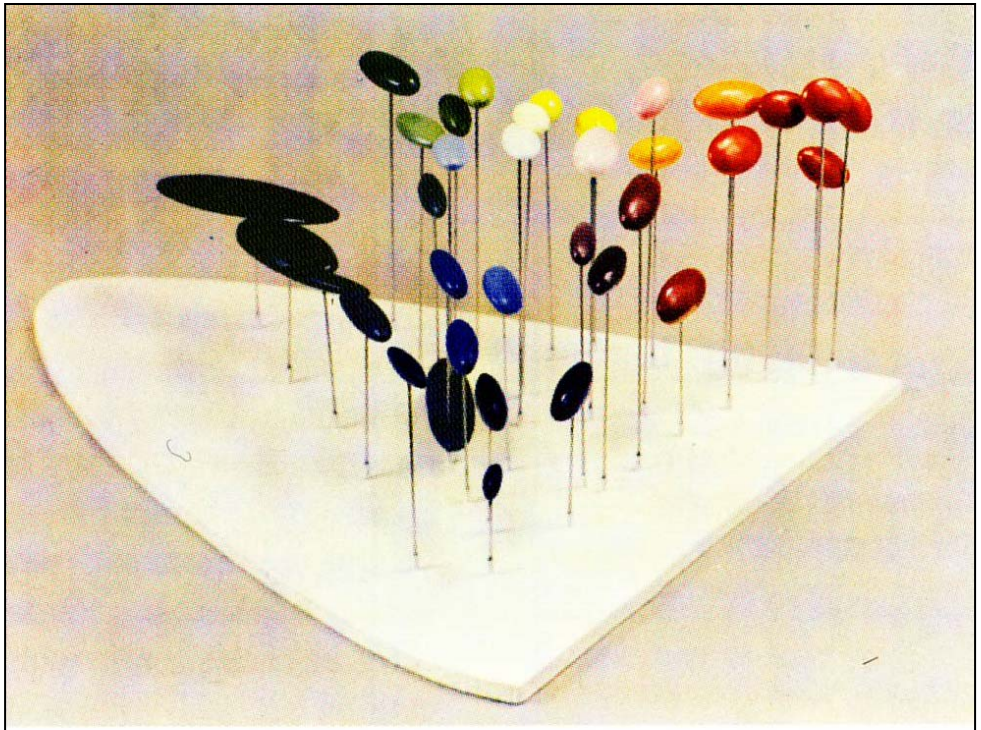


The 25 ellipses measured in famous MacAdam's 1942 experiment, plotted 10 times their real sizes.

Note that smallest ellipses are in the blue region.

7.2. Threshold, suprathreshold and large color differences

Color difference ellipsoids (influence of *Y*): color is three-dimensional



When the experiment included changes in luminance factor in addition to chromaticity, ellipsoids result, such as those derived by Brown (1949).

Brown-MacAdam (1949) ellipsoids

Discrimination improves (i.e. smaller *x*,*y* ellipses) when *Y* increases. However the major semi-axis decreases with *Y* faster than the minor semi-axis.

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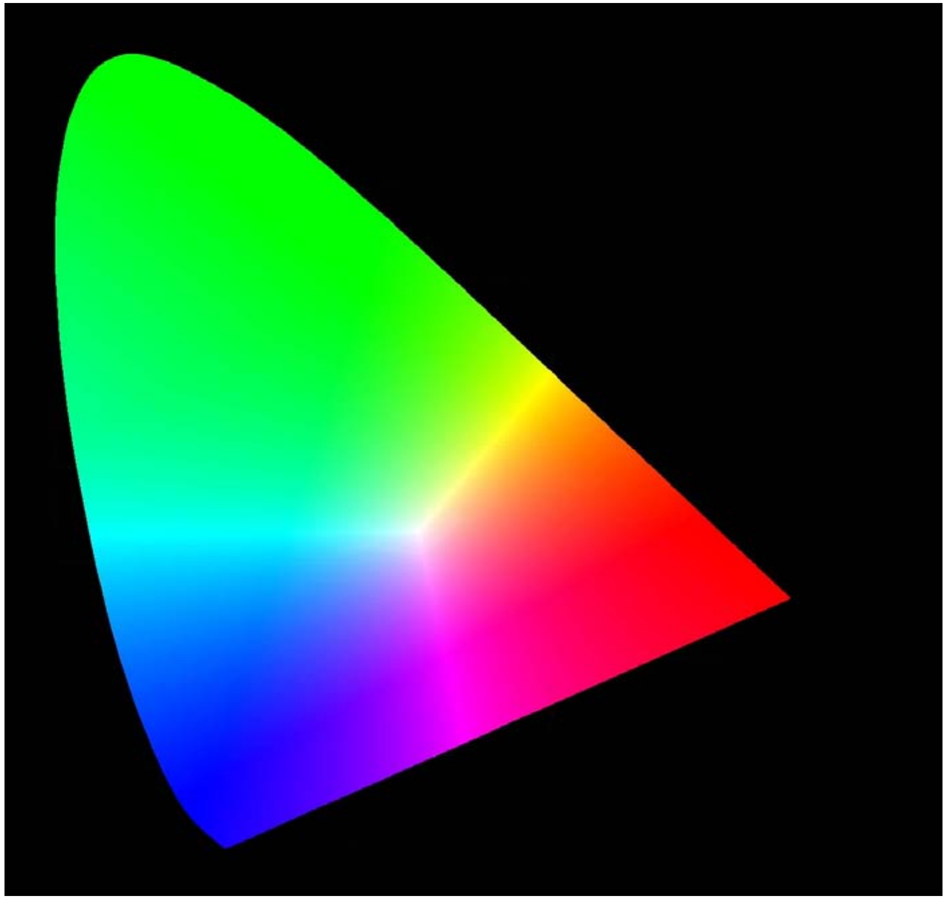
7.3. Number of discernible color

How many colors can we distinguish?

- A lot, infinity!
- Munsell Atlas has around 1600 different samples
- NCS Atlas has around 2000 different colors
- 8 bits images have 256Rx256Gx256B…about 16.000.000



7.3. Number of discernible color

- **Titchener (1896):** 700 brightness + 150 spectral colors + 30.000 color mixed sensations = 30.850 different colors (~33.000 in revised data).
- **Boring et al. (1939):** about 300.000 colors. 156 JND in hue, 16-23 JNDs in saturation, and 572 in brightness.
- **Judd and Kelly (1939):** they mention “10.000.000 surface colors distinguishable in daylight to the trained human eye”, 1.000 gray levels x 100 green-red x 100 yellow-blue.
- **Nickerson and Newhall (1943): f**rom Munsell Book of Color they concluded that, under usual conditions, a normal observer could distinguish 1.875.000 colors, and, under the best viewing conditions 7.500.000 colors.
- **Pointer and Attridge (1998)**: 2.280.000 colors.
- **Chamberlin (1997)**: 220 discernible steps in the Lovibond Red Scale x 220 in the Yellow Scale x 185 in the Blue Scale = 8.954.000 colors.

7.3. Number of discernible color

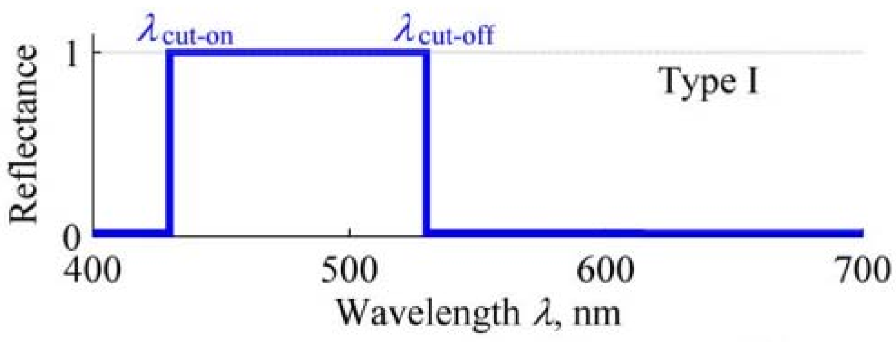
Optimal colors

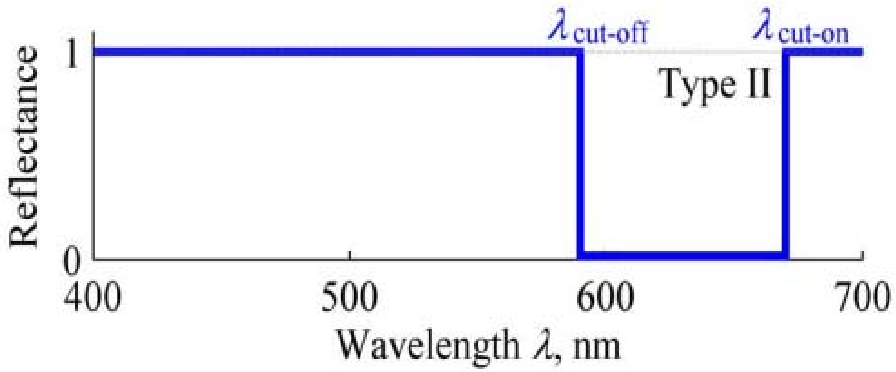
Number of optimal colors could be the limits.

“..the maximum attainable purity for a material, from a specific given visual efficiency and wavelength, can be obtained if the spectrophotometric curve has as possible values zero or one only…”

McAddam 1935, based on Schrödinguer works.

Stxq epgspsw kmzi yw xli pq mxsjtivgitxfpi gspsvih wxq ypyw.





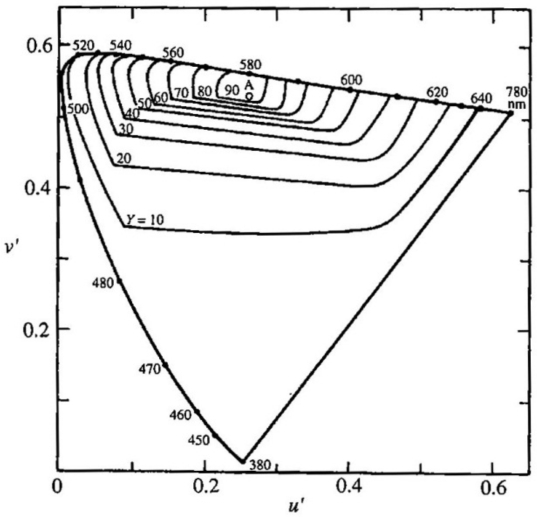
Two types of spectral reflectance/transmittance:

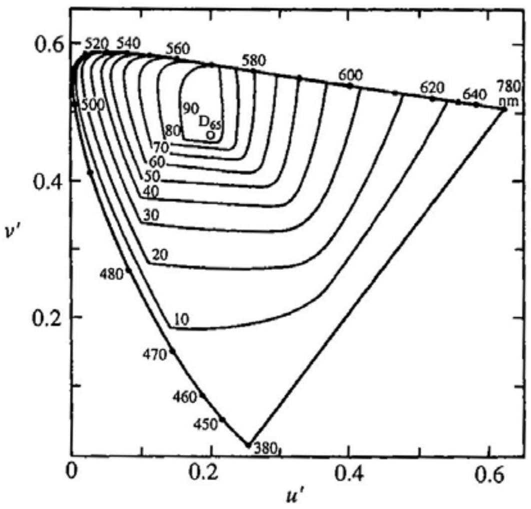
- Type 1 only reflected/transmitted light from λ_{cut-on} to $\lambda_{cut-off}$.
- Type 2 only does not reflected/transmitted light from $\lambda_{cut-off}$ to λ_{cut-on}.

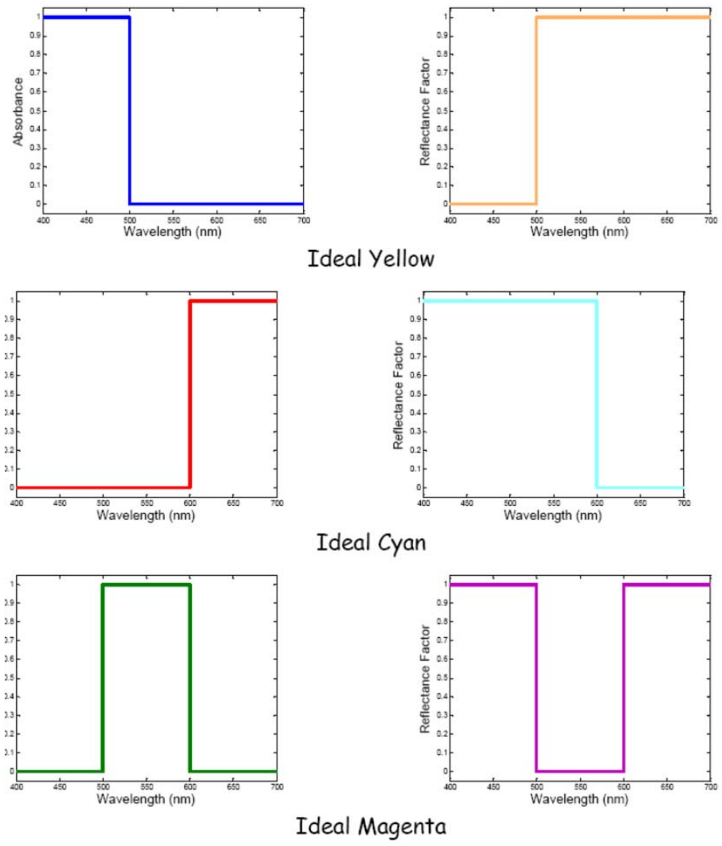
7.3. Number of discernible color

Optimal colors

- This type of reflectance/transmittance is unrealistic.

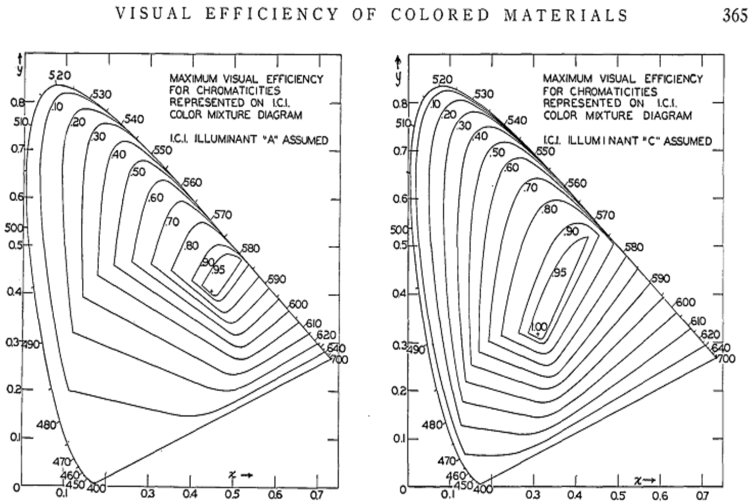




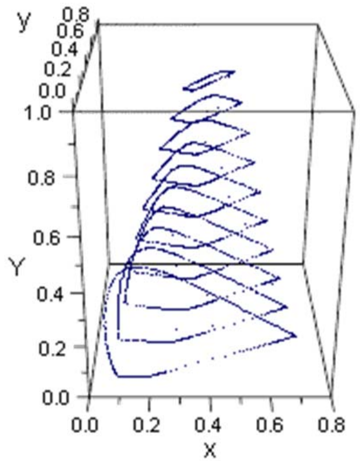


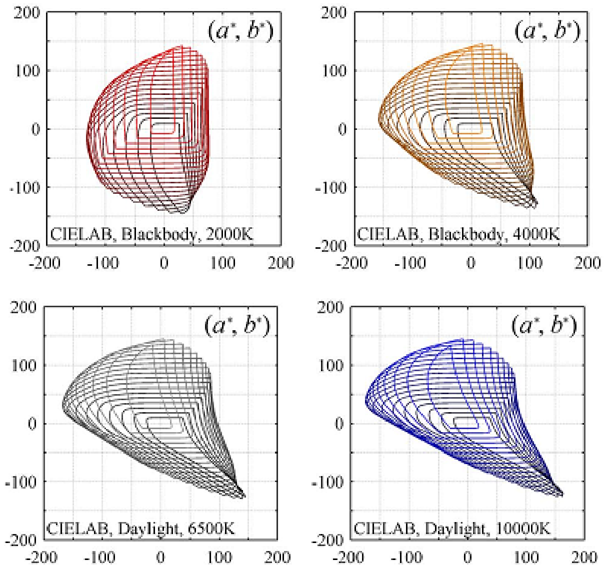
7.3. Number of discernible color

Optimal colors



David L. MacAdam (1935)

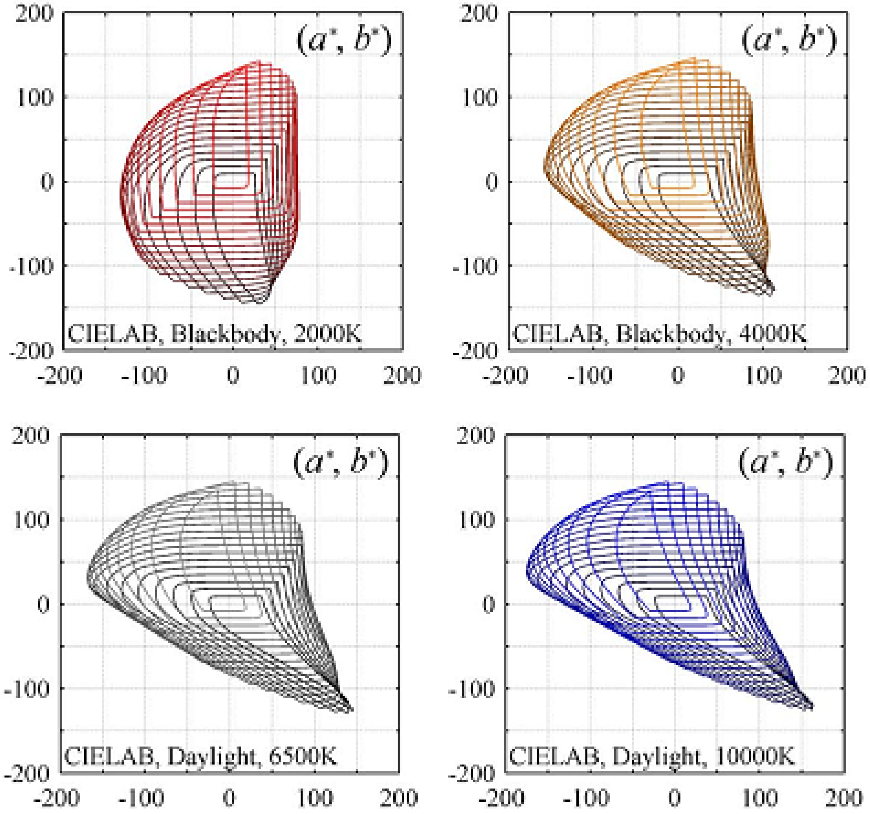




7.3. Number of discernible color

Optimal colors

- Optimal colors give us the limit of perceptible colored stimulus.

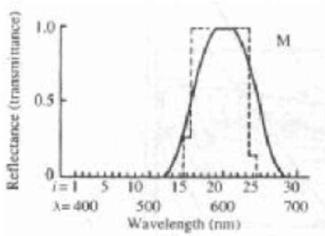


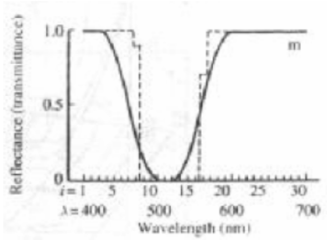
Kenichiro Masaoka 2013

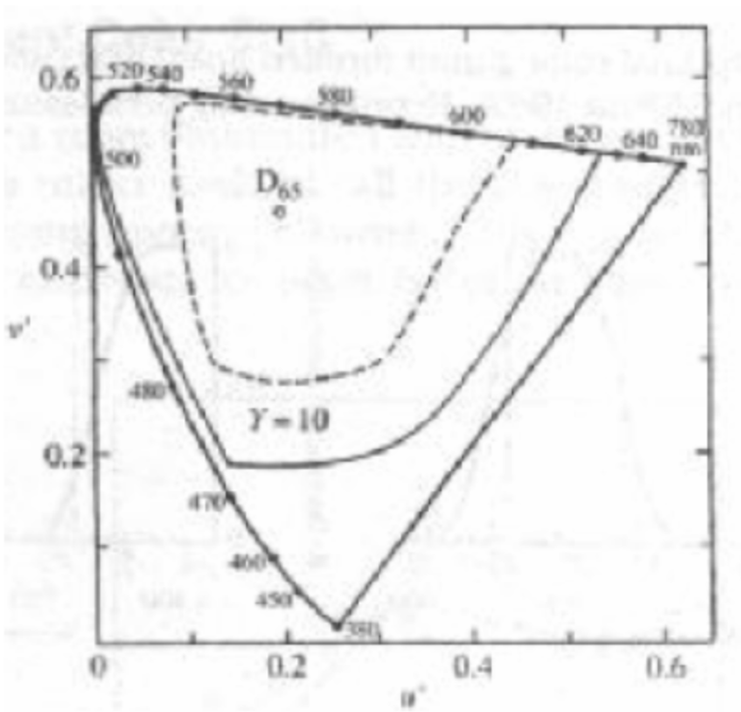
7.3. Number of discernible color

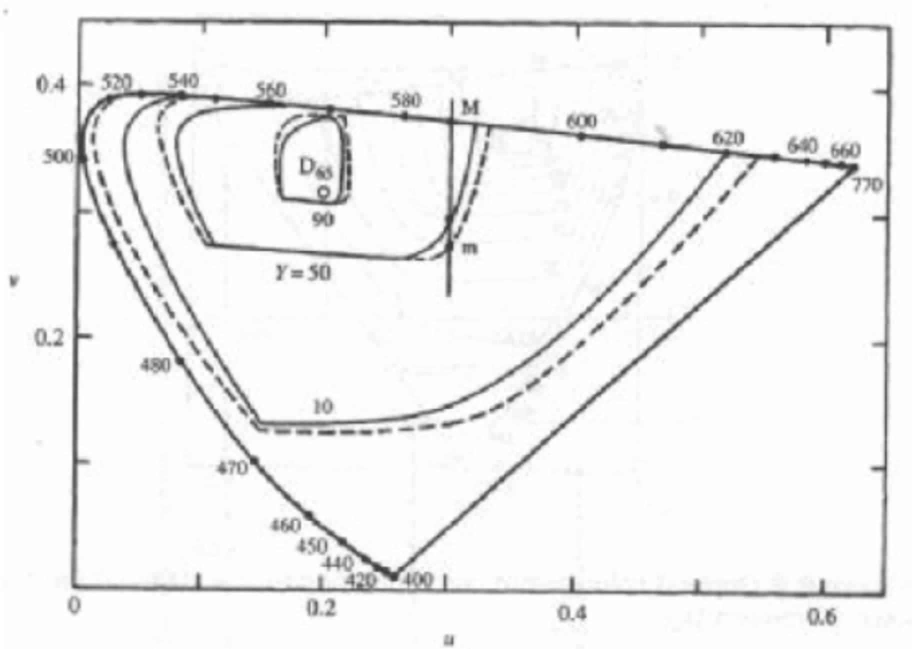
Optimal colors

- It is possible to calculated **pseudo optimal colors** with smooth spectral curves and excitation purity as high as possible.





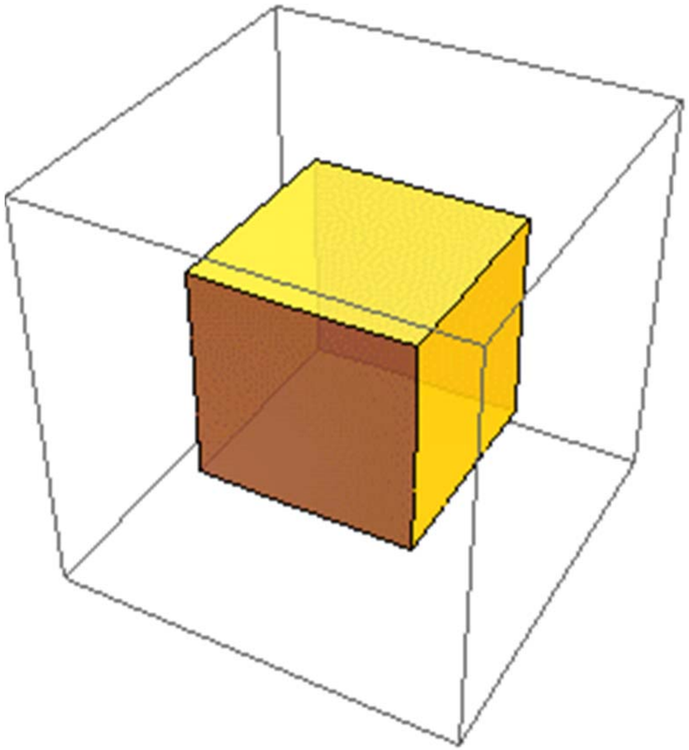




7.3. Number of discernible color

Discernible colors

- How many 1 JND edges cubes are there inside all the color volume?



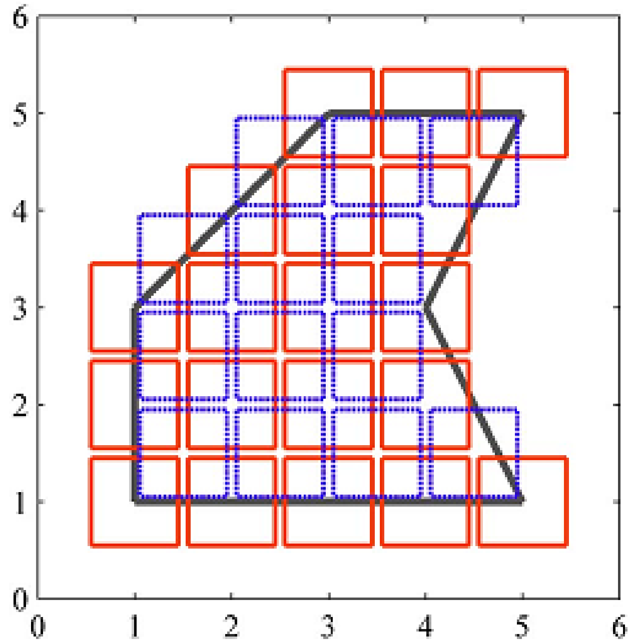
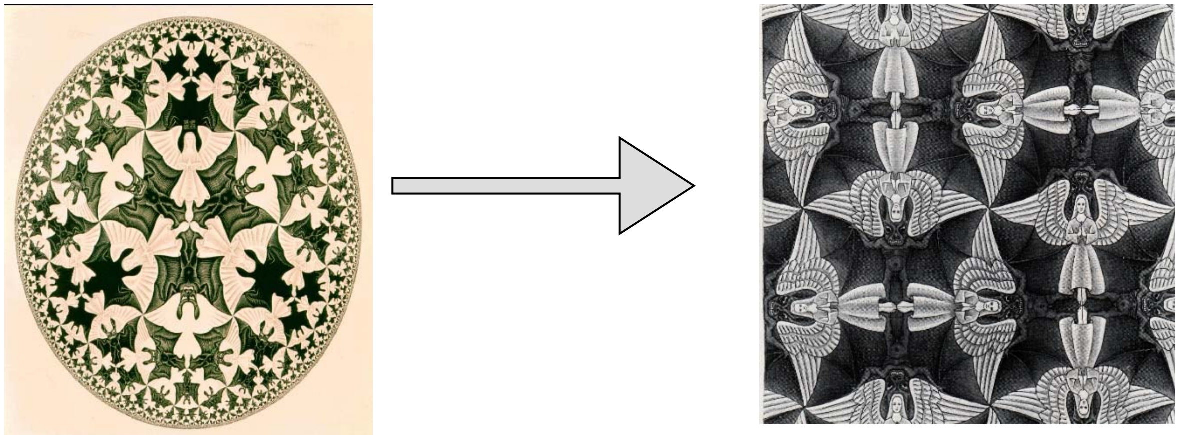


Fig. 5. (Color online) Diagram of square-packing method. The solid line is a true locus; the dotted and solid squares are squares with different sampling sites.

7.3. Number of discernible color

The number of discernible colors depends strongly on the conditions

- The illuminant and the observer.
- Adaptation of the observer, background and surround.
- Colour space, we need a real Euclidean space.
- What is a 1 JND? Color difference formula.
- Optimal colors are ideal situations derived from the spectrum.



7.3. Number of discernible color

Table 1. History of the Estimates of the Number of Discernible Colors

Year	Researcher	Estimate	Illuminant	Color Data/Color Model
1896	Titchener [3]	30,850		700 "brightness qualities" + 150 "spectral colors" + 30,000 "colors mixed with origin"
1899	Titchener [4]	32,820		660 "brightness qualities" + 160 "spectral colors" + 32,000 "colors mixed with origin"
1939	Boring *et al.* [5]	300,000		156 hue × 16–23 saturation × 572 brightness
1939	Judd and Kelly [6]	10,000,000		Unknown
1943	Nickerson and Newhall [17]	7,295,000		Optimal color solid/Munsell notation
1951	Halsey and Chapanis [8]	1,000,000		Unknown
1981	Hård and Sivik [9]	10,000–20,000		Unknown
1998	Pointer and Attridge [18]	2,280,000	D65	Optimal color solid/CIELAB
2007	Wen [19]	352,263	D65	Optimal color solid/CIE94
2007	Martínez-Verdú *et al.* [20]	2,050,000	E	Optimal color solid/CIECAM02 lightness–colorfulness (Ja_Mb_M)
		2,046,000	C	
		2,013,000	D65	
		1,968,000	F7	
		1,753,000	A	
		1,735,000	F11	
		1,665,000	F2	
2008	Morovic [22]	1,900,000	D50	Optimal color solid/CIECAM02 lightness–chroma (Ja_Cb_C)
2012	Morovic *et al.* [23]	4,200,000	F11	Optimal color solid/CIECAM02 lightness–chroma (Ja_Cb_C)
		3,800,000	D50	
		3,500,000	A	
		1,700,000	D50	LUTCHI/CIECAM02 lightness–chroma (Ja_Cb_C)

7.3. Number of discernible color

João Manuel Maciel Linhares method (2008)

- Better to “count” the real colors that there are in real life
- 50 hyperspectral images of “..rural scenes contained natural elements such as dark terrain, trees, grass, ferns, flowers, rocks, and stones, and urban scenes contained buildings and painted or treated surfaces.”
- Spectral radiances were converted into tristimulus values for the CIE 1931 Standard Colorimetric Observer and then converted into CIELAB coordinates.
- The number of discernible colors was to segment the color space in just noticeable subvolumes and to count the number of these containing the color representation of at least one pixel.

7.3. Number of discernible color

João Manuel Maciel Linhares method (2008)

Linhares et al. Vol. 25, No. 12/December 2008/J. Opt. Soc. Am. A 2919

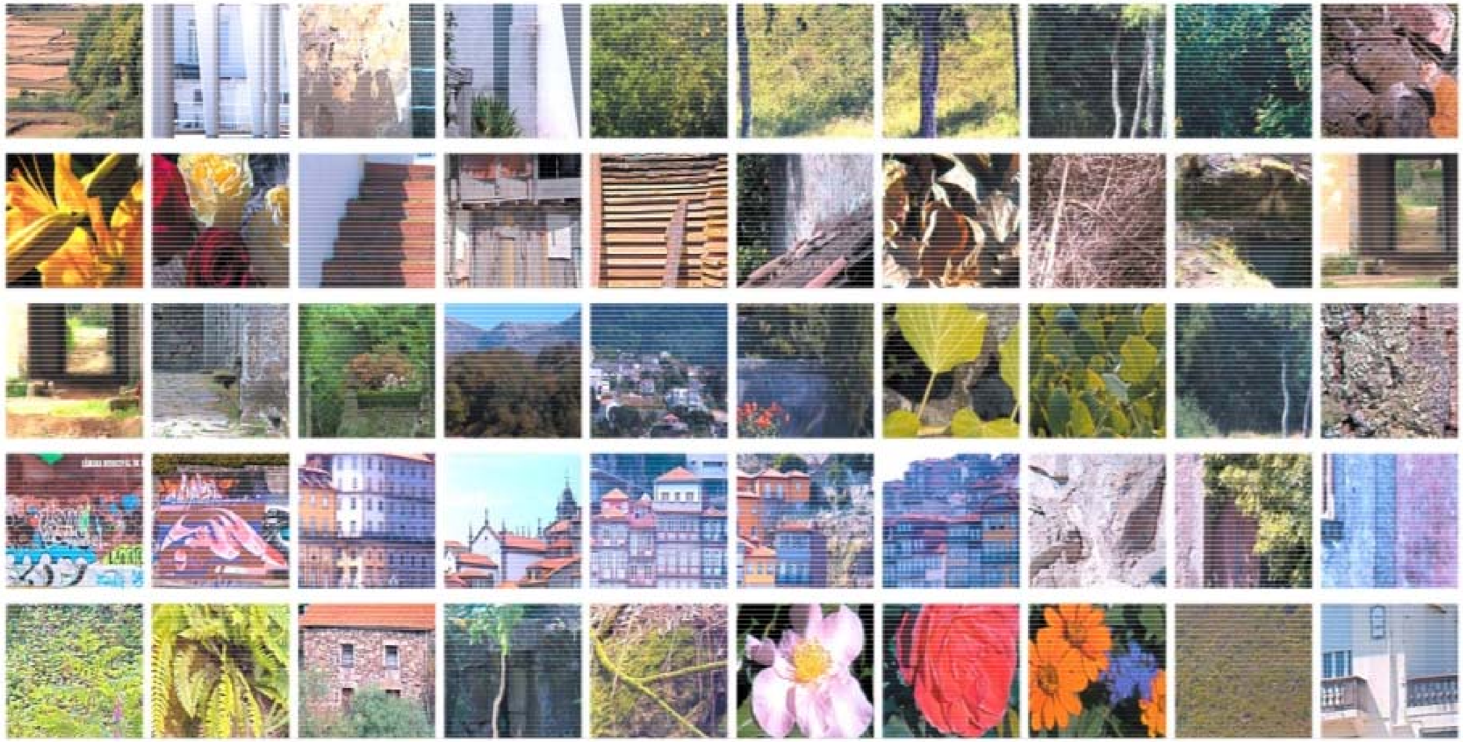
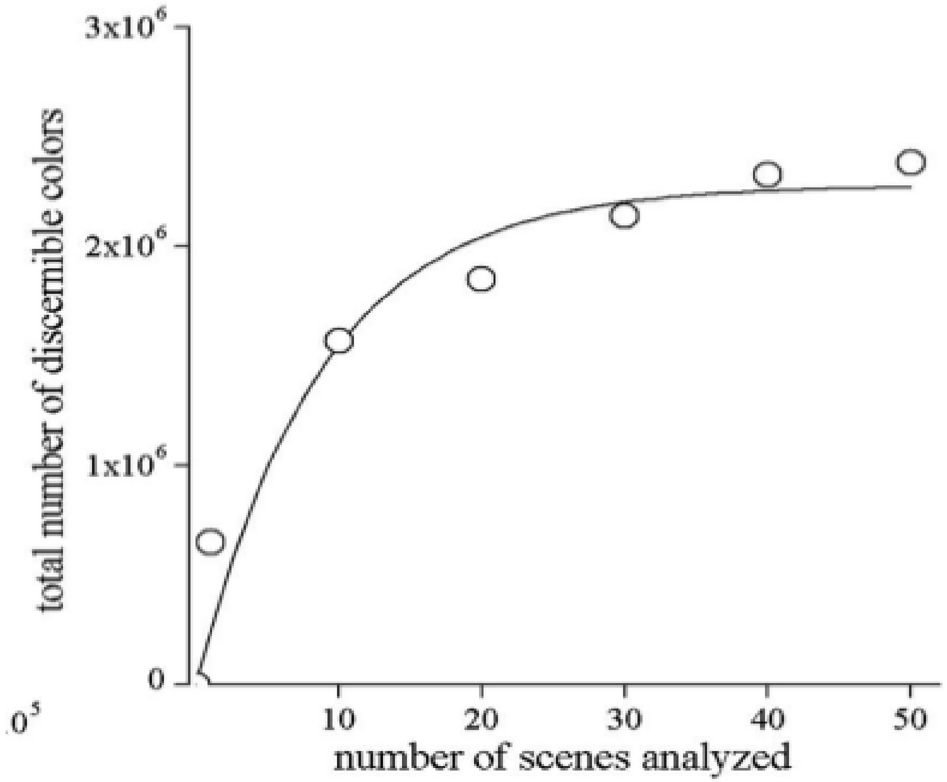


Fig. 1. (Color online) Thumbnails of the 50 scenes analyzed in this study.

7.3. Number of discernible color

João Manuel Maciel Linhares method (2008)

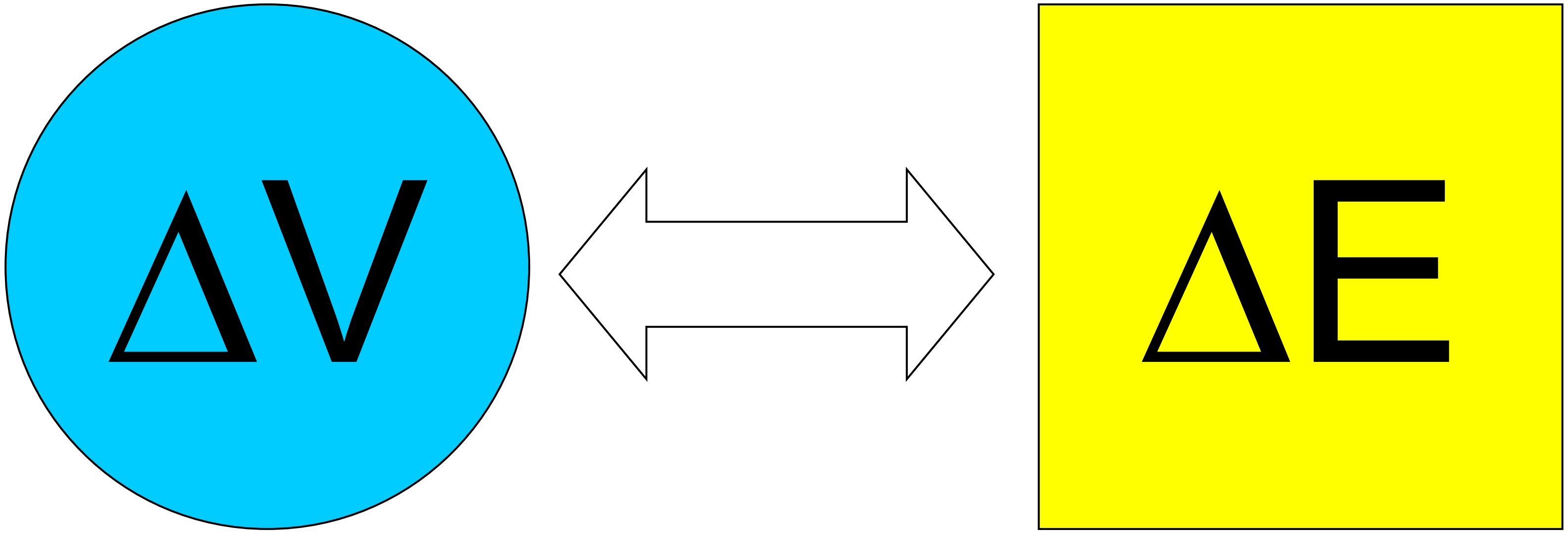


Parameter	(L^*, a^*, b^*)	(a^*, b^*)
Average number of discernible colors	274,736 (92,976)	11,276 (3,232)
Asymptotic values	2,275,698	26,256

Contents

7.4. Color-difference formulas

Visual and computed color-differences in industrial applications



Visually-perceived color differences (subjective)

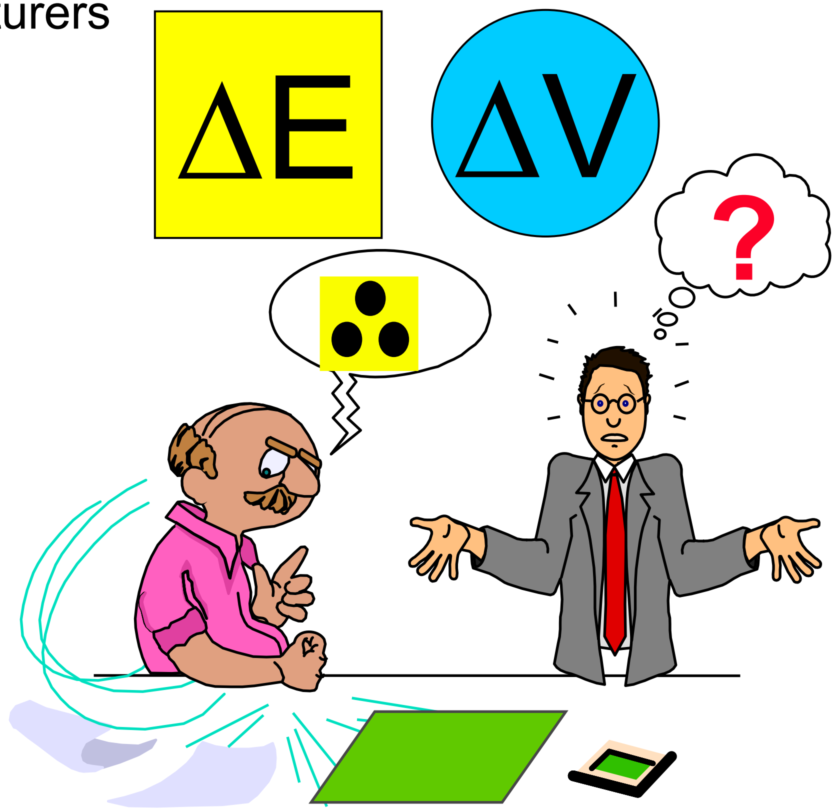
Instrumentally-measured color differences (objective)

7.4. Color-difference formulas

Visual and computed color-differences in industrial applications

- Goal: To replace visual judgments by instrumental measurements, avoiding conflicts between customers and manufacturers

Konica Minolta Sensing, Inc.
Precise Color Communication. 1998.



7.4. Color-difference formulas

Visual and computed color-differences in industrial applications

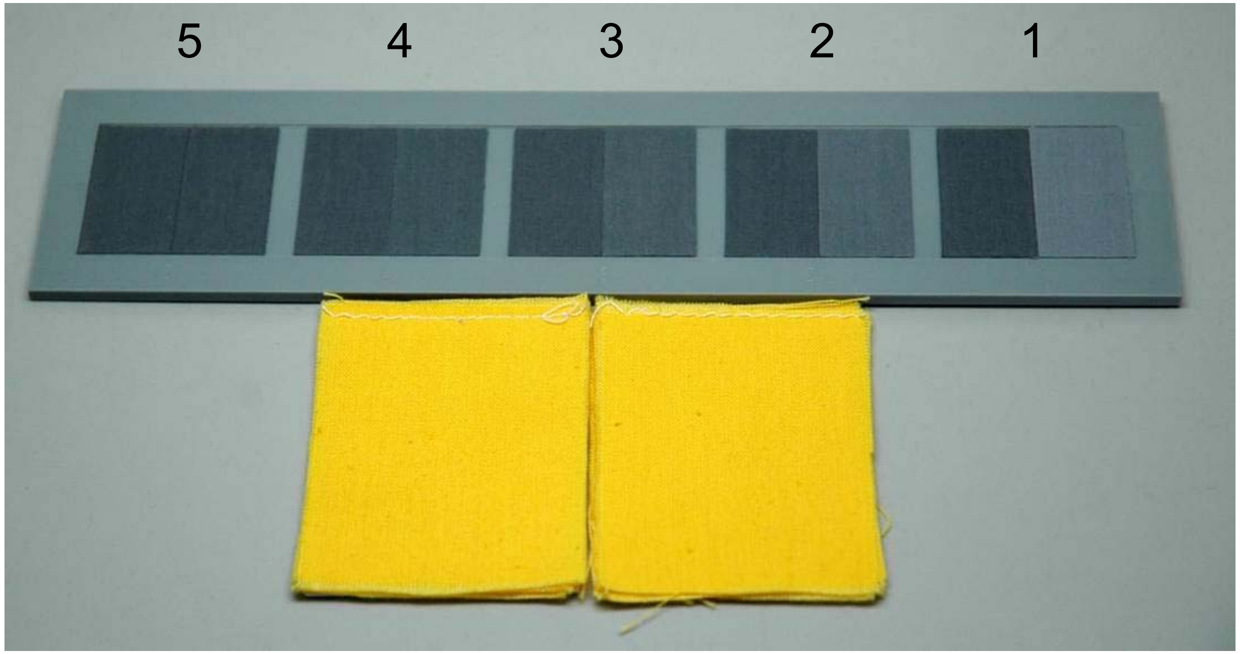
- Industry is interested in color differences and total appearance (i.e. color + gloss + texture + smell…)

7.4. Color-difference formulas

Visual color-differences in industrial applications

ΔV

Experiment with a Gray Scale

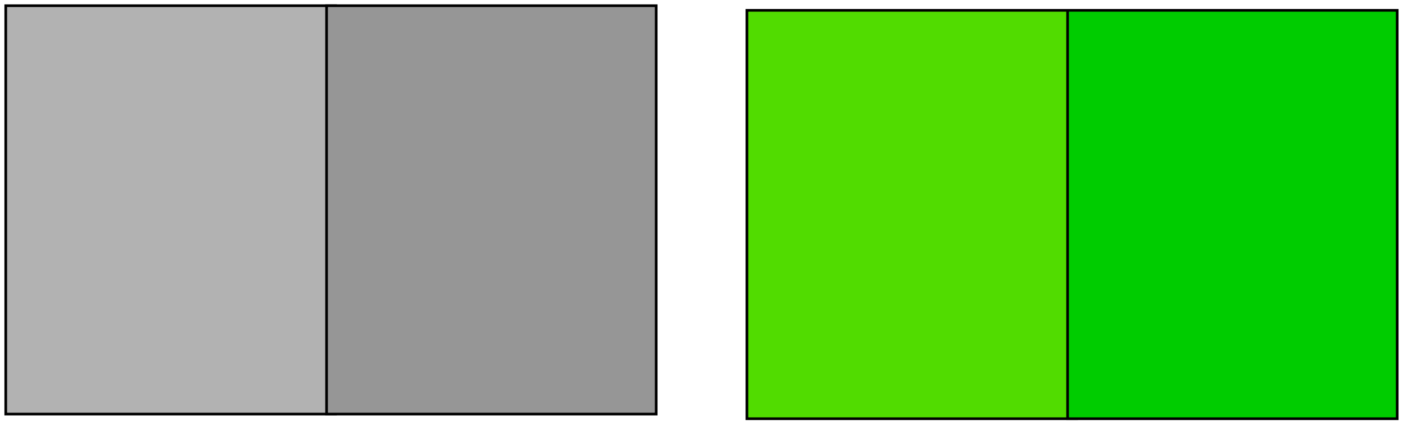


7.4. Color-difference formulas

Visual color-differences in industrial applications

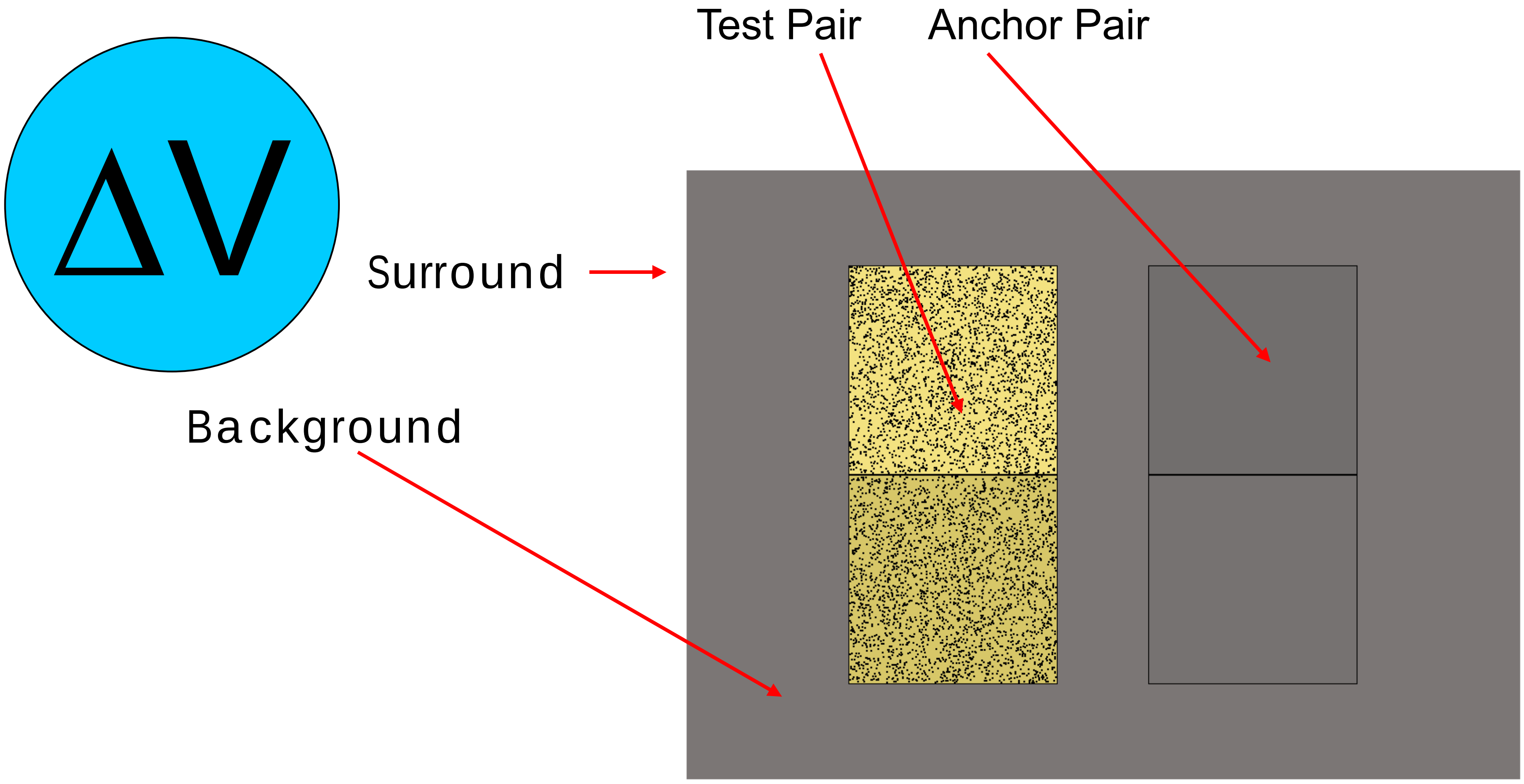
ΔV

Experiment with an Anchor Pair



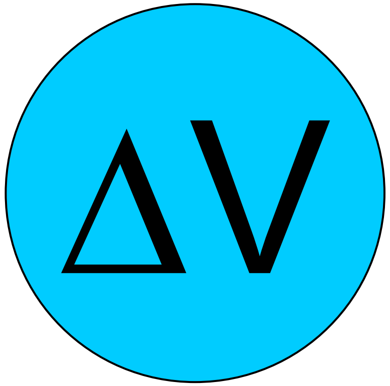
7.4. Color-difference formulas

Visual color-differences in industrial applications

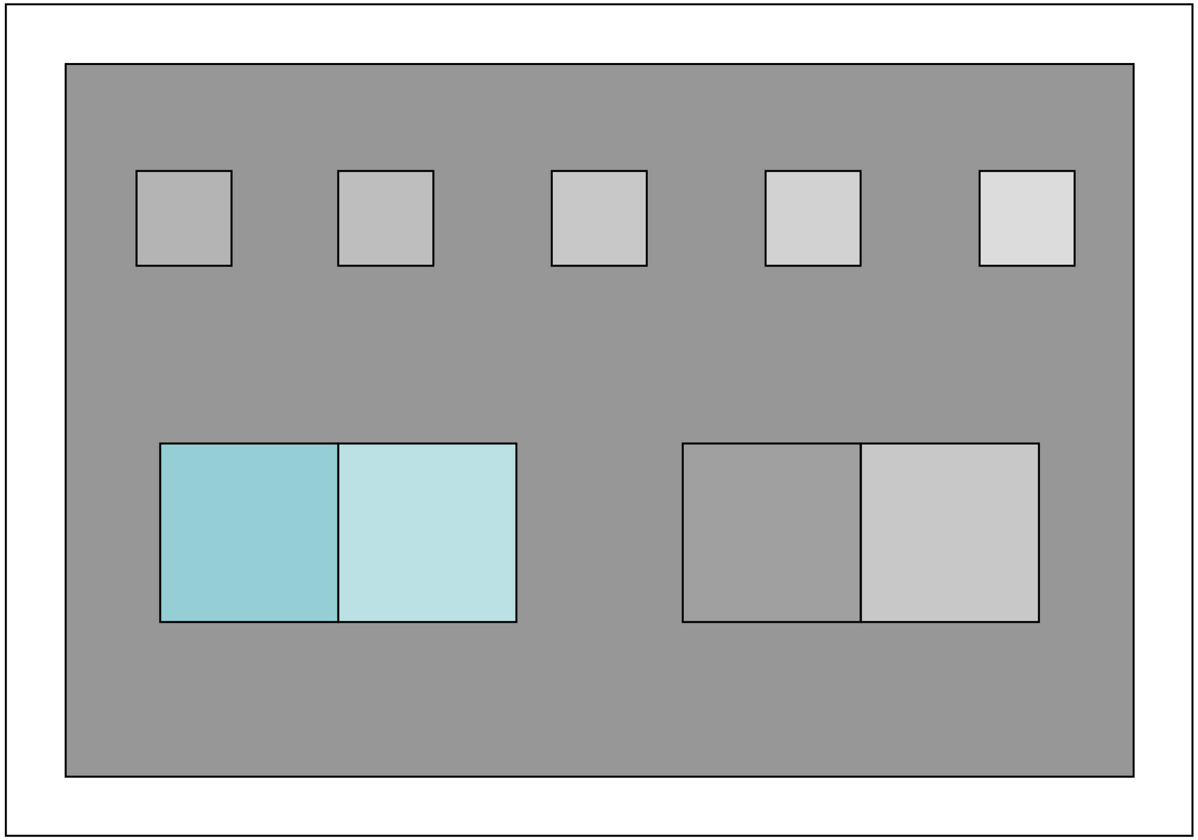


7.4. Color-difference formulas

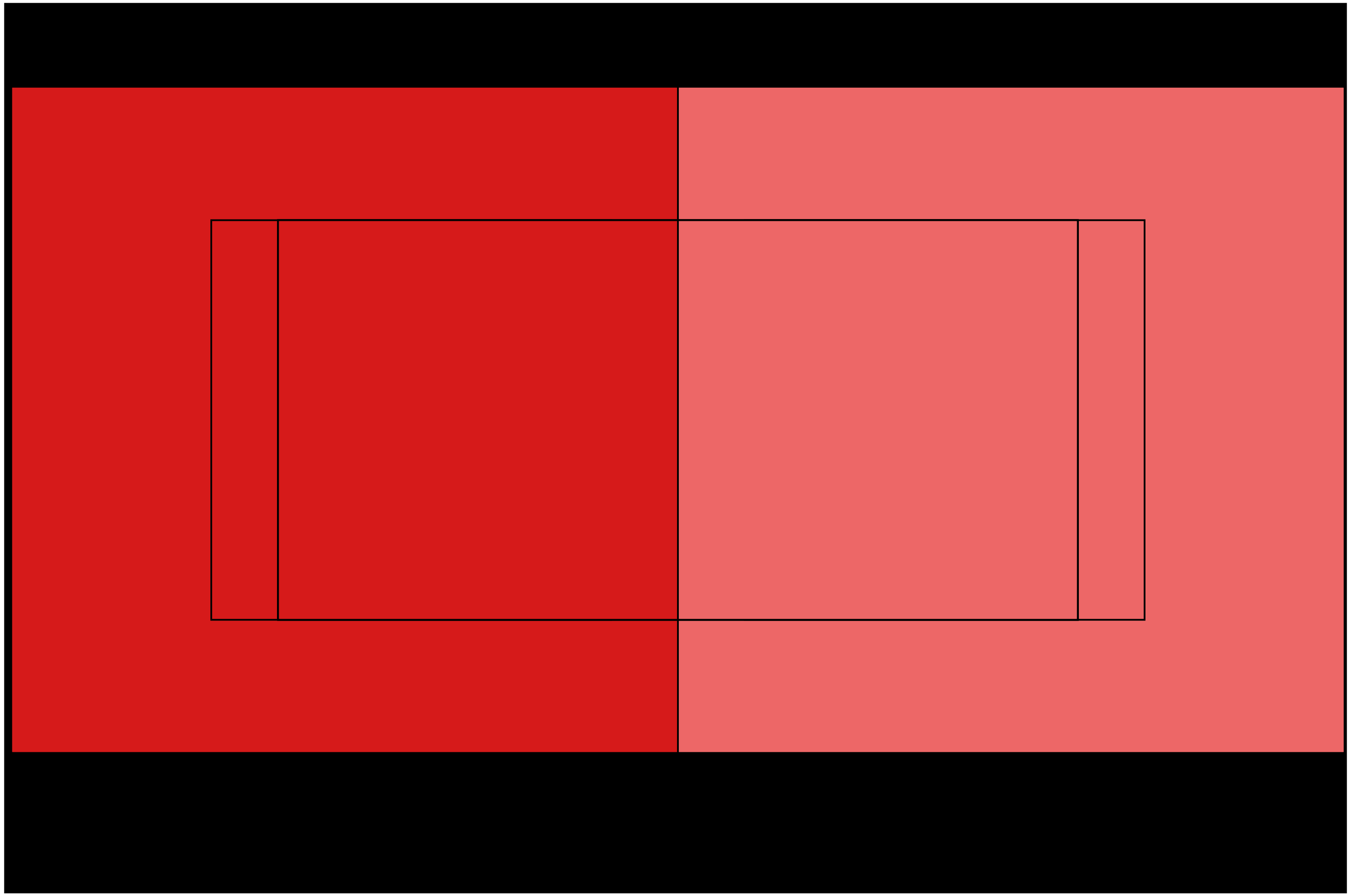
Visual color-differences in industrial applications



Experiment with a variable Anchor Pair



Rafael Huertas Roa
Javier Hernández Andrés
Eva Valero Benito



7.4. Color-difference formulas

Visual color-differences in industrial applications

CIE 1978 (A.R. Robertson): Parametric effects to be considered for research in color-difference evaluation.

- Sample size
- Illumination level
- Sample separation
- Texture
- Color of surround
- Luminance factor
- Size of ΔE
- Observer variability
- Duration of observation
- Monocular or binocular observing

CIE Publication 101 (1993)

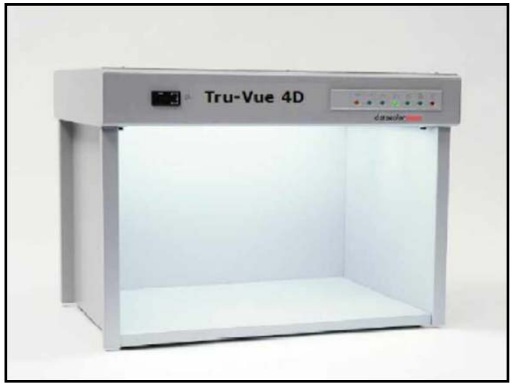
- Proposal of 5 CIE color centers: Gray, Red, Yellow, Green, Blue.

7.4. Color-difference formulas

Visual color-differences in industrial applications

Why color assessment cabinets (light booths)?

- ✓ To obtain “stable” lighting over time.
- ✓ To simulate different artificial illuminations. Note that natural illumination is not easy to simulate, both in spectral power distribution and illuminance level.
- ✓ To provide a combination of directional and diffuse lighting (a grey surround – the cabinet’s walls- is being assumed) allowing differences in texture be observable.



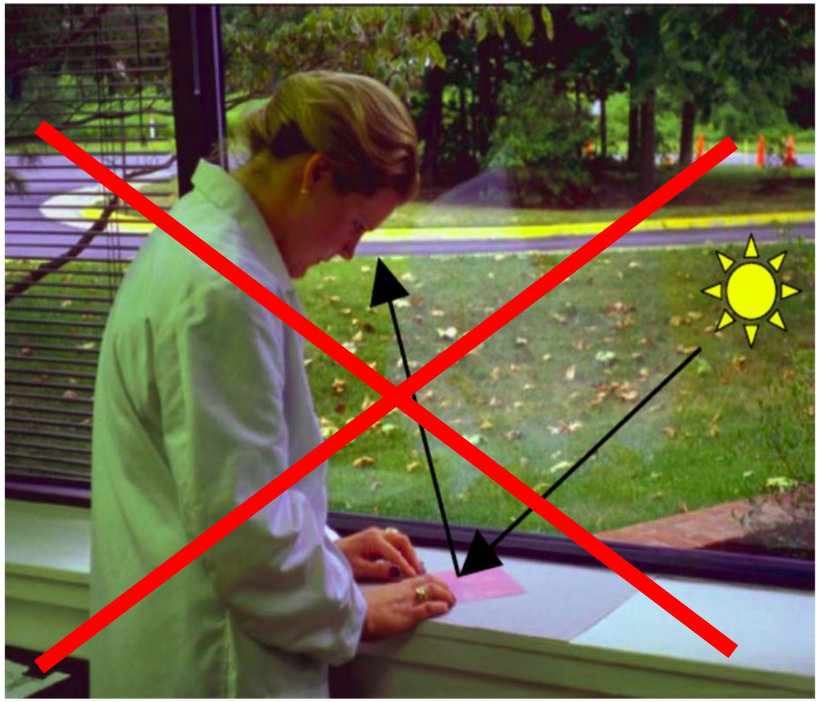
7.4. Color-difference formulas

Visual color-differences in industrial applications

What is “natural” daylight?

Is it light at noon or in the morning?

Light during winter or summer?



7.4. Color-difference formulas

Visual color-differences in industrial applications

Some practical issues in color cabinets

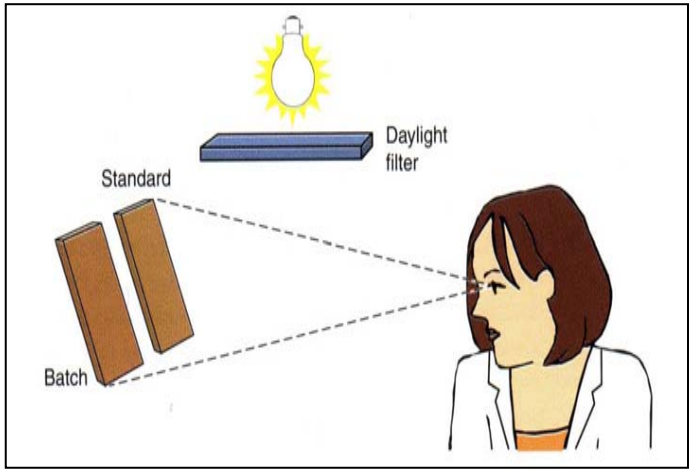
- ✓ The overhead lights should be turned off.
- ✓ Place the sample/s in the center of the cabinet and keep constant the observer's position.
- ✓ Control background behind the samples (usually gray matte, L*=50).
- ✓ 1000 lx is a reasonable aim illuminance for visual evaluations. The different sources available in a cabinet provide a widely variable illuminance.
- ✓ Most light booths walls (surround) have L* between 60 and 70. If highly glossy materials are evaluated, the back of the booth should have a black velvet to avoid seeing an image of the back of the booth by specular reflections.
- ✓ Unfortunately, for ideal communication between buyers and sellers, we must use identical model booth of the same manufacturer.

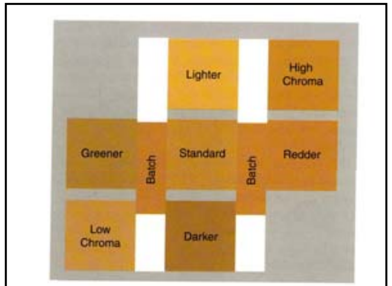
7.4. Color-difference formulas

Visual color-differences in industrial applications

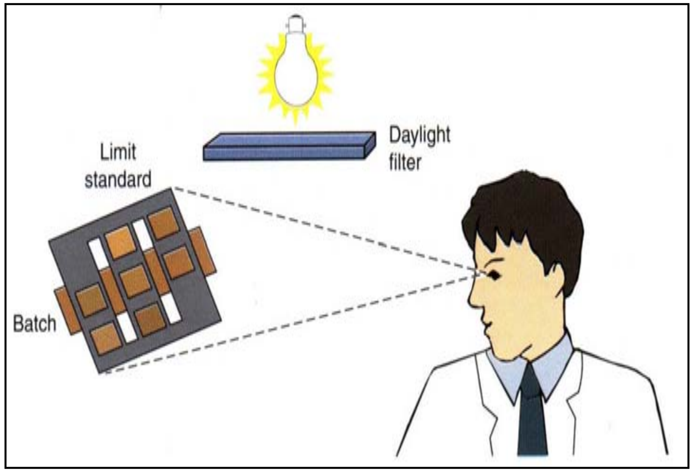
Measuring Color Equality: Sample & single/multiple Standard/s

- ✓ In most cases a single light source is not adequate for proper inspection, and multiple standardized sources should be agreed on between customer and manufacturer (Berns, p. 81, 2000).
- ✓ If sample and standard do not match we would like to know both how and by how much they differ. A set of limit standards is very useful:





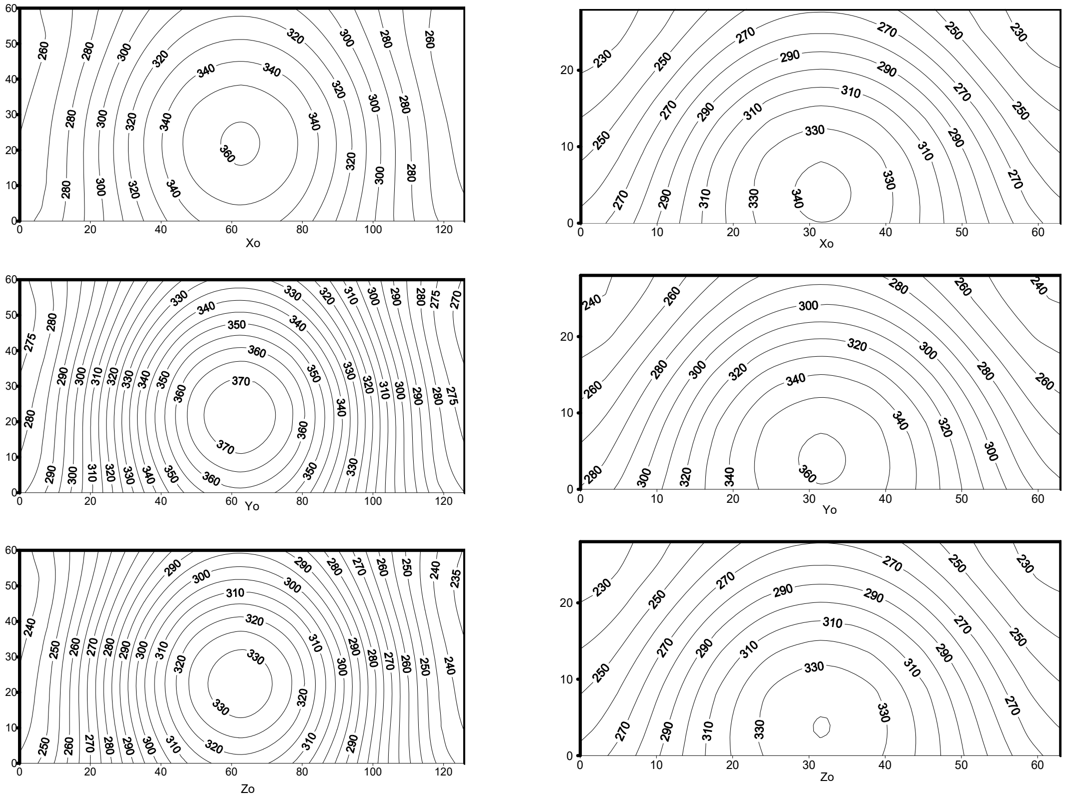
Visual tolerance charts are sometimes used in evaluating color quality. There are lightness, hue, and chroma limits.



7.4. Color-difference formulas

Visual color-differences in industrial applications

Uniformity of lighting in some color assessment cabinets

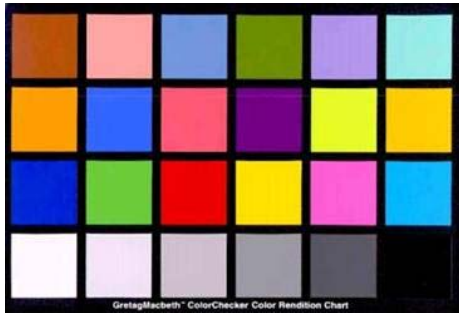


Tristimulus values X_{10} Y_{10} Z_{10} of a standard white on the floor of the CAC 120 (left) and Portable (right) Verivide light booths, under their D65 sources.

7.4. Color-difference formulas

Visual color-differences in industrial applications

Average color differences for the 24 GretagMacbetch color samples placed at the center and corners (up and down) of the CAC 120 and Portable VeriVide cabinets. Three different color difference formulas (CIELAB, CIE94, and CIEDE2000) have been tested.



		CAC 120 cabinet			Portable cabinet		
		CIELAB	CIE94	CIEDE2000	CIELAB	CIE94	CIEDE2000
D65	Center-Up	1.695	0.945	0.870	0.744	0.475	0.442
	Center-Down	0.376	0.289	0.275	0.791	0.457	0.418
F	Center-Up	1.658	1.335	0.913	3.703	3.303	2.566
	Center-Down	0.698	0.669	0.548	1.194	0.982	0.666

7.4. Color-difference formulas

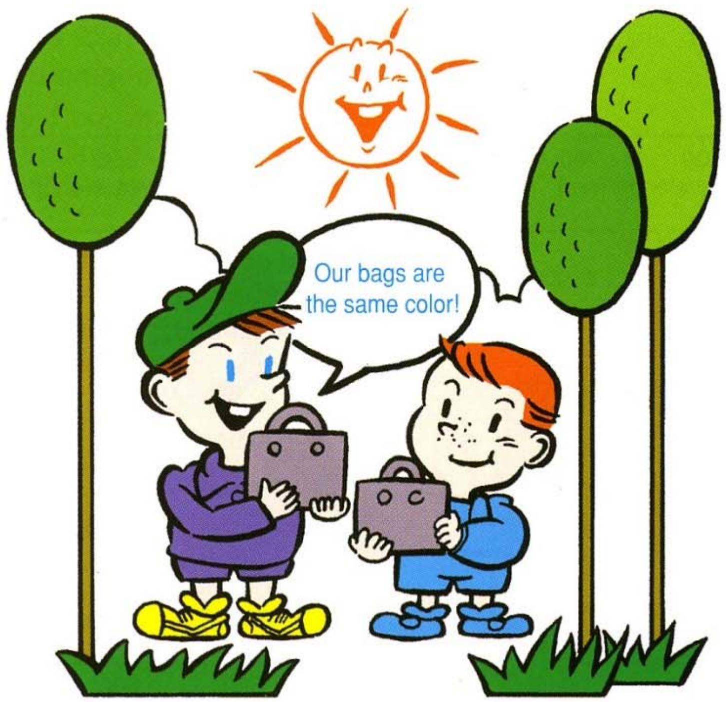
ΔE

Color-Difference Formula

$$\Delta E = f(X_1, Y_1, Z_1, X_2, Y_2, Z_2, \text{etc.})$$

7.4. Color-difference formulas

Special metamerism index: change in illuminant (CIE 15:2004, p.23-25)

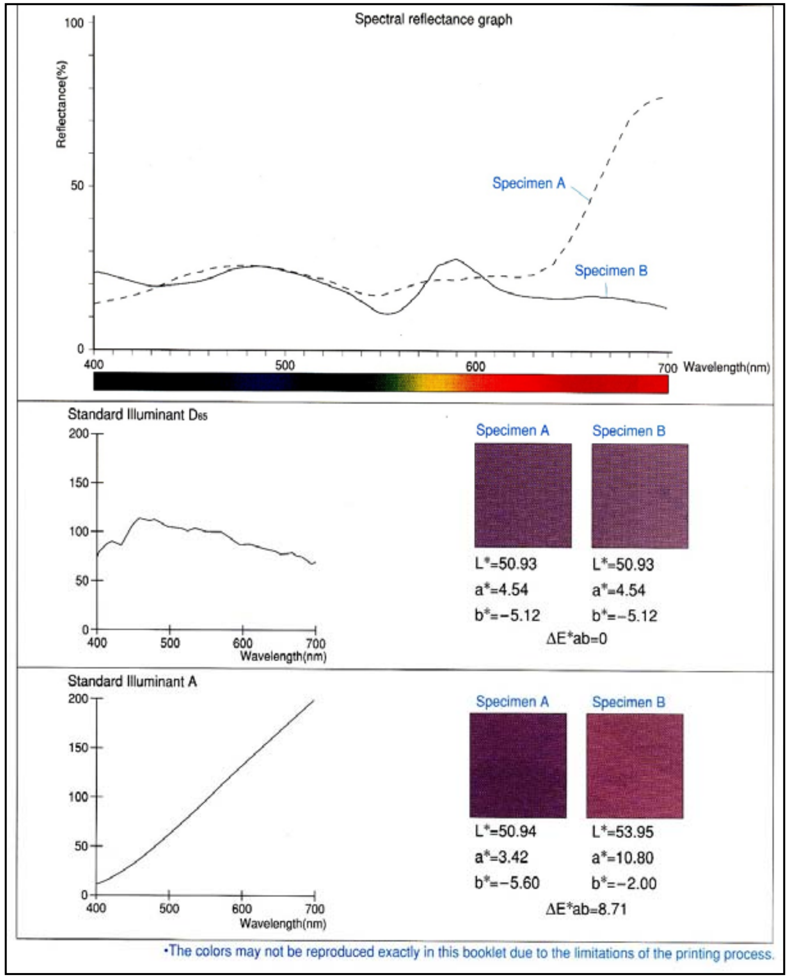


Test Illuminant

$$M_{ilm\ \#} = \Delta E^*_{ab}\ (\text{or } \Delta E_{00})$$

7.4. Color-difference formulas

Special metamerism index: change in illuminant (CIE 15:2004, p.23-25)



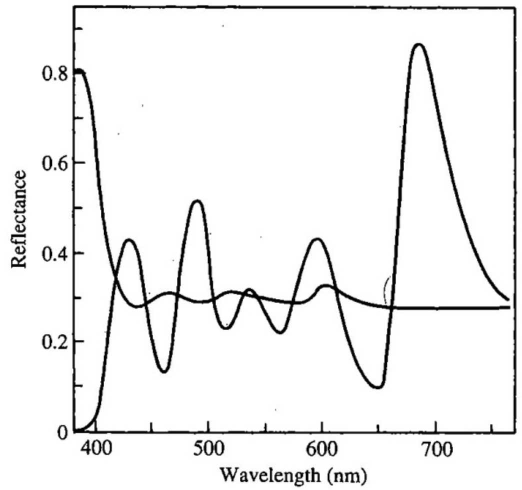
Example of two metameric pairs

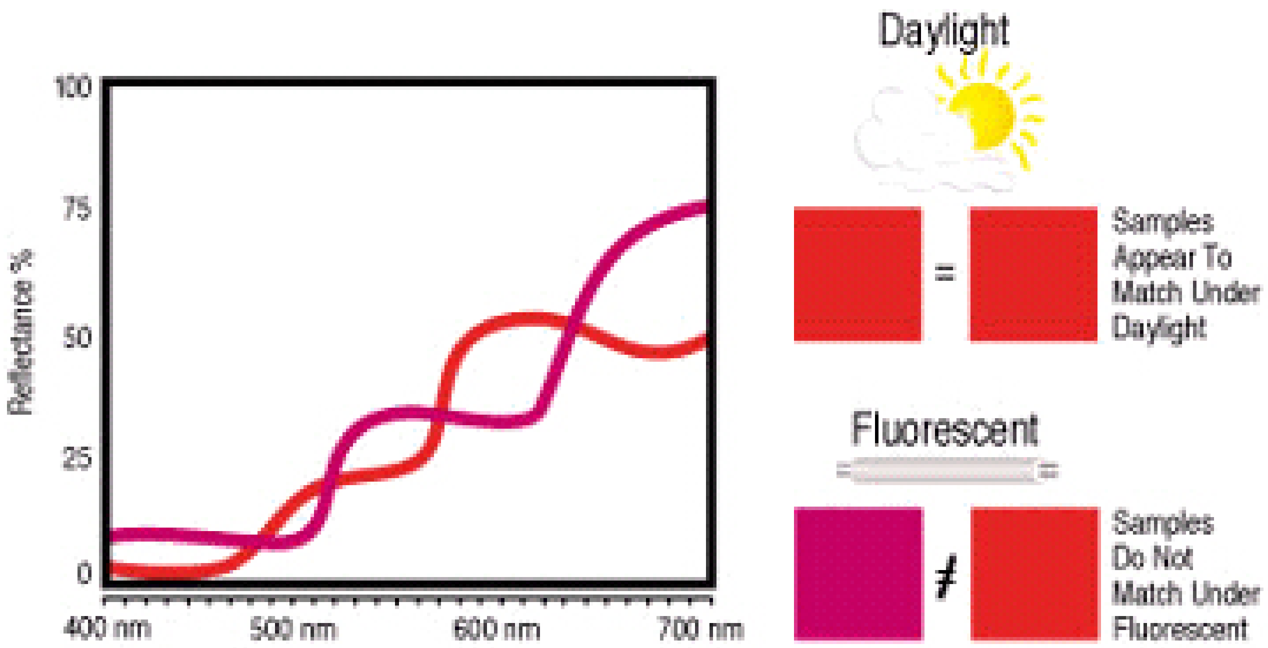
Ref. "Precise Color Communication". Konica Minolta, 1998

7.4. Color-difference formulas

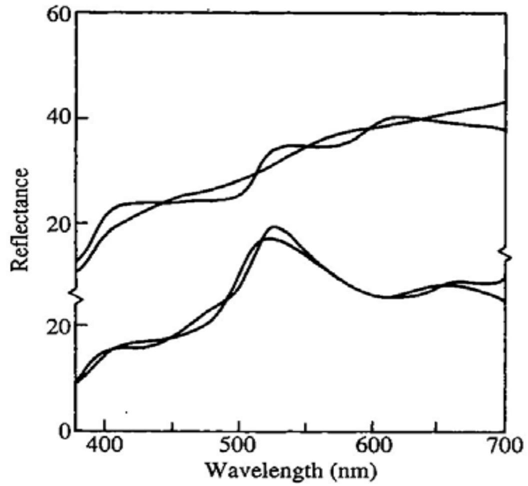
Analysis of Metamerism

Metamerism: a pair of color stimuli, differing in spectral distribution, match in color under certain conditions.





Reflectance Curves of a Metameric Pair



7.4. Color-difference formulas

Analysis of Metamerism

Metamerism indices

Degree of metamerism: the degree to which a match is susceptible to change.
Metamerism index: an index that quantifies this degree.
Depending on the condition that is changed: **object-color metamerism**, **illuminant metamerism** and **observer metamerism**.

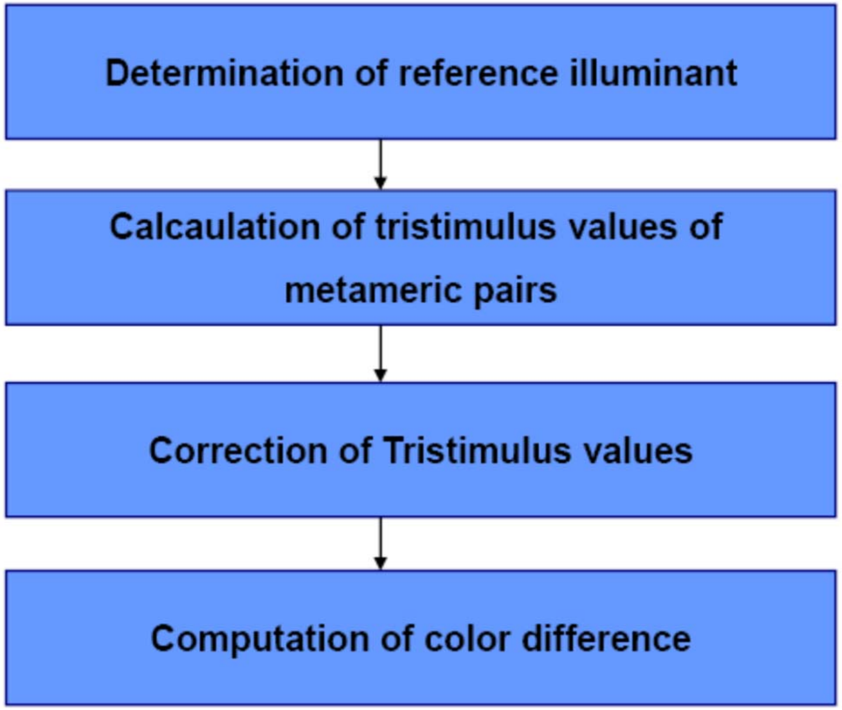
Object of evaluation (metameric pair)	Means of evaluation (variable)	Examples of application
Object colors (spectral reflectances)	Illuminants	Illuminant metamerism
	Observers	Observer metamerism
Illuminants (spectral distribution)	Object colors	Evaluation of illuminants
	Observers	Observer metamerism
Observers (color matching functions)	Illuminant	Evaluation of color: Separation systems colorimeters
	Object colors	

7.4. Color-difference formulas

Evaluation of Degree of Metamerism for Change of Illuminant

The CIE '**special metamerism index: change in illuminant**', sometimes abbreviated as the '**illuminant metamerism index**'[1].

Deviation from matching when the spectral distribution of the illuminant changes.

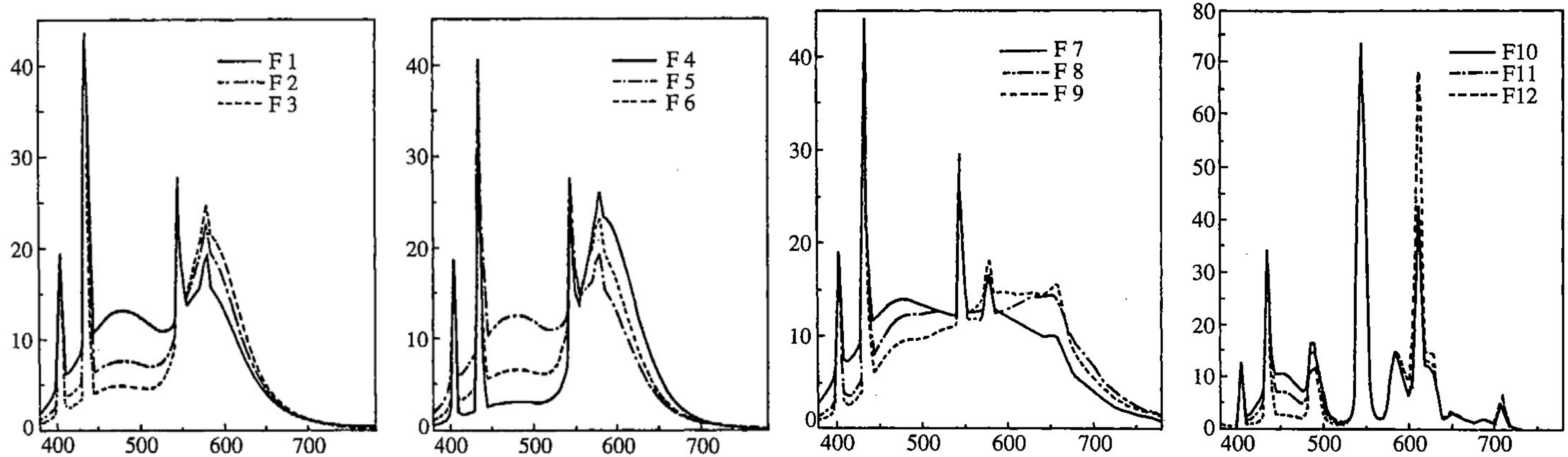


1. CIE Publ. 15:2004. Colorimetry. 3rd Edition ed. 2004, CIE Central Bureau: Vienna.

7.4. Color-difference formulas

Evaluation of Degree of Metamerism for Change of Illuminant

Referent illuminant and test light



(a) Standard (b) Standard (c) High color rendering (d) Three band

Usually illuminant $\mathbf{D_{65}}$ is employed as the **reference illuminant** and illuminant **A** or a fluorescence lamp (**F1 to F12**) as the **test light**.

7.4. Color-difference formulas

Evaluation of Degree of Metamerism for Change of Illuminant

Tristimulus values of metameric pairs

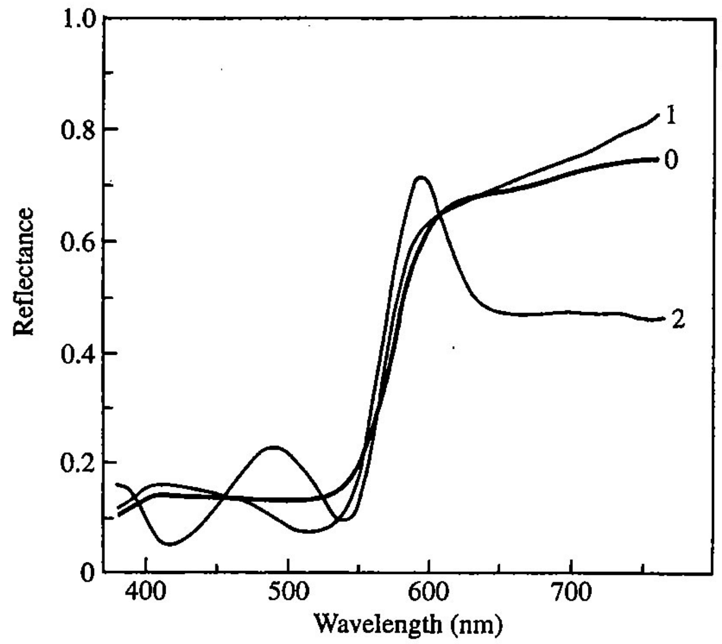
Computation of the tristimulus values:

X_{r1}, Y_{r1}, Z_{r1} and X_{r2}, Y_{r2}, Z_{r2}

under the **reference light** (r)

X_{t1}, Y_{t1}, Z_{t1} and X_{t2}, Y_{t2}, Z_{t2}

under the **test light** (t).



Correction of tristimulus values

If match is not perfect under the reference light:

$$X'_{t2} = X_{t2}\frac{X_{r1}}{X_{r2}};\ Y'_{t2} = Y_{t2}\frac{Y_{r1}}{Y_{r2}};\ Z'_{t2} = Z_{t2}\frac{Z_{r1}}{Z_{r2}}$$

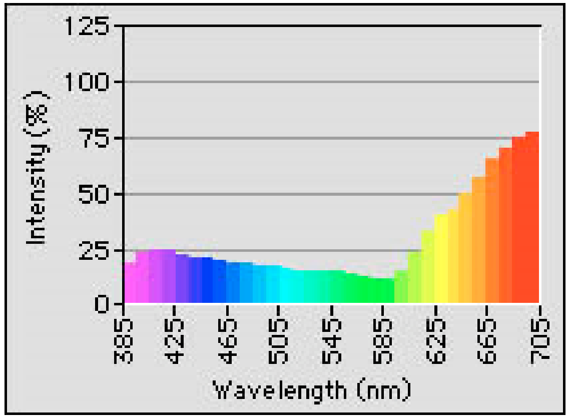
7.4. Color-difference formulas

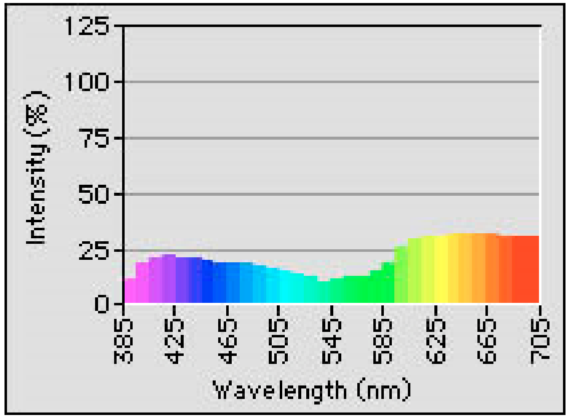
Evaluation of Degree of Metamerism for Change of Illuminant

Illuminant metamerism index M_{ilm}

$$M_{ilm} = \Delta E_{ab}$$

Color difference of the metameric pair under the test light.





7.4. Color-difference formulas

General Color Rendering Index (CIE 13.3-1995)

F2 (TC=3500 K) ; Ra=64

F8 (TC=5000 K) ; Ra=90

$$\Delta E_i = \sqrt{(U*_{r.i} - U*_{t.i})^2 + (V*_{r.i} - V*_{t.i})^2 + (W*_{r.i} - W*_{t.i})^2}$$

CIE 1964 UCS + CAT

$$R_i = 100 - 4.6\,\Delta E_i$$

$$R_a = \frac{\sum_{i=1}^{8} R_i}{8}$$

7.4. Color-difference formulas

Evaluation of the Color Rendering Properties of Light Sources

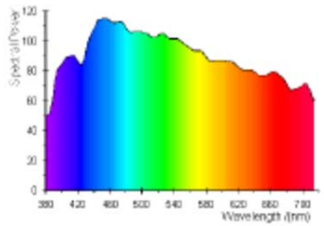
Color rendering

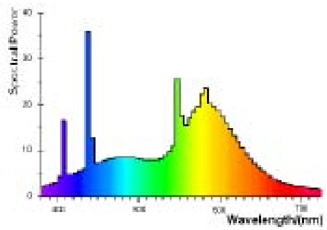
Differences between color appearance of objects seen under different illuminants.

Daylight or incandescent lamp are usually used as reference.

Color rendering of an illuminant: the similarity of color appearance of objects with respect to their color appearance under a reference source.

Reference source





Test source

7.4. Color-difference formulas

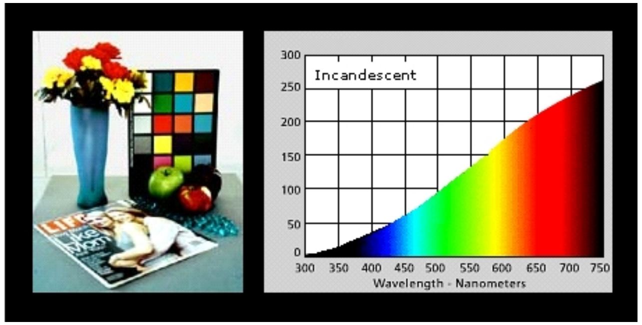
Evaluation of the Color Rendering Properties of Light Sources

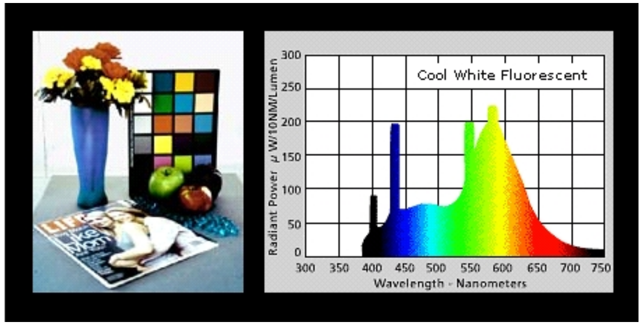
Color rendering index

Classification:

- Methods based on the difference in spectral distributions.
- Methods based on the difference in color appearance of a series of object colors used as representative colors (**test colors**): CIE color rendering index[1].

Degree of matching of color appearance of objects under a test light source with the color appearance under a **reference illuminant**.





1. CIE Publ. 13.3:1995. Method of Measuring and Specifying Colour Rendering Properties of Light Sources. 1995, CIE Central Bureau: Vienna.

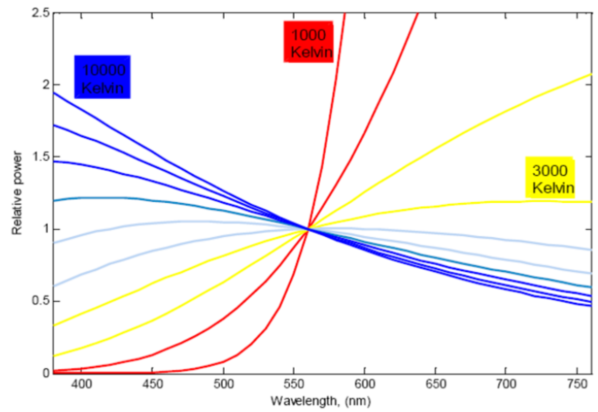
7.4. Color-difference formulas

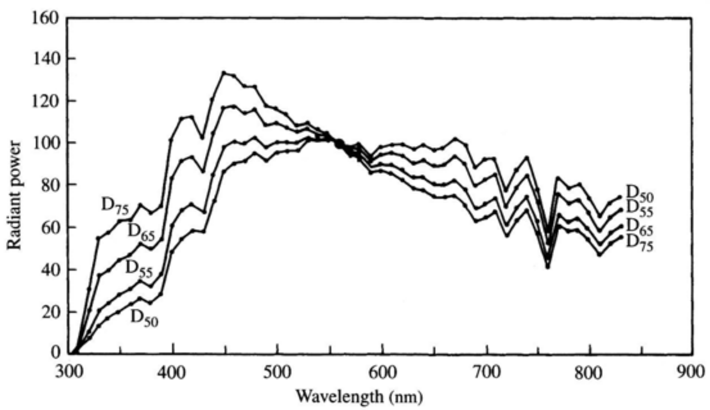
Evaluation of the Color Rendering Properties of Light Sources

Reference illuminant

Depending on CCT of the test source:

- If CCT < 5000 K a black-body radiator is used.
- If CCT ≥ 5000 K a CIE daylight illuminant is used.





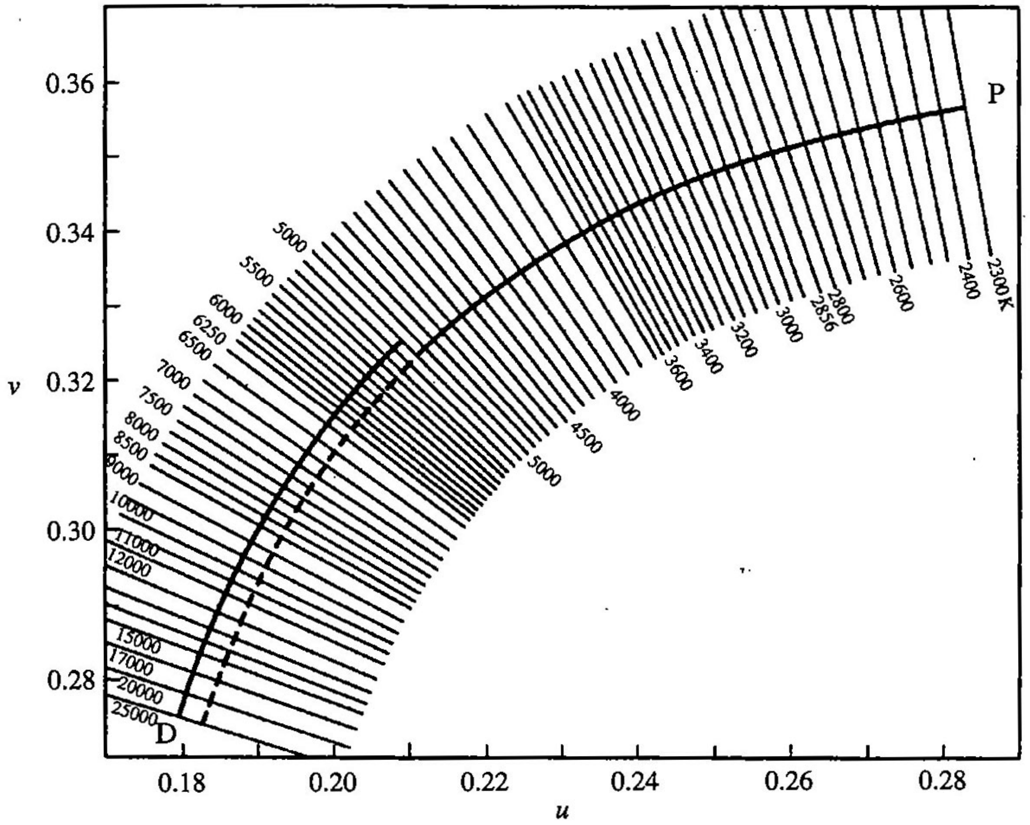
The CCT of the referent illuminant must be equal to that of the test source.

For special purpose a CIE standard illuminant or any other illuminant can be used.

7.4. Color-difference formulas

Evaluation of the Color Rendering Properties of Light Sources

Computation of the correlated color temperature



7.4. Color-difference formulas

Evaluation of the Color Rendering Properties of Light Sources

Test colors

CIE General Color Rendering Index

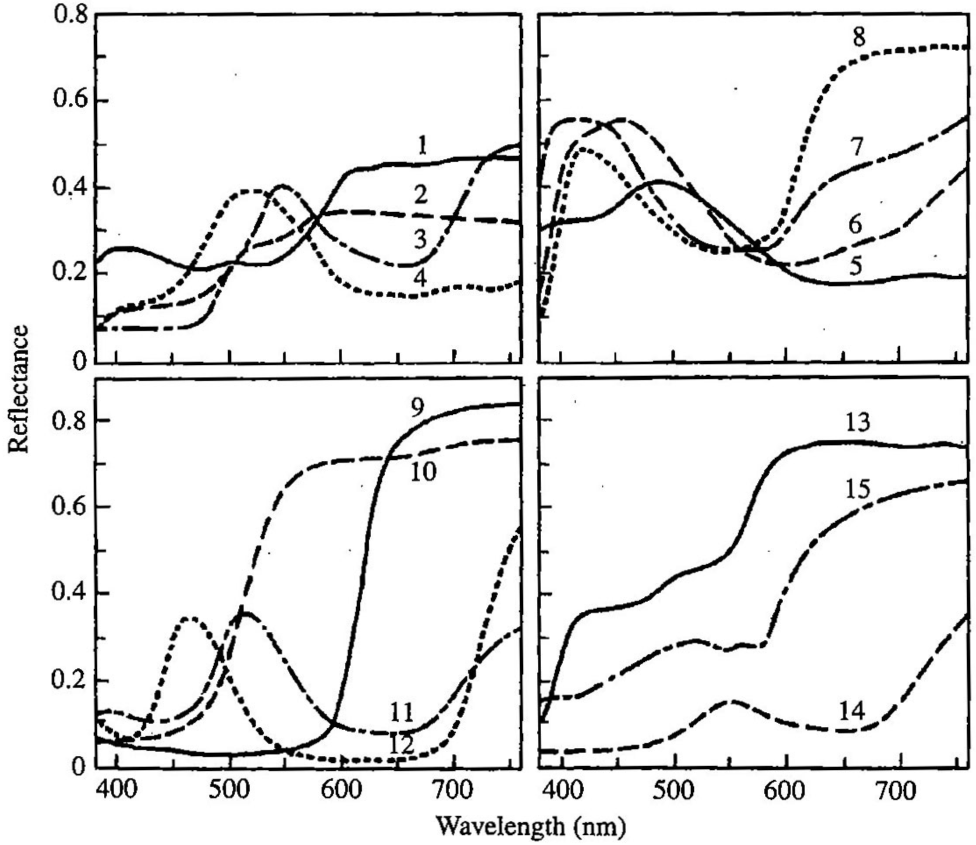
Special Color Rendering Indices

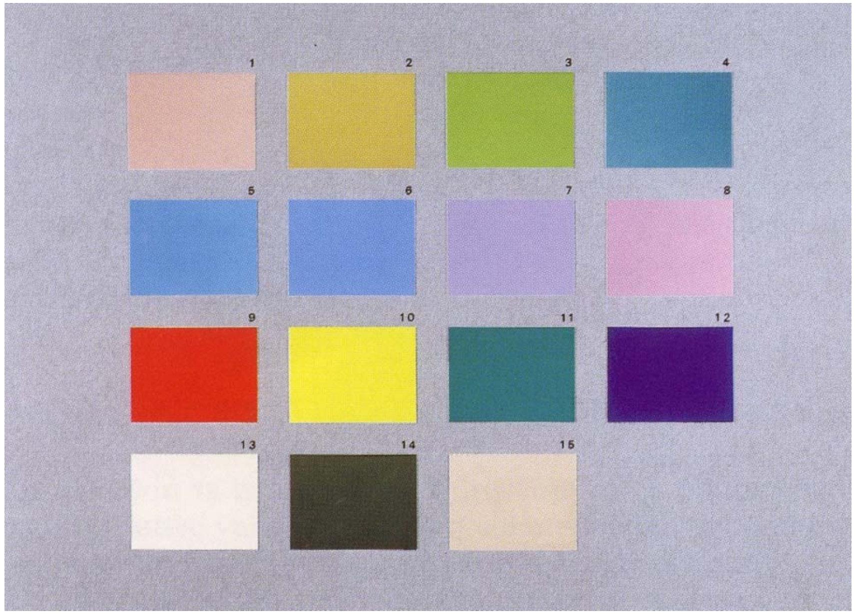
Number	Munsell notation	Color name
1	7.5R6/4	Light grayish red
2	5Y6/4	Dark grayish yellow
3	5GY6/8	Deep yellow green
4	2.5G6/6	Yellowish green
5	10BG6/4	Light bluish green
6	5PB6/8	Light blue
7	2.5P6/8	Light violet
8	10P6/8	Light reddish purple
9	4.5R4/13	Deep red
10	5Y8/10	Deep yellow
11	4.5G5/8	Deep green
12	3PB3/11	Deep blue
13	5YR8/4	Caucasian skin
14	5GY4/4	Foliage green
15	1YR6/4	Japanese skin

7.4. Color-difference formulas

Evaluation of the Color Rendering Properties of Light Sources

Test colors

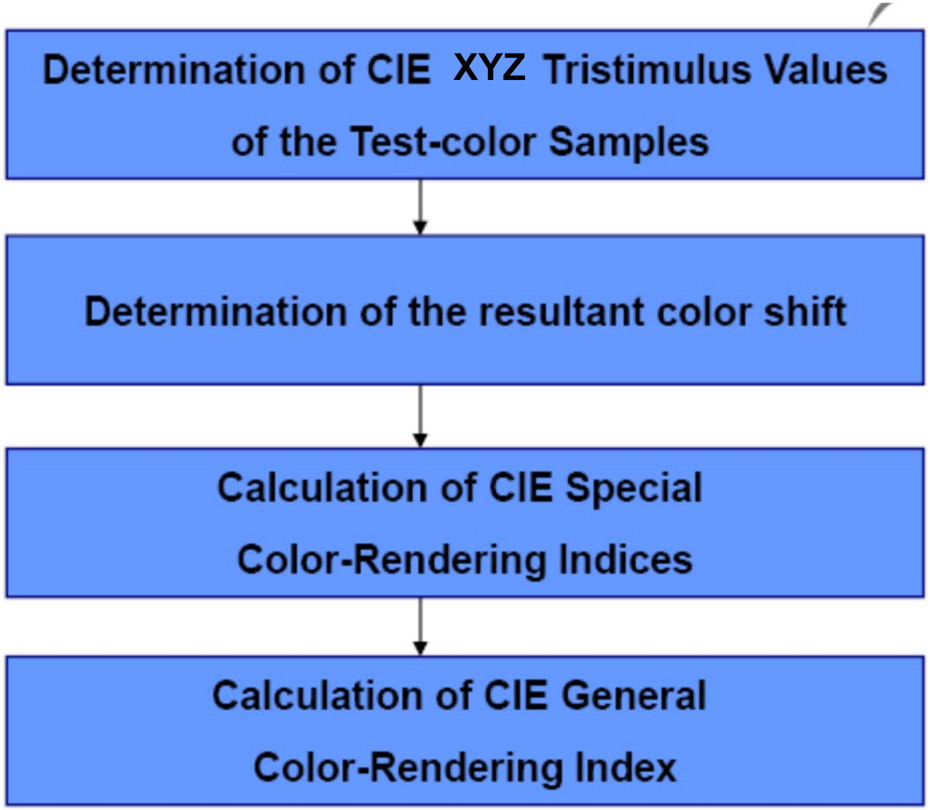




7.4. Color-difference formulas

Evaluation of the Color Rendering Properties of Light Sources

Steps involved in the calculation of CIE-CRIs



7.4. Color-difference formulas

Evaluation of the Color Rendering Properties of Light Sources

Color space

The CIE 1964 U*W*V* uniform color space is proposed for use:

$$W^* = 25Y^{1/3} - 17$$

$$U^* = 13W^*(u - u_n)$$

$$V^* = 13W^*(v - v_n)$$

Chromaticity coordinates in the CIE 1960 chromaticity diagram:

$$u = \frac{4X}{X + 15Y + 3Z} = \frac{4x}{-2x + 12y + 3}$$

$$v = \frac{6Y}{X + 15Y + 3Z} = \frac{6y}{-2x + 12y + 3}$$

7.4. Color-difference formulas

Evaluation of the Color Rendering Properties of Light Sources

Chromatic adaptation correction: *u' v'*

Von Kries type of transformation:

$$u'_k = u_r$$

$$v'_k = v_r$$

$$u'_{k,i} = \frac{10.872 + \dfrac{0.404 c_r c_{k,i}}{c_k} - \dfrac{4 d_r d_{k,i}}{d_k}}{16.518 + \dfrac{1.481 c_r c_{k,i}}{c_k} - \dfrac{d_r d_{k,i}}{d_k}}$$

$$v'_{k,i} = \frac{5.520}{16.518 + \dfrac{1.481 c_r c_{k,i}}{c_k} - \dfrac{d_r d_{k,i}}{d_k}}$$

Subscript k: chromaticity coordinates of the test source.

Subscript r: chromaticity coordinates of the reference illuminant.

$u_{k,i}$ and $v_{k,i}$: chromaticity coordinates for test color *j* under the test source.

c_r, d_r, c_k, d_k, $c_{k,i}$ *and* $d_{k,i}$ are coefficients computed from the chromaticity coordinates *u* and *v* (*s* means subcript) :

$$c_s = \frac{4 - u_s - 10 v_s}{v_s}$$

$$d_s = \frac{1.708 v_s + 0.404 - 1.481 u_s}{v_s}$$

7.4. Color-difference formulas

Evaluation of the Color Rendering Properties of Light Sources

Computing of color rendering indices

1. Inputs needed: $S_k(\lambda)$, $S_r(\lambda)$, and x_k, y_k of the test samples, u_k and v_k of the test illuminant.
2. Chromaticity coordinates u, v for all samples under the test ($u_{k,i}$, $v_{k,i}$) and the reference illuminant ($u_{r,i}$, $v_{r,i}$).
3. Chromatic adaptation correction. Calculate c_r, c_k, $c_{k,i}$, d_r, d_k, $d_{k,i}$. Calculate $u'_{k,i}$, $v'_{k,i}$, u'_k, v'_k.
4. Compute the tristimulus values: $W^*_{r,i}$, $U^*_{r,i}$, $V^*_{r,i}$ and $W^*_{k,i}$, $U^*_{k,i}$, $V^*_{k,i}$.

Warm White 3000k - 52 CRI | SPX 30 3000k - 82 CRI | SPX 65 6500k - 82 CRI

7.4. Color-difference formulas

Evaluation of the Color Rendering Properties of Light Sources

Computing of color rendering indices

5. Color differences ΔEi (i=1,2,…15) for each sample under the two illuminants:

$$\Delta E_i = \left[\left(U^*_{r,i} - U^*_{k,i}\right)^2 + \left(V^*_{r,i} - V^*_{k,i}\right)^2 + \left(W^*_{r,i} - W^*_{k,i}\right)^2\right]^{1/2}$$

6. The special color rendering indices R_i for each of the test colors are obtained by:

$$R_i = 100 - 4.6\Delta E_i$$

7. The general color rendering index R_a is obtained by:

$$R_a = \frac{\sum_{i=1}^{8} R_i}{8}$$

7.4. Color-difference formulas

Usual size of industrial color differences

Autores	Observadores	Número de Centros o Pares Estudiados	ΔE^*_{ab}
MacAdam, 1942	**PGN**	**24**	**0.73**
Brown et al., 1949	WRJB	34	0.57
	DLM	33	0.55
Brown, 1957	Sin ponderar	21	0.90
	Ponderado	21	0.71
Wyszecki et al., 1971	GF	28	1.04
	AR	28	1.00
	GW	28	1.12
Witt, 1990	22-24 sujetos	5	0.38
Luo et al., 1986	---	131	1.14
Cheung et al., 1986	20 sujetos	5	1.79
RIT-Dupont, 1991	**50 sujetos**	**19**	**1.75**
Munsell Book of Color (Acabado Brillante)	**Hue Variable Value = 5 1 Paso en Croma**	**350**	**10.24**
	1 Paso en Hue Value = 5 Croma Variable	**365**	**8.45**
	Hue = 5R 1 Paso en Value Croma Variable	**53**	**10.86**

Main industrial color differences are in the range 0-5 CIELAB units

M. Melgosa et al. Opt. Pur. Apl. 34, 1-10 (2001)

7.4. Color-difference formulas

Considerations about ∆E measurements in industry

- One limitation of developing a color-difference formula that is based on **just-perceptible difference** is that the visual differences are too small compared to the typical variability of most industrial processes. It could be argued that this measure is solely a useful measure for physiology...

- ***Perceptibility:*** "Can you see a difference in color?" "Is this difference in color greater than or less than the difference in color between members of a standard pair?" It is just a visual judgment without interpreting its importance.

- ***Acceptability:*** "Is this difference in color acceptable?"

- When color differences are slightly above threshold (***suprathreshold***), *perceptibility* and *acceptability* measurements maybe identical. However as the size of the colour difference increases, *acceptability* judgements are made that are often different from the corresponding *perceptibility* judgement enlarged by a commercial factor. The acceptability criteria may be diffuse and maybe different acceptability criteria are used in different industries.

7.4. Color-difference formulas

The goal of any dyehouse is to deliver products that satisfy the shade requirements of its customers.

Bach to batch variation is impossible to eliminate completely, so an agreement must be reached between the dyer and the customer as to what represents **acceptable** shade variations. To avoid day to day shade assessments by eye, the use of a pass/fail reliable software based on a single number is highly recommendable.

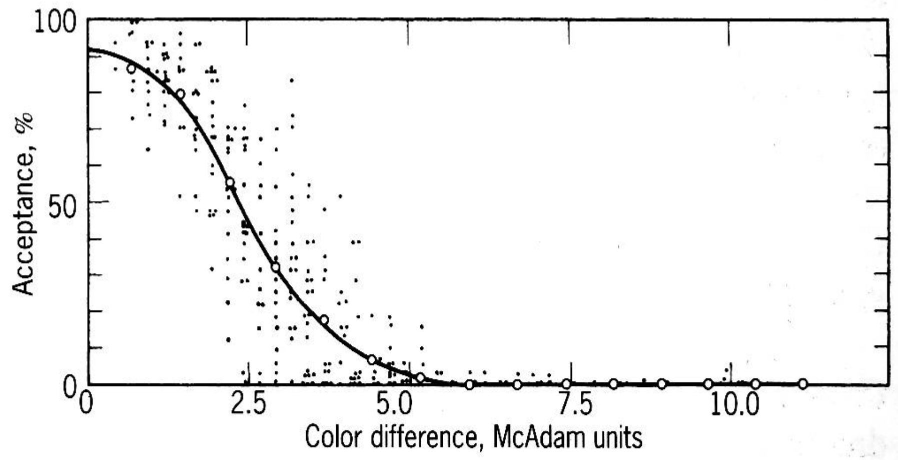
Be aware that small tolerances entail high costs while large tolerances are indicative of a lack of rigorous work. A compromise must be reached in each case.

7.4. Color-difference formulas

Pass / Fail decisions in industrial applications

In industries such as textiles, plastics or coatings, a number of samples are produced about a standard (it is not possible a continuous color variation as in visual colorimeters). Under a defined set of illuminating and viewing conditions the observers "accept" or "pass" a sample if the color difference between the standard and itself was smaller than a defined matching criterion, or "reject" or "fail" it in the opposite case.

A "tolerance limit" may be also fixed by minimizing the number of wrong decisions.

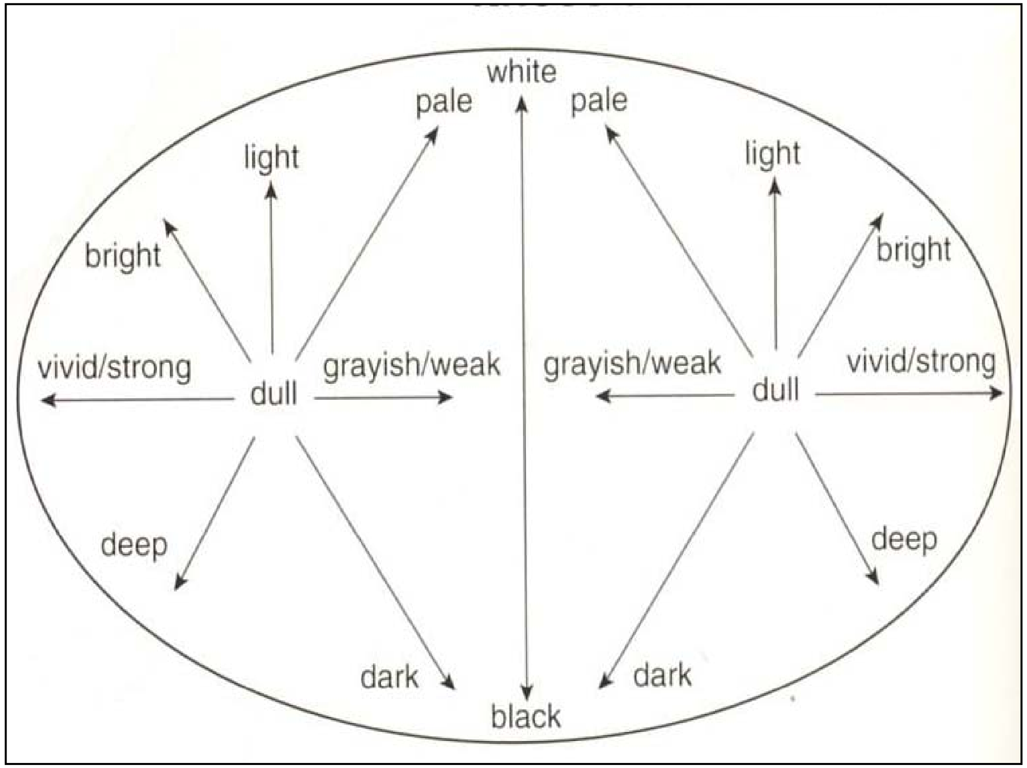


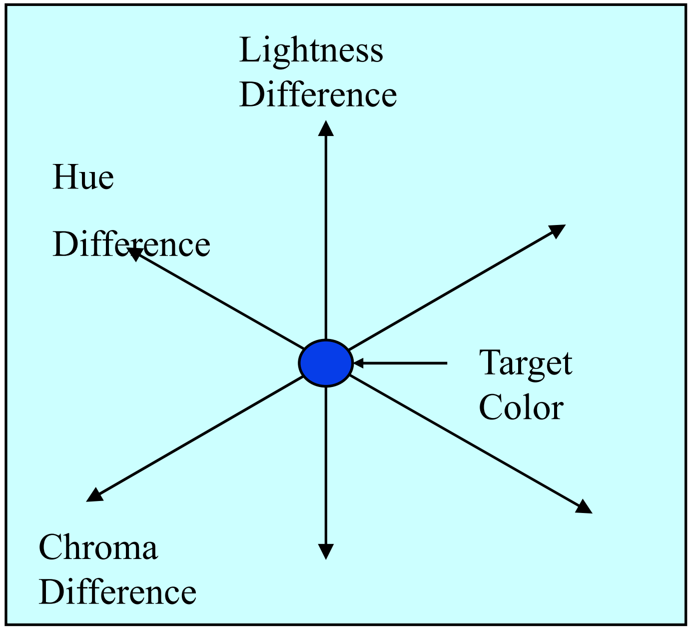
This figure (Davidson 1953) shows that, over a wide range of color differences (here, MacAdam units), some observers will consider a given color difference acceptable, while others will reject it. But the *average* acceptability (solid line) varies smoothly with the size of the color difference.

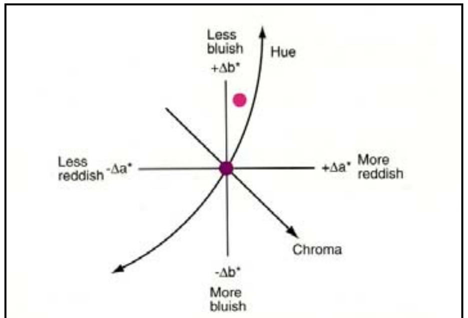
7.4. Color-difference formulas

Tolerance limits in industry

Color Difference can be plotted in any three-dimensional color space.



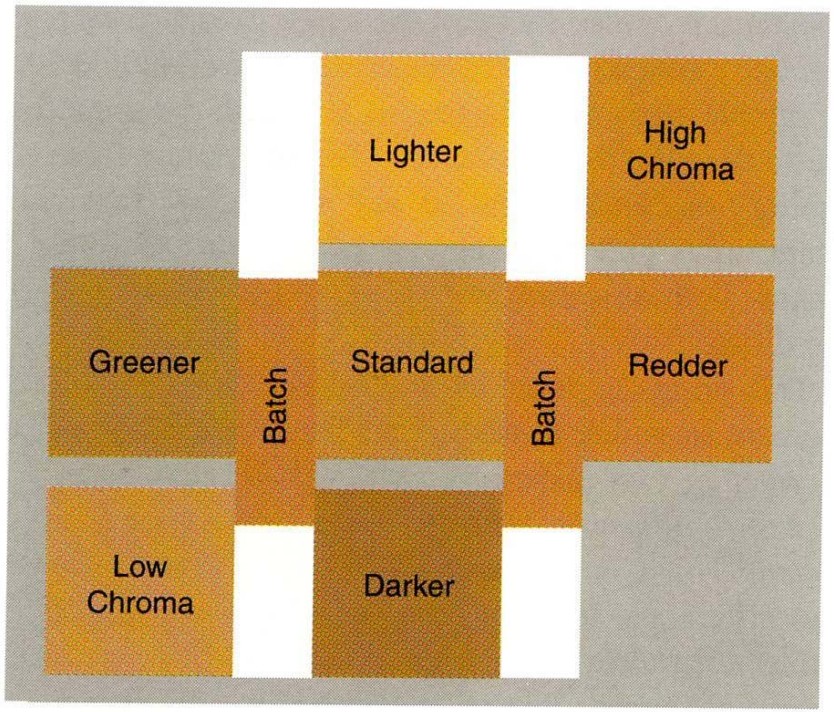




Rather than show the rotated axes, a $\Delta a^* \Delta b^*$ plot along with lines of constant hue angle and chroma are used. The arrow on the constant hue angle line indicates the position of the neutral point, and thus the color of the standard. The arc's radius indicates the chroma of the standard.

7.4. Color-difference formulas

Tolerance limits in industry



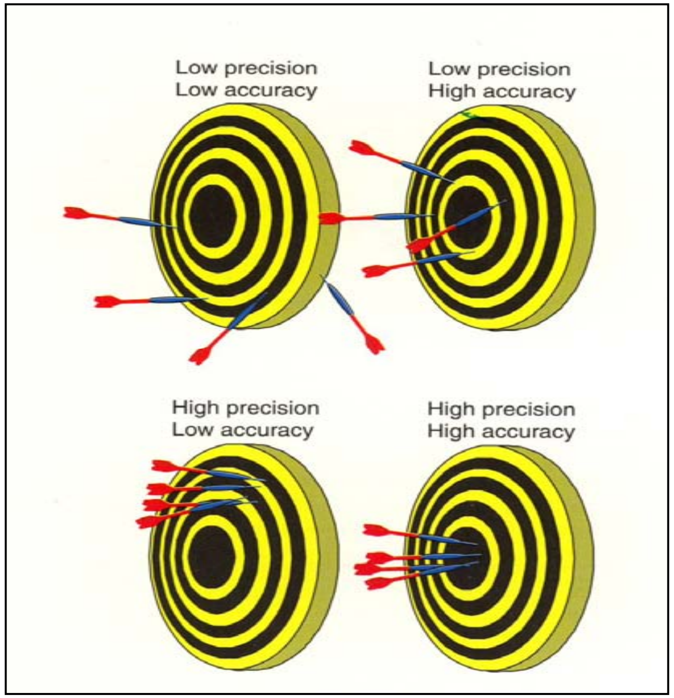
Visual tolerance charts are sometimes used in evaluating color quality. There are lightness, hue, and chroma limits.

Small industrial tolerances increase production costs, and large tolerances may affect product quality. A compromise may be necessary. (R.D. Lozano)

Tolerance: Color-difference value corresponding to the transition between 2 categories of judgment.
(D.H. Alman, et al., CR&A 14, p.140, 1989).

7.4. Color-difference formulas

Evaluating Precision



First we must distinguish between **precision** and **accuracy** (see figure).

Precision is divided into repeatability and reproducibility (Berns, p. 96-97):

- **Repeatability**: The closeness of agreement between the results of successive measurements of the same test, carried out in a single lab, by the same method of measurement, operator, and measuring instrument.
- **Reproducibility**: Idem before, but now changing conditions such as the operator, lab, measuring instrument or time.

Precision is measured using the mean color difference from the mean MCDM:

$$MCDM = \frac{\sum_{i=1,N}\left[\left(L_i^* - \overline{L^*}\right)^2 + \left(a_i^* - \overline{a^*}\right)^2 + \left(b_i^* - \overline{b^*}\right)^2\right]^{1/2}}{N}$$

7.4. Color-difference formulas

Brief history of color-difference formulas

More than 40 different ΔE's have been proposed…

Phase 1: Before 1976. ΔE's based on the Munsell system, MacAdam's ellipses, and transformations of tristimulus values X,Y,Z.

Phase 2: Proposal of CIELUV and CIELAB in 1976.

Phase 3: After 1976. CIELAB-based formulas.

7.4. Color-difference formulas

Source: M.R. Luo, Alicante 2004

Category of formulae	Munsell data	MacAdam's data	Transformation from XYZ	Others
Before 1976				
1935			Judd	
1936	Index of fading			
1937			MacAdam	
1939	Balinkin			
1942			JHNBS	
1943	Munsell renotation	MacAdam g_{ij}		
1944	ANLAB			
1946	Saunderson-Milner			
1951	Godlove			
1955				DIN
1958	Glasser cube root	Simon-Goodwin	Hunter LAB	
1963			CIE U*V*W*	
1965		Friele		
1967		FMC-I		
1969	Moton cube root			
1971	MLR	FMC-II		
1972	MCR			
1974	ΔEa			OSA
1976	**CIELAB**		**CIELUV**	

7.4. Color-difference formulas

Source: M.R. Luo, Alicante 2004

Category of formulae	Munsell data	MacAdam's data	Transformation from XYZ	Others
After 1976				
1978		FCM		
1980	JPC79	LABNHU		
1984	CMC	ATD		
1986		SVF		
1987	BFD			
1991	KC-III			
1995	CIE94			
1997	LCD			
1999	Kuehni			
2001	CIEDE2000	Oleari		
After 2001				
2002				DIN99d
2006				CAM02
2006				OSA-GP
2009				OSA-GP Euc.

7.4. Color-difference formulas

Nickerson (1936)

Maybe the first color difference formula (used as a index of fading). Based on Munsell system: H, V, C are the Munsell coordinates (Hue, Value, Chroma).

$$\Delta E = \frac{2}{5} C \Delta H + 6 \Delta V + 3 \Delta C$$

Adams-Nickerson (1942): ANLAB40

$$L = 0.23 V_Y \qquad a = (V_X - V_Y) \qquad b = 0.4(V_Y - V_Z)$$

$$\Delta E_{ANLAB40} = 40\sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2}$$

The factor “40” allows to obtain a similar scale to the ones from other formulas

7.4. Color-difference formulas

Hunter (1942): NBS unit of color difference

$$\alpha = \frac{2.4266x - 1.3631y - 0.3214}{1.0000x + 2.2633y + 1.1054} \qquad \beta = \frac{0.5710x - 1.2447y - 0.5708}{1.0000x + 2.2633y + 1.1054}$$

$$\Delta E = f_g \left\{ \left[221 Y_m^{1/4} (\Delta\alpha^2 + \Delta\beta^2)^{1/2} \right]^2 + \left[k\Delta\left(Y^{1/2}\right) \right]^2 \right\}^{1/2}$$

where f_g (gloss factor) takes account of the masking influence of a glossy surface on the detection of color differences, Y_m is the arithmetical mean of the luminance of the samples, and k considers the relative importance of the lightness and chromaticity in the total color difference, and is usually taken as 10 for a very narrow dividing line (parametric factor)

$$f_g = \frac{Y_m}{(Y_m + 2.5)} \qquad Y_m = (Y_1 + Y_2)/2$$

7.4. Color-difference formulas

Glasser cubic-root (1958)

Based on a linear transformation of tristimulus values, followed by cubic roots (as a valid approximation to the Munsell Value function), and finally two opponent signals and an achromatic one. The structure of this formula show it as a clear precedent of CIELAB.

$$R = 1{,}1084X + 0{,}0852Y - 0{,}1454Z$$

$$G = -0{,}0010X + 1{,}0005Y + 0{,}0004Z$$

$$B = -0{,}0062X + 0{,}0394Y + 0{,}8192Z$$

$$K_a = 105 \text{ pro } R < G \;\; a \;\; K_b = 30{,}5 \text{ pro B} < G$$

$$K_a = 125 \text{ pro } R > G \;\; a \;\; K_b = 53{,}6 \text{ pro B} > G$$

$$L = 25{,}29G^{1/3} - 18{,}38\,,$$

$$a = K_a\left(R^{1/3} - G^{1/3}\right),$$

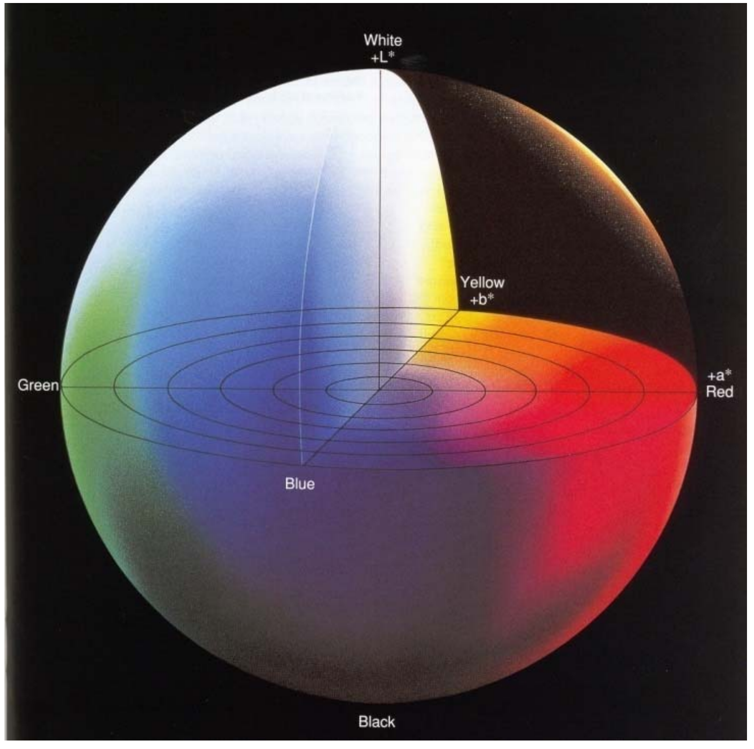
$$b = K_b\left(G^{1/3} - B^{1/3}\right),$$

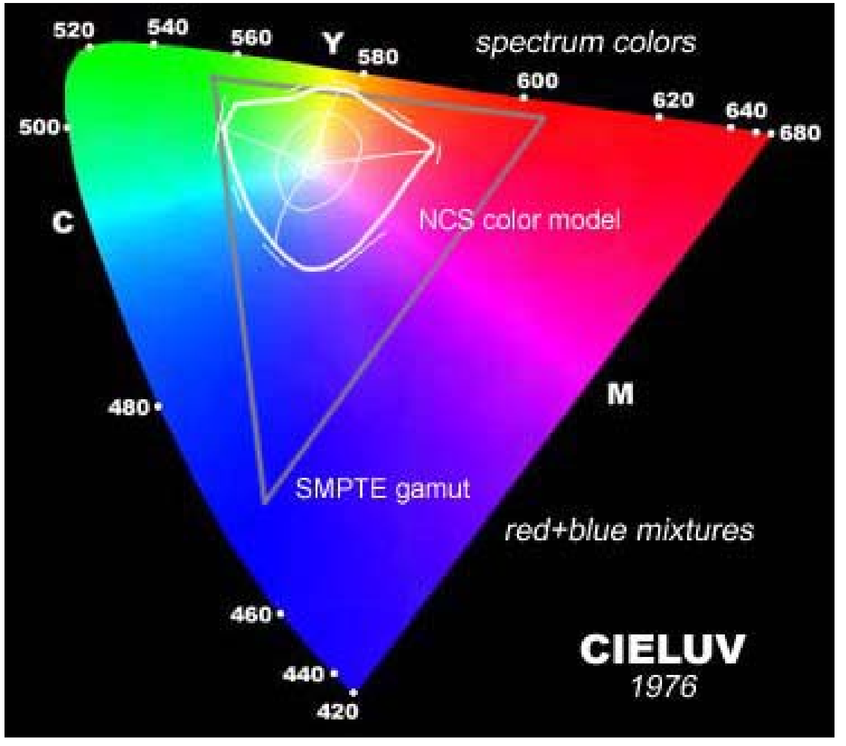
$$\Delta E = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2}$$

7.4. Color-difference formulas

CIELAB and CIELUV

The CIE 1976 *L*a*b** color space (CIELAB) and the CIE 1976 *L*u*v** color space (CIELUV), can be considered color appearance models.





7.4. Color-difference formulas

CIELAB

CIELAB as a color space to be used for color differences.

CIELAB uniform color space.

CIELAB can be considered a color appearance model.

CIELAB coordinates

Modified von Kries chromatic adaptation transform by normalizing the stimulus tristimulus values by those of the white (i.e., X/X_n, Y/Y_n, and Z/Z_n).

$$L^* = 116\left(\frac{Y}{Y_o}\right)^{1/3} - 16 \quad \text{if } \left(\frac{Y}{Y_o}\right) > 0.008856$$

$$L^* = 903.3\left(\frac{Y}{Y_o}\right) \quad \text{if } \left(\frac{Y}{Y_o}\right) \leq 0.008856$$

$$a^* = 500[f(X/X_o) - f(Y/Y_o)]$$

$$b^* = 200[f(Y/Y_o) - f(Z/Z_o)]$$

7.4. Color-difference formulas

CIELAB coordinates

A compressive nonlinearity by a cube root.

Three response dimensions corresponding to the light-dark, red-green, and yellow-blue responses of the opponent theory of color vision.

Appropriate multiplicative constants.

$$L^* = 116\left(\frac{Y}{Y_o}\right)^{1/3} - 16 \quad \text{if} \left(\frac{Y}{Y_o}\right) > 0.008856$$

$$L^* = 903.3\left(\frac{Y}{Y_o}\right) \quad \text{if} \left(\frac{Y}{Y_o}\right) \leq 0.008856$$

$$a^* = 500[f(X/X_o) - f(Y/Y_o)]$$

$$b^* = 200[f(Y/Y_o) - f(Z/Z_o)]$$

$$f(\alpha) = \alpha^{1/3} \quad \text{if } \alpha > 0.008856$$

$$f(\alpha) = 7.787\alpha + \frac{16}{116} \quad \text{if } \alpha \leq 0.008856$$

7.4. Color-difference formulas

CIELAB coordinates

L^* is correlate to perceived lightness ranging from 0.0 to 100.0 for a diffuse white.

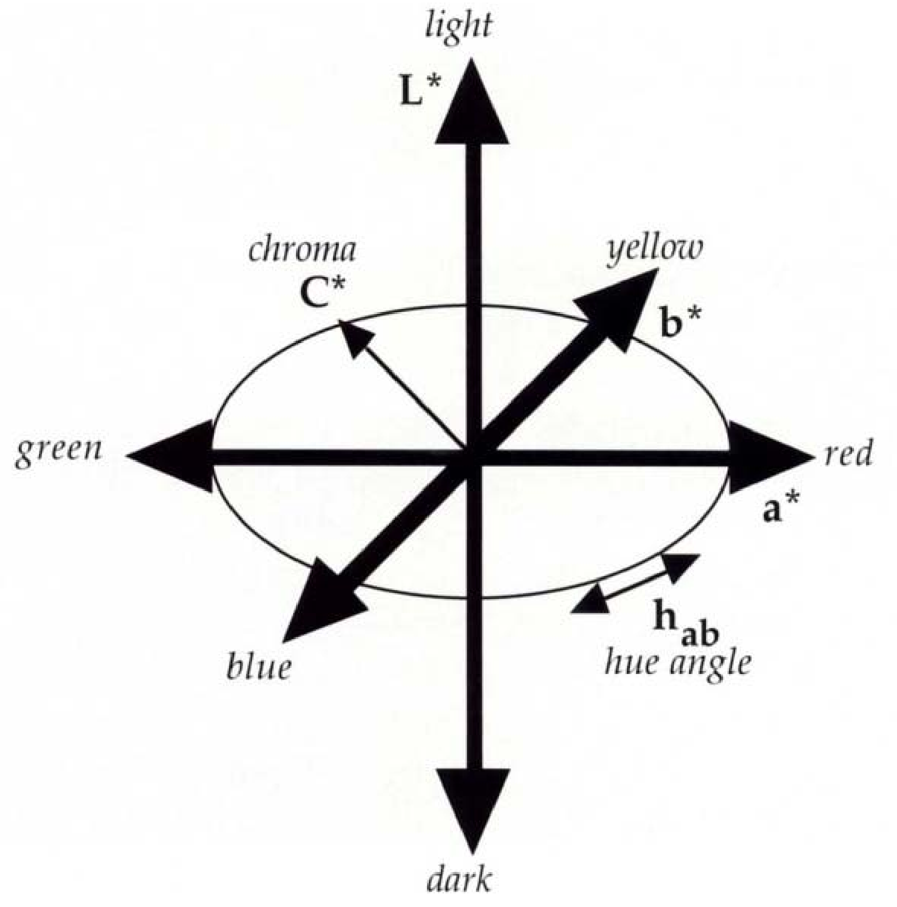
a^* and b^* correlate with red-green and yellow-blue chroma perceptions.

CIELAB L^*, a^*, and b^* are Cartesian coordinates.

Cylindrical coordinates, which provides predictors of chroma C^*_{ab} and hue h_{ab}.

$$C^*_{ab} = \sqrt{(a^*)^2 + (b^*)^2}$$

$$h_{ab} = \arctan \frac{b^*}{a^*}$$



Rafael Huertas Roa
Javier Hernández Andrés
Eva Valero Benito

7.4. Color-difference formulas

CIELUV

CIELUV similar properties as CIELAB.

CIELUV different form of chromatic adaptation transform: a subtractive shift in chromaticity coordinates ($u'-u'_n$, $v'-v'_n$).

The subtractive adaptation transform is farther from physiology. The CIELUV adaptation transform is extremely inaccurate.

$$\boxed{\begin{aligned} u^* &= 13L^*(u' - u'_o) \\ v^* &= 13L^*(v' - v'_o) \end{aligned}}$$

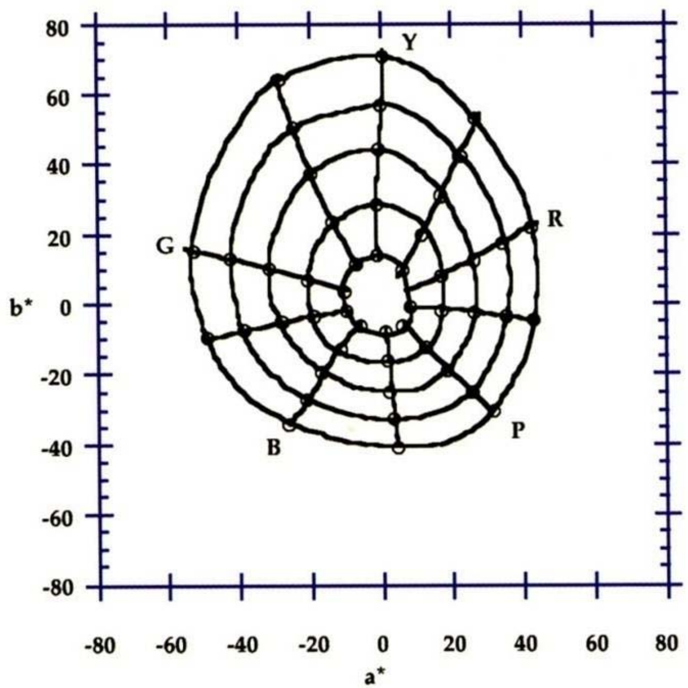
$$u' = \frac{4X}{X + 15Y + 3Z} \quad \text{or} \quad \mathrm{u}' = \frac{4\mathrm{x}}{-2\mathrm{x} + 12\mathrm{y} + 3}$$

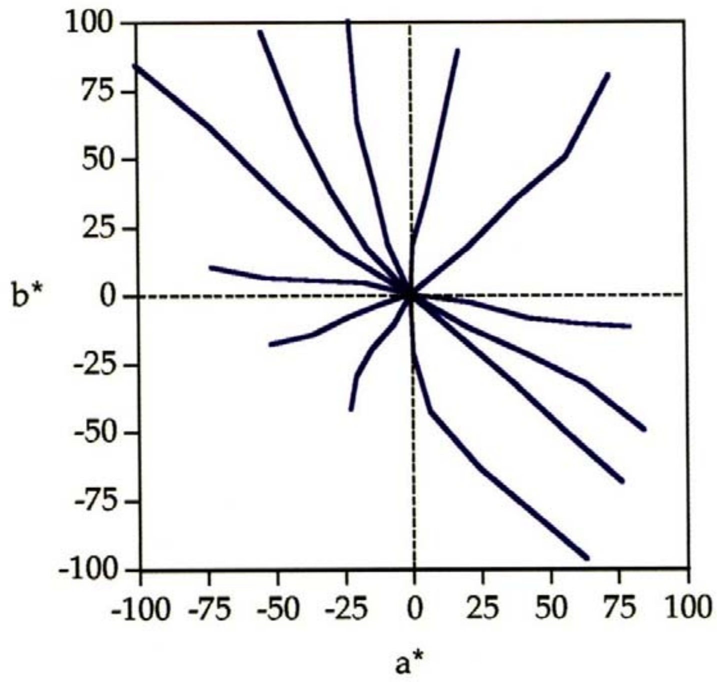
$$v' = \frac{9Y}{X + 15Y + 3Z} \quad \text{or} \quad \mathrm{v}' = \frac{9\mathrm{y}}{-2\mathrm{x} + 12\mathrm{y} + 3}$$

7.4. Color-difference formulas

Limitations of CIELAB:

- The perceptual non-uniformity of the CIELAB space.
  Plots of constant hue and chroma contours from the Munsell Book of Color.
  Plots of constant hue from Hung and Berns' work.





7.4. Color-difference formulas

CIELAB and CIELUV

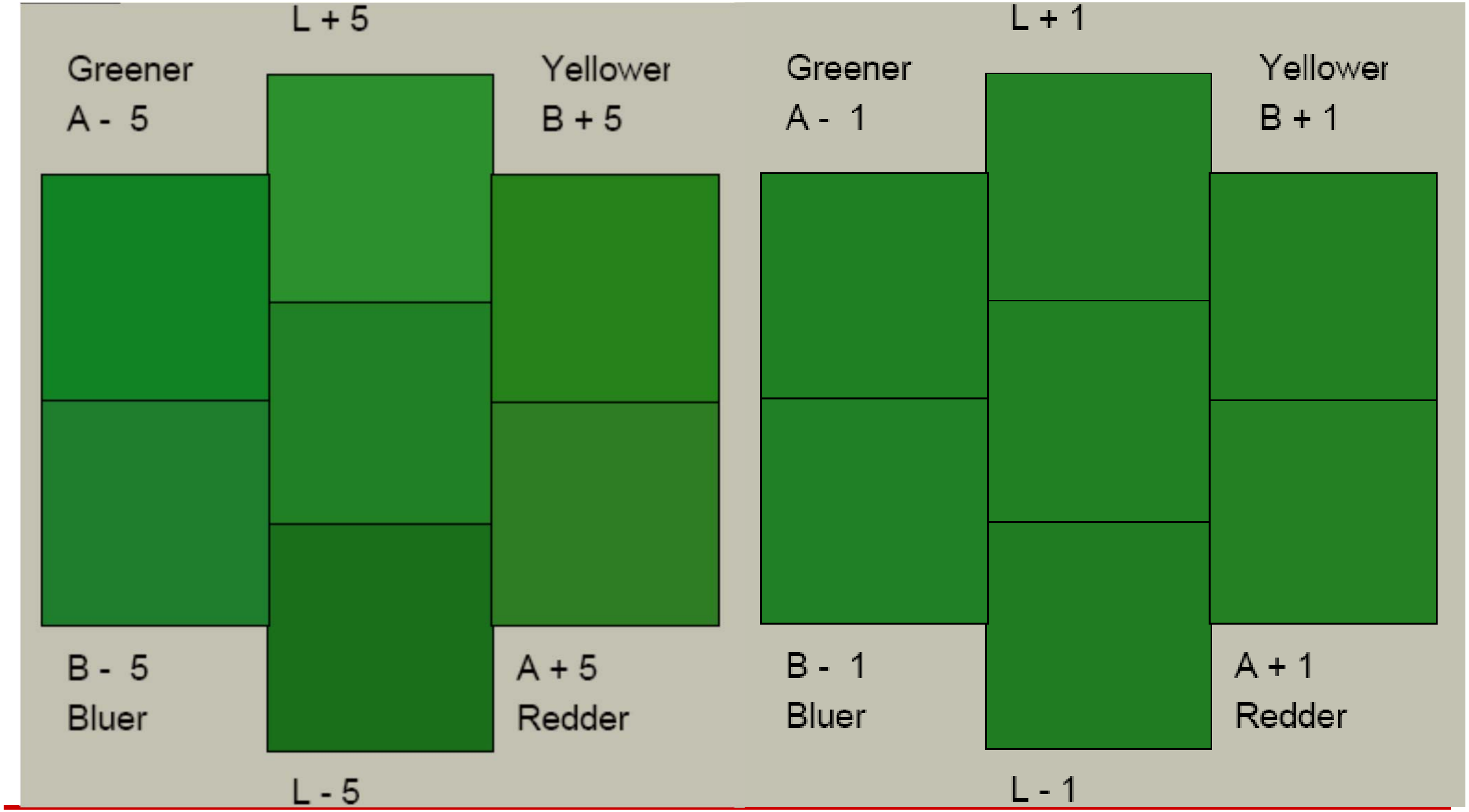
Note 6 on the CIELAB space from CIE publication 15.2 states:

"*These spaces are intended to apply to comparisons of differences between object colours of the same size and shape, viewed in identical white to middle grey surroundings, by an observer photopically adapted to a field of chromaticity not too different from that of average daylight.*"

CIELAB space is a simple model that can be used as a benchmark to measure more sophisticated models.

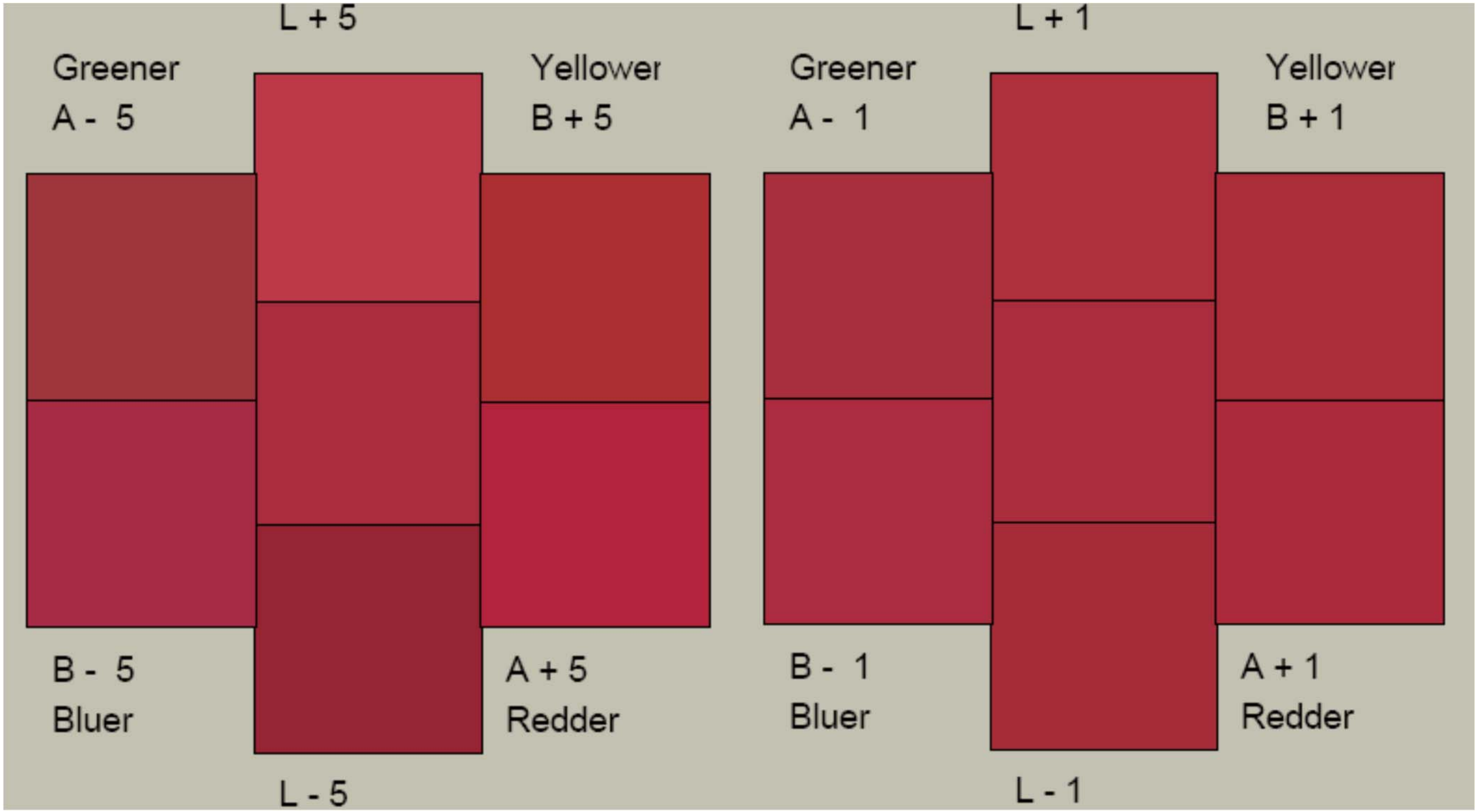
7.4. Color-difference formulas

Visual non-uniformity of CIELAB



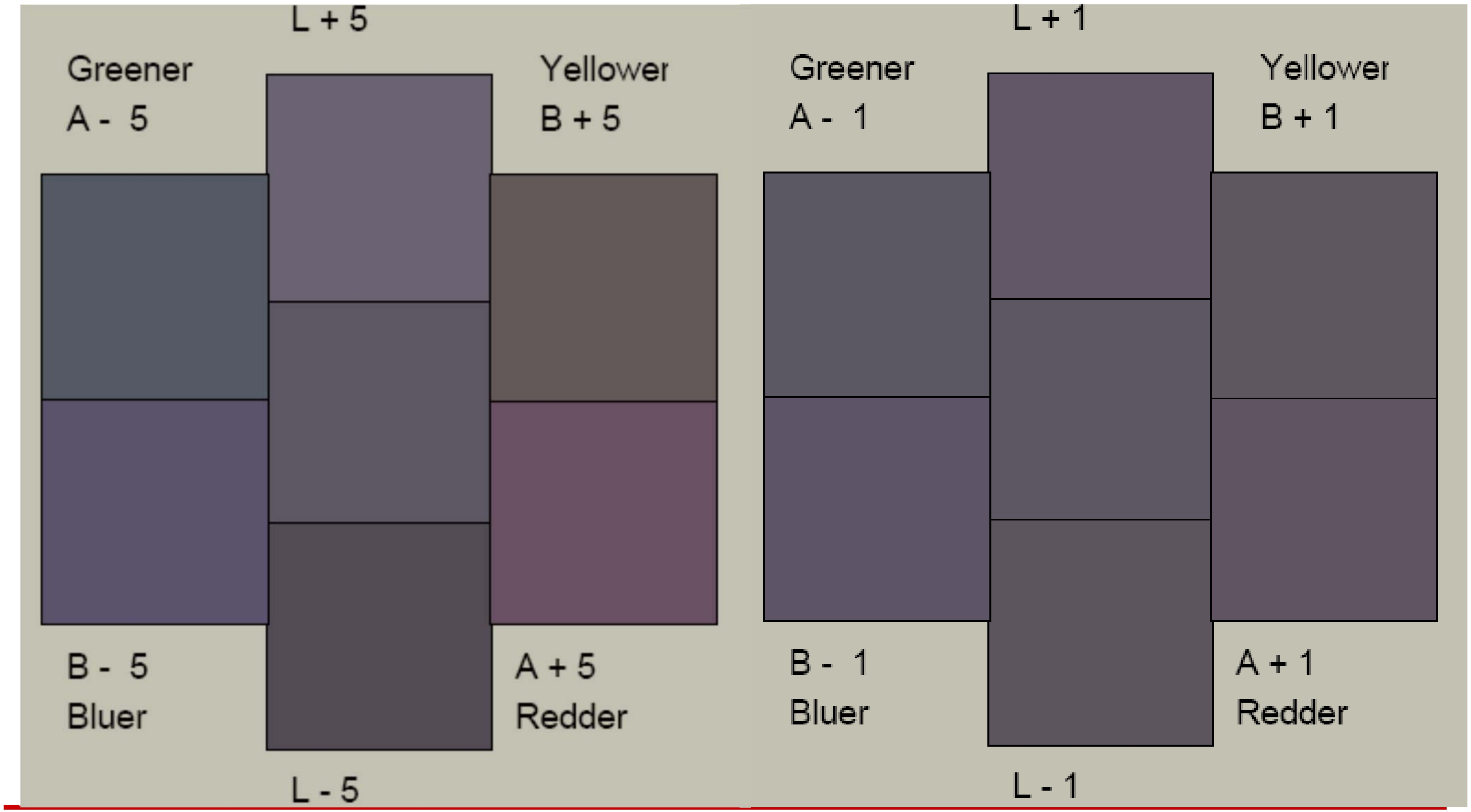
7.4. Color-difference formulas

Visual non-uniformity of CIELAB



7.4. Color-difference formulas

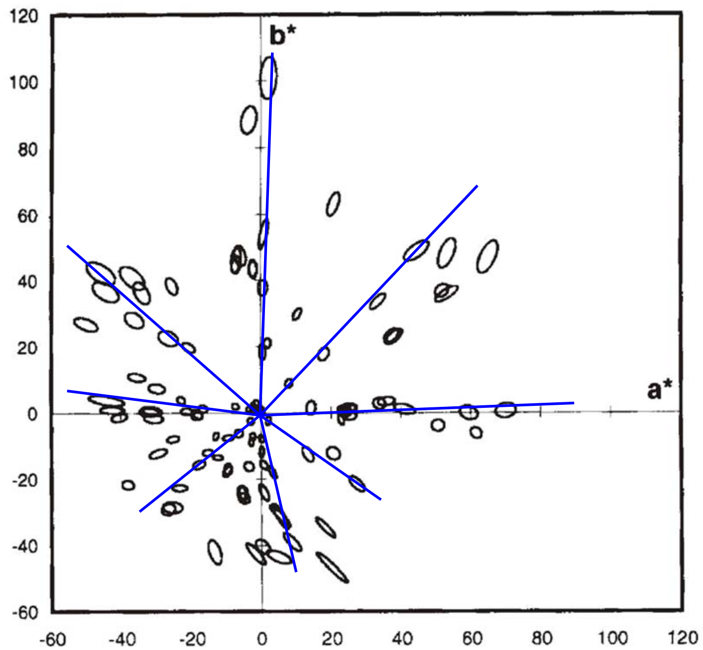
Visual non-uniformity of CIELAB



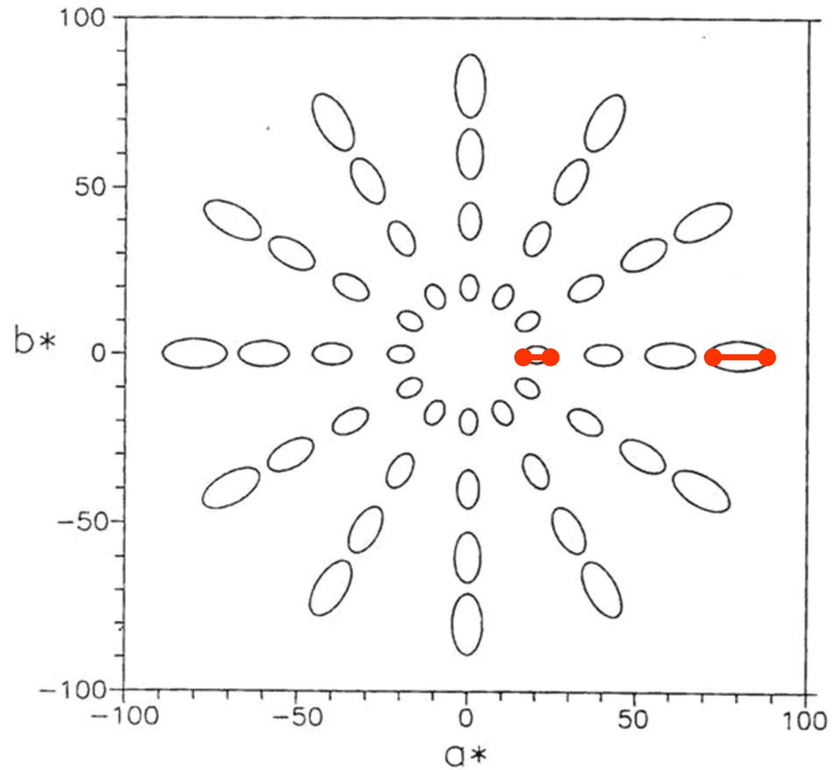
7.4. Color-difference formulas

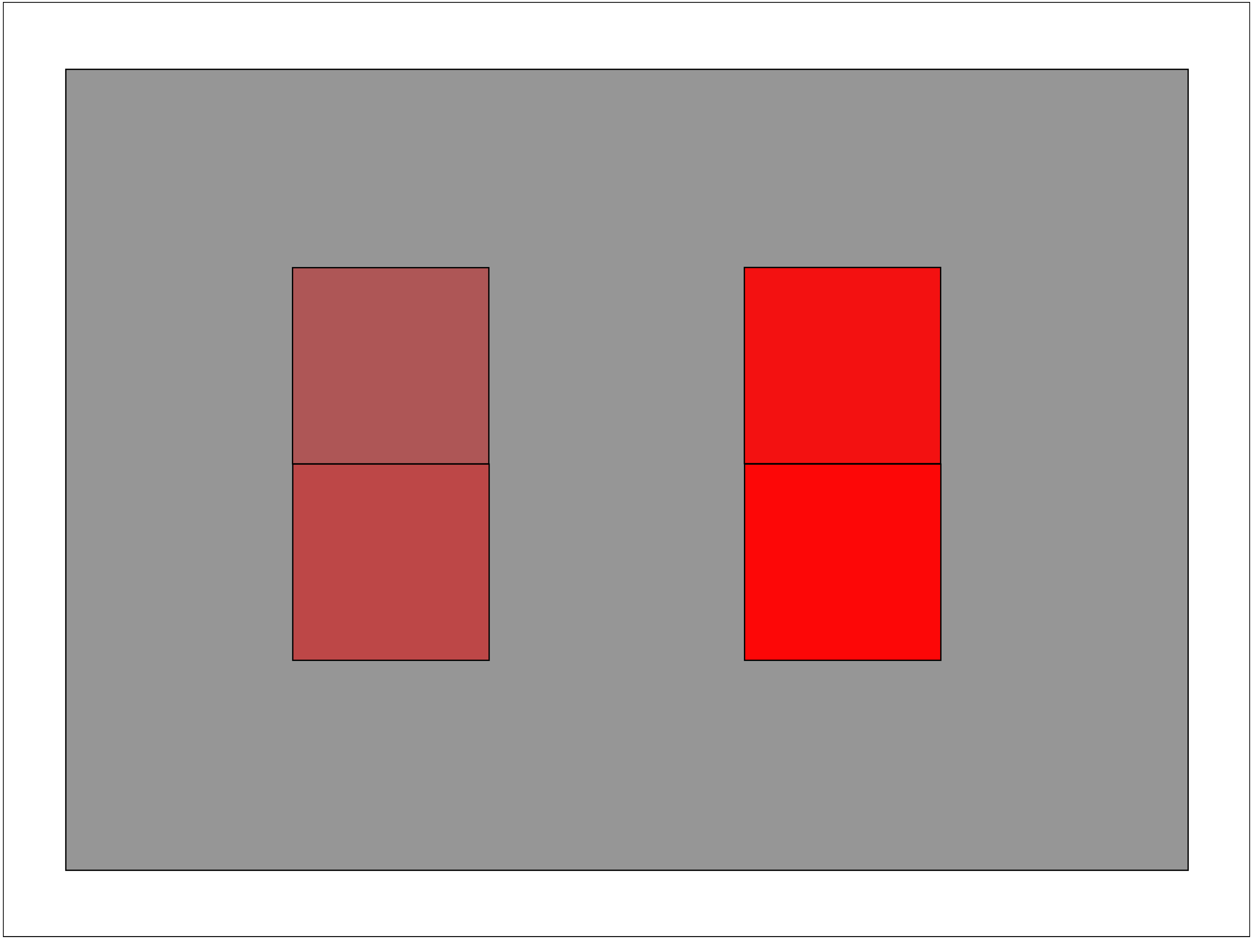
The increasing chroma tolerance with chroma in CIELAB space.

The lack of uniformity of CIELAB (i.e. tolerances given by spheres with identical size in all color space) led to the development of many CIELAB-based formulas after 1976: JPC79, CMC, BFD, LCD, etc.



Elipses BFD-P en a*b*
(Col. Res. Appl., 26, 340-350, 2001)

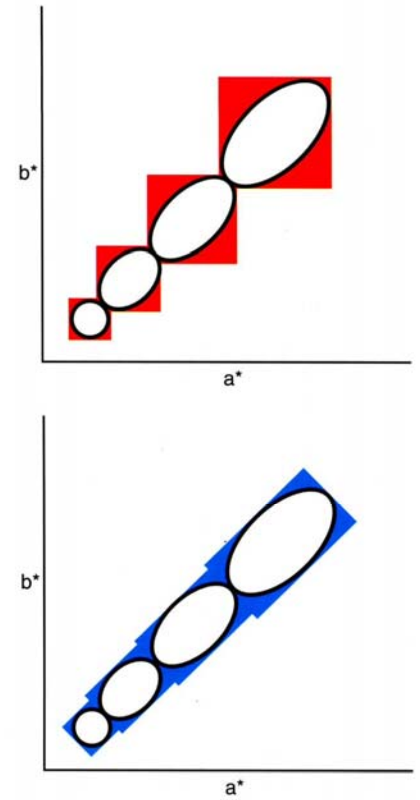




7.4. Color-difference formulas

Cylindrical or Euclidean CIELAB coordinates?

CIELAB-based color difference formulas: JPC79, CMC, BFD, LCD, CIE94



Visual tolerances, shown as ellipses, can be approximated by $\Delta a^*\Delta b^*$ tolerances, shown in the upper figure as the red rectangles, or $\Delta C^*_{ab}\ \Delta H^*_{ab}$ tolerances, shown in the lower figure as the cyan rectangles. The difference in area between each rectangle and corresponding ellipse is smaller when $\Delta C^*_{ab}\ \Delta H^*_{ab}$ tolerances are used. Thus, in general, a $\Delta C^*_{ab}\ \Delta H^*_{ab}$ tolerance is a closer approximation to the visual data.

7.4. Color-difference formulas

CIE94 color-difference formula

$$\Delta E_{94}^{*} = \left[\left(\frac{\Delta L^{*}}{k_L S_L}\right)^2 + \left(\frac{\Delta C_{ab}^{*}}{k_C S_C}\right)^2 + \left(\frac{\Delta H_{ab}^{*}}{k_H S_H}\right)^2\right]^{1/2}$$

The development of CIE94 from BFD-P and RIT-DuPont datasets (Witt's data only refer to the 5 CIE 1978 centers)

- Weighting Factors: S_L, S_C, S_H

  To correct the lack of uniformity of CIELAB space.

$$S_L = 1 \qquad S_C = 1 + 0.045\bar{C}_{ab}^{*} \qquad S_H = 1 + 0.015\bar{C}_{ab}^{*}$$

$$\bar{C}_{ab}^{*} = \sqrt{C_{ab,1}^{*} C_{ab,2}^{*}}$$

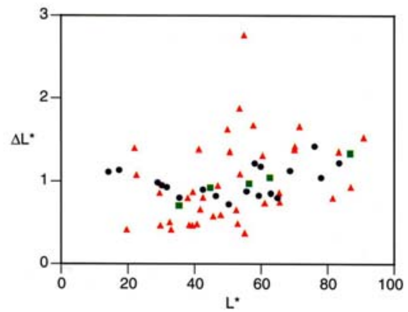
- Parametric Factors: k_L, k_C, k_H

  To correct for the influence of experimental viewing conditions (first time introduced in a CIE formula).

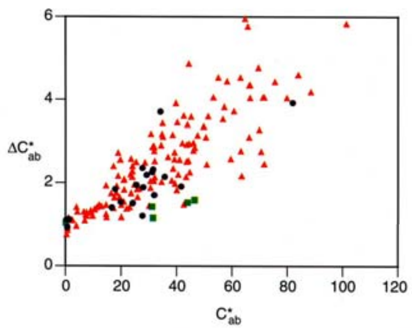
7.4. Color-difference formulas

CIE94 color-difference formula

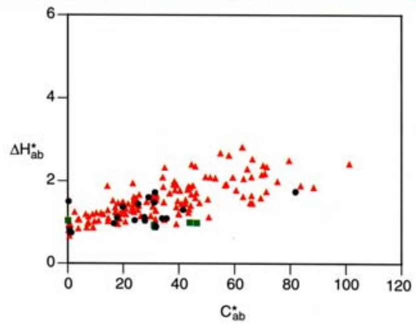
Three datasets were evaluated by CIE technical committee 1-29: Luo–Rigg (Luo 1986) shown as red triangles, Witt (1983, 1987) shown as green squares, and RIT–DuPont (Alman 1989, Berns 1991) shown as blue dots.



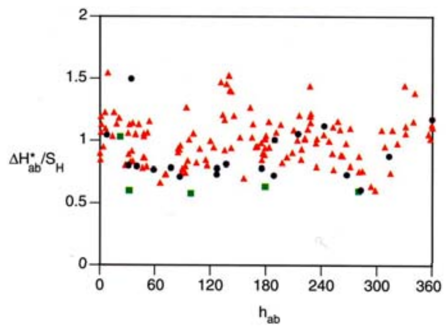
Because each dataset has a different match criterion, normalizations are required. For lightness, the average ΔL^* was scaled to equal unity. Thus in this plot, the average ΔL^* for each dataset equals 1.0.



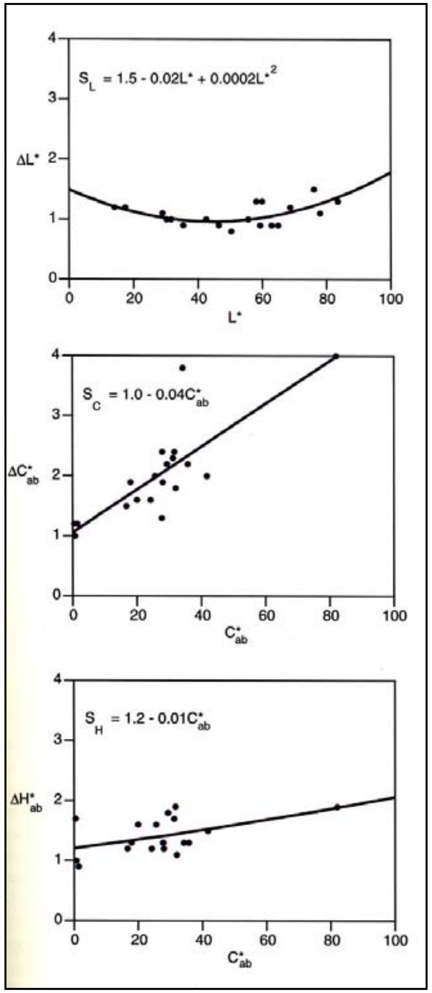
The three datasets are normalized by first fitting least-squares straight lines (i.e., fitting an offset and slope). Next, each offset is adjusted to equal unity.



The three datasets are normalized by first fitting least-squares straight lines (i.e., fitting an offset and slope). Next, each offset is adjusted to equal unity.



The three datasets are normalized by first fitting least-squares straight lines (i.e., fitting an offset and slope). Next, each offset is adjusted to equal unity. Finally, the ΔH^*_{ab} is adjusted for the chroma of the standard by dividing by $(1 + 0.015C^*_{ab})$, the CIE94 S_H weighting function.



7.4. Color-difference formulas

CIE94 color-difference formula

k_L=k_C=k_H=1 under 'reference conditions' (usual practice):

- Illumination: D65 source.
- Illuminance: 1000 lx.
- Observer: Normal color vision.
- Background field: Uniform, neutral gray with L^*=50.
- Viewing mode: Object.
- Sample size: Greater than 4 degrees.
- Sample separation: Direct edge contact.
- Sample color-difference magnitude: Lower than 5.0 ΔE^*_{ab}.
- Sample structure: Homogeneous (without texture).

Strong/Weak points for CIE94:

- It starts from CIELAB.
- It is simple and versatile.
- It was a very conservative approach…

7.4. Color-difference formulas

Comparing CIELAB-based color-difference formulas

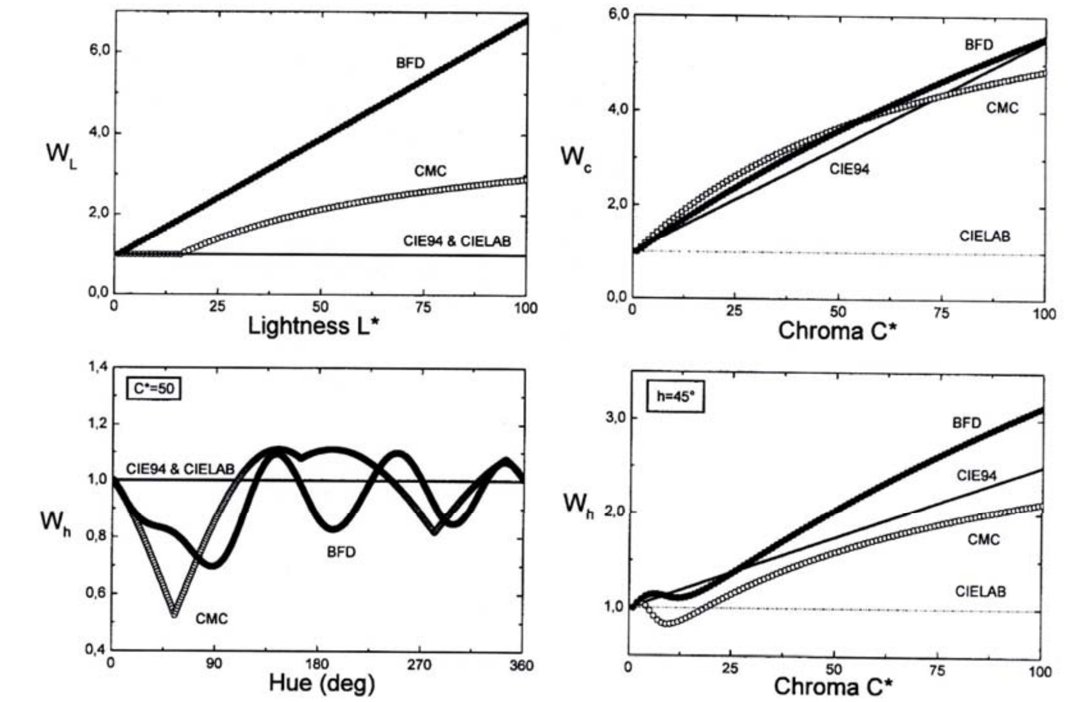


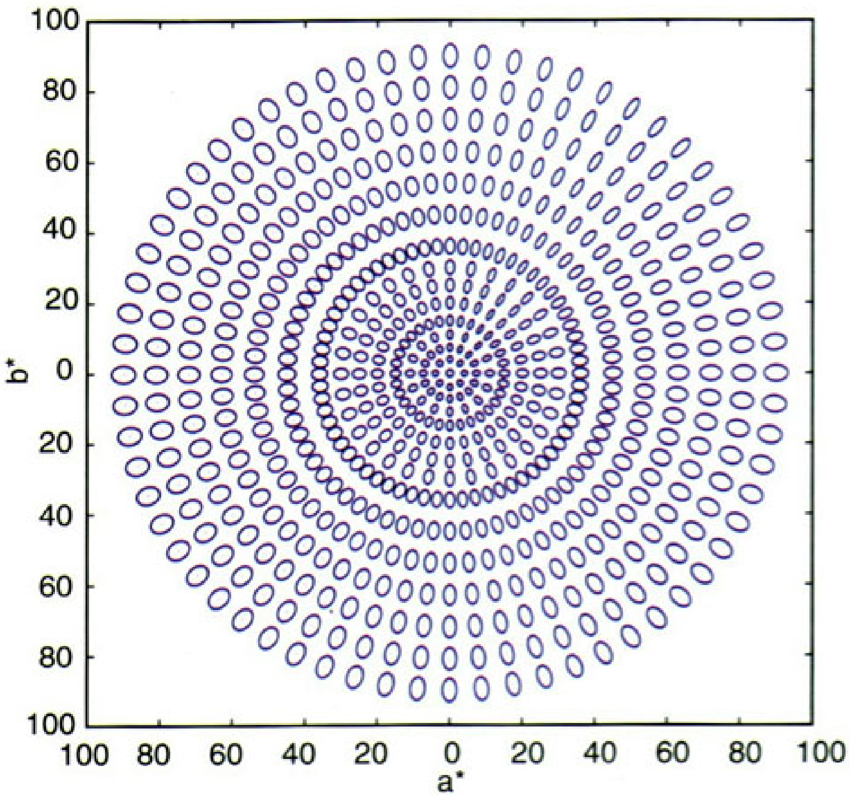
FIG. 1. Dependences of the weighting functions for lightness, chroma, and hue for different color-difference formulas. A common origin with CIELAB has been adopted in each plot by multiplying by the scaling factors given in Table I.

$$\Delta E = \left(\left(\frac{\Delta L^*}{W_L} \right)^2 + \left(\frac{\Delta C^*_{ab}}{W_C} \right)^2 + \left(\frac{\Delta H^*_{ab}}{W_H} \right)^2 \right)^{1/2}$$

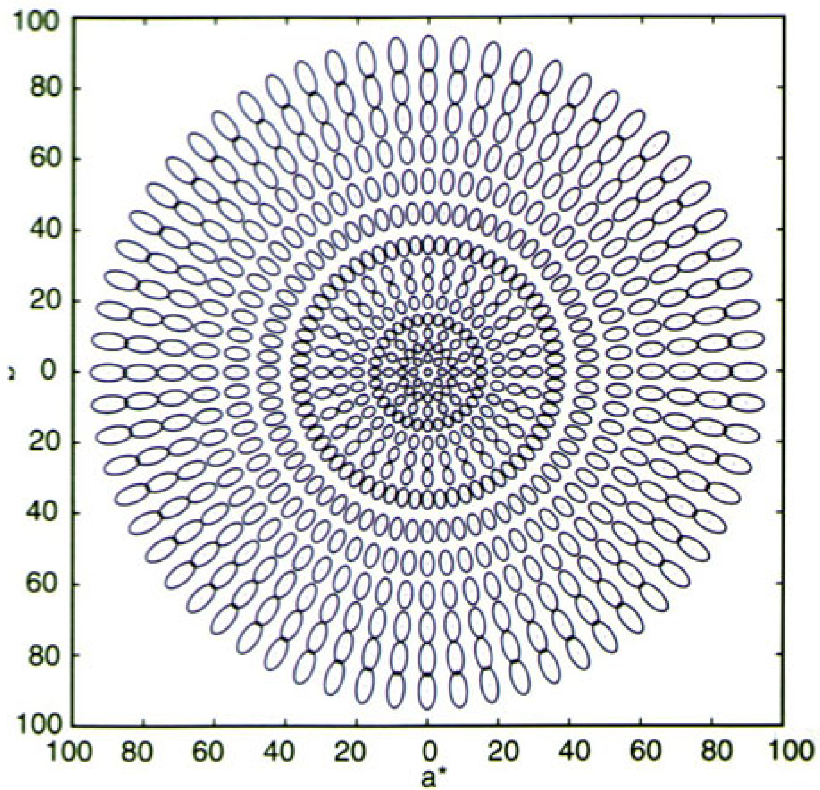
Note the smaller S_H value around 60º for the CMC(l:c) formula, but not for CIE94, which S_H is hue independent.

7.4. Color-difference formulas

Comparing CIELAB-based color-difference formulas



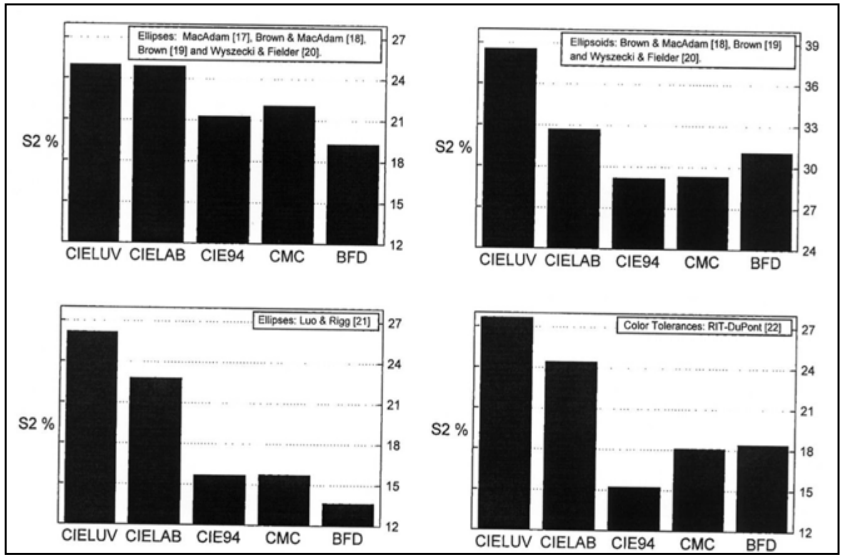
CMC(*l:c*)



CIE1994

7.4. Color-difference formulas

Comparing CIELAB-based color-difference formulas



CIE94, CMC and BFD report satisfactory results for “classical” data in colorimetry

Classical Literature: Ellipses [17-20]

	CIELUV	CIELAB	CIE94	CMC	BFD
CIELUV			*		*
CIELAB			*		*
CIE94	*	*			*
CMC					*
BFD	*	*	*	*	

Classical Literature: Ellipsoids [18-20]

	CIELUV	CIELAB	CIE94	CMC	BFD
CIELUV		*	*	*	*
CIELAB	*		*	*	
CIE94	*	*			*
CMC	*	*			*
BFD	*		*	*	

Luo & Rigg [21]

	CIELUV	CIELAB	CIE94	CMC	BFD
CIELUV			*	*	*
CIELAB			*	*	*
CIE94	*	*			
CMC	*	*			
BFD	*	*			

Color Tolerances: RIT-DuPont [22]

	CIELUV	CIELAB	CIE94	CMC	BFD
CIELUV		*	*	*	*
CIELAB	*		*	*	*
CIE94	*	*			*
CMC	*	*			
BFD	*	*	*		

FIG. 7. Results of the nonparametric U-test from the values of our parameter *S2%*. The asterisks indicate for each dataset the formulas significantly different at a confidence level of 90%.

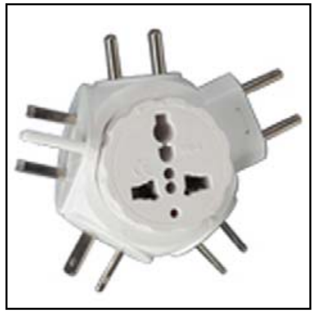
CIE94 is significantly different (and better) than CIELAB

7.4. Color-difference formulas

Scale factors among ΔE's?

Referencia	Fórmula de Diferencia de Color	Equivalencia
R.D. Lozano *El color y su medición*. Cap.VI, pp. 276-277. Ed. Americalee, (1978)	CIELAB	1.00
	CIELUV	1.21
	Raíz Cúbica de Glasser	0.99
	Adams-Nickerson (AN40)	0.90
	FMC II (Unidad MacAdam)	1.78
	Judd-Hunter (NBS)	0.74
	Saunderson-Milner	0.21
M. Melgosa et al. *Appl. Opt.*, **33**, 8069-8077 (1994).	CIELAB	1.00
	CIELUV	1.25 ± 0.15
	JPC79	0.72 ± 0.27
	CMC(1:1)	0.84 ± 0.28
	BFD(1:1)	1.01 ± 0.25
	CIE94(1:1)	0.72 ± 0.15
	CDF-G**	1.85 ± 0.77

Estimated conversion factors from 1.0 CIELAB units as reference.



Warning on current situation:

Communication may be a very big problem, and the landmark achieved with the adoption of CIELUV and CIELAB in 1976 to promote uniformity of practice must be remembered. This doesn't mean that the current CIE recommended color-difference formula CIEDE2000 be a final answer…

(R.G. Kuehni, CR&A 27, 126-127, 2002)

7.4. Color-difference formulas

CIEDE2000 color-difference formula

$$\Delta E_{00} = \left(\left(\frac{\Delta L*}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T\left(\frac{\Delta C' \Delta H'}{S_C S_H}\right)\right)^{1/2}$$

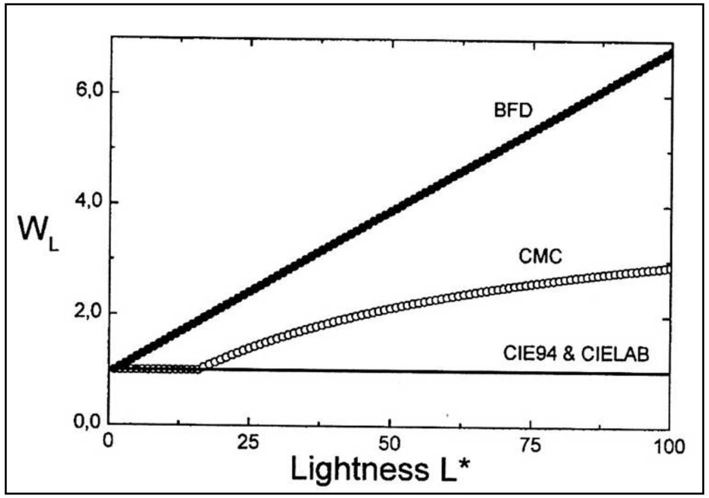
Five corrections to CIELAB:

- New S_L function (crispening effect)
- The same S_C function proposed by CIE94
- New S_H function depending on both C^*_{ab} and h_{ab}
- Additional rotation term R_T
- New a^* scale (only for color-difference purposes)

7.4. Color-difference formulas

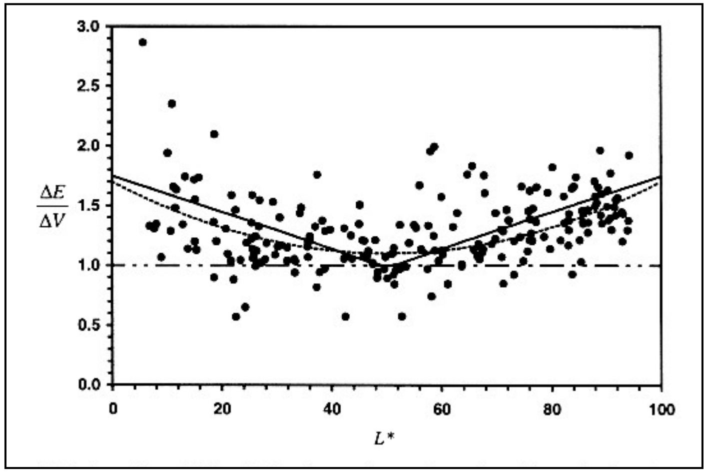
CIEDE2000 color-difference formula: S_L

One of the major differences between CMC, BFD and CIE94 was the S_L function.



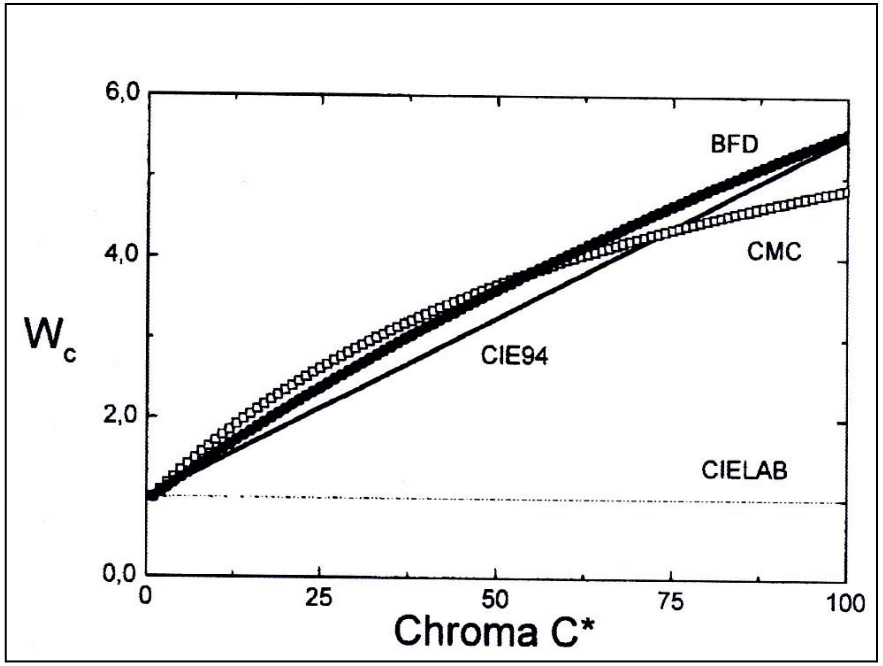
$$S_L = 1 + \frac{0{,}015(\bar{L}' - 50)^2}{\sqrt{20 + (\bar{L}' - 50)^2}}$$

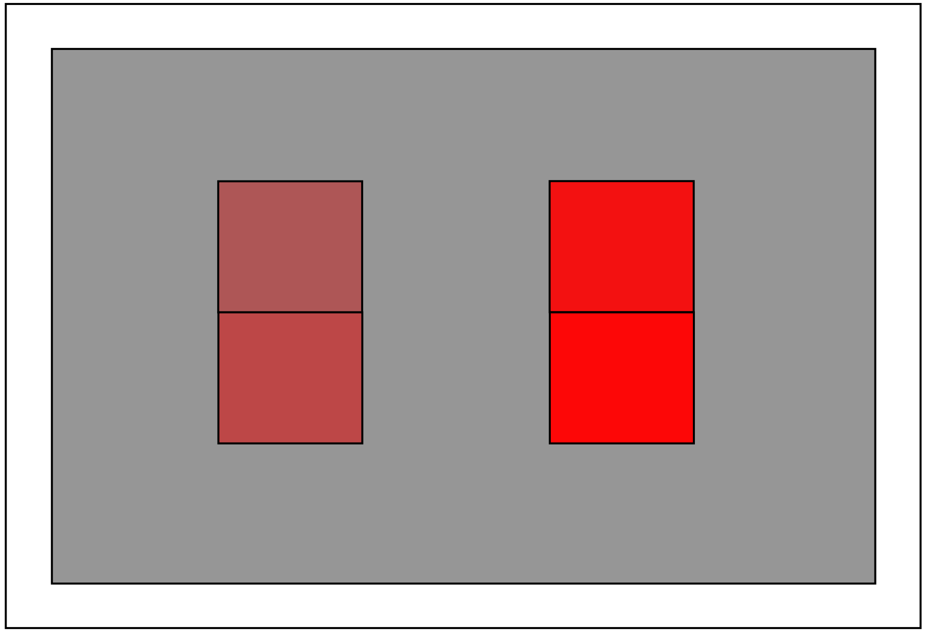
The results from Nobbs et al. (2001) moved the CIE to propose for CIEDE200 a V-shaped S_L function, mainly considering its relationship with the so-called 'crispening effect', and assuming a background with L^*=50.



7.4. Color-difference formulas

CIEDE2000 color-difference formula: S_C





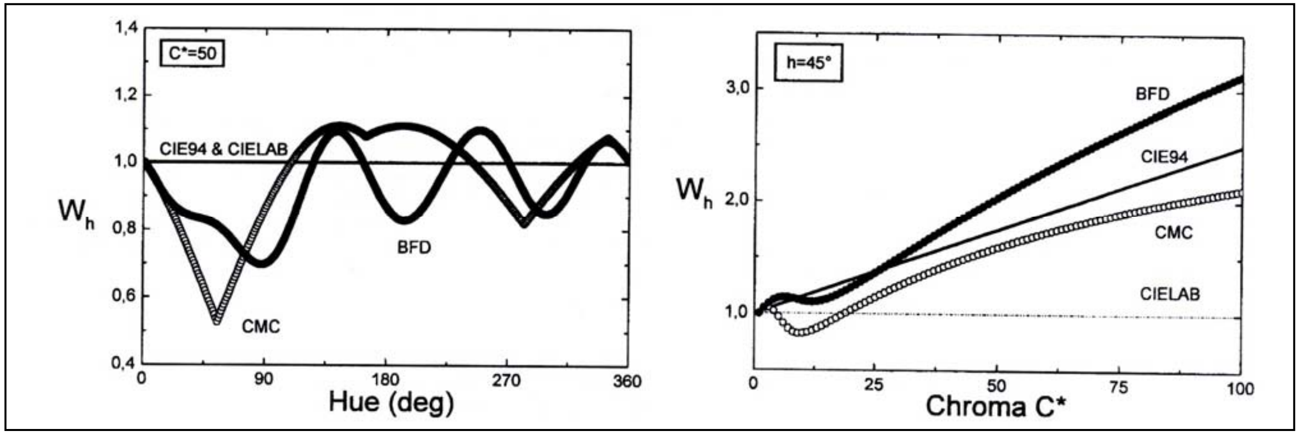
The CIEDE200 SC weighting function is identical to the one in CIE94.

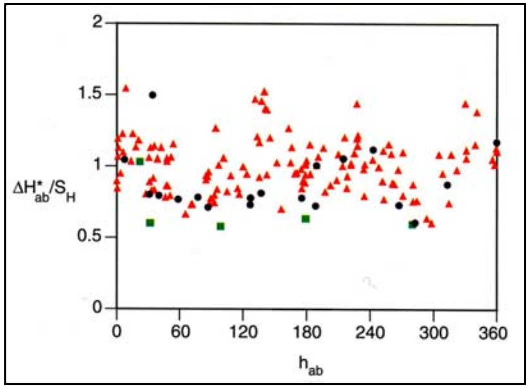
Note that the S_C proposed by CMC, BFD and CIE94 formulas are very similar, and CIE94 adopted the simplest (linear) dependence. Remember that this is one of the most important positional deficiencies of CIELAB.

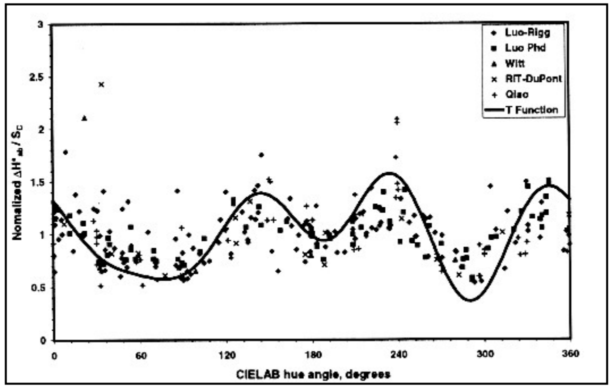
7.4. Color-difference formulas

CIEDE2000 color-difference formula: S_H

The CIEDE200 SH weighting function considers in addition to the chroma dependence a hue-angle dependence.







Experiments at RIT led to a hue-angle dependence in the S_H function of the CIEDE2000 formula in addition to the C^*_{ab} dependence.

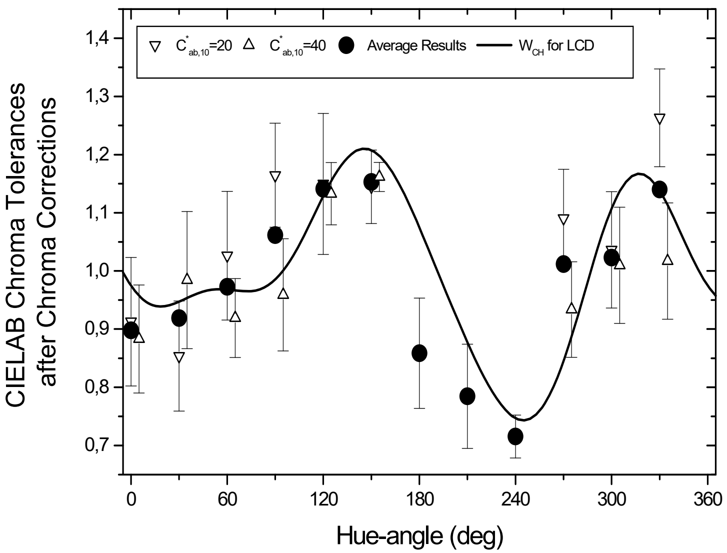
7.4. Color-difference formulas

CIEDE2000 color-difference formula: S_{CH}

$$S_{CH} = 1 - 0.036\sin(h^{o} + 10.6^{o}) + 0.177\cos(2h^{o} + 77.7^{o}) - 0.109\cos(3h^{o} + 36.0^{o}) - 0.013\cos(4h^{o} - 26.8)$$

Is the chroma-tolerance SC dependent on hue-angle?

The important S_C correction to CIELAB may mask a potential S_{CH} function (employed in the LCD formula). Experiment at UGR with CRT, 12 observers, and 21 centers (L^*=40 ; C^*_{ab}=20 and 40 ; h_{ab} in steps of 30º):



COM Data (3657 pairs)

PF/3 (CIEDE2000) = 33.7

PF/3 (CIEDE2000_Mod) = 33.4

The very small improvement achieved by the S_{CH} function do not justify to add it to the CIEDE2000 formula.

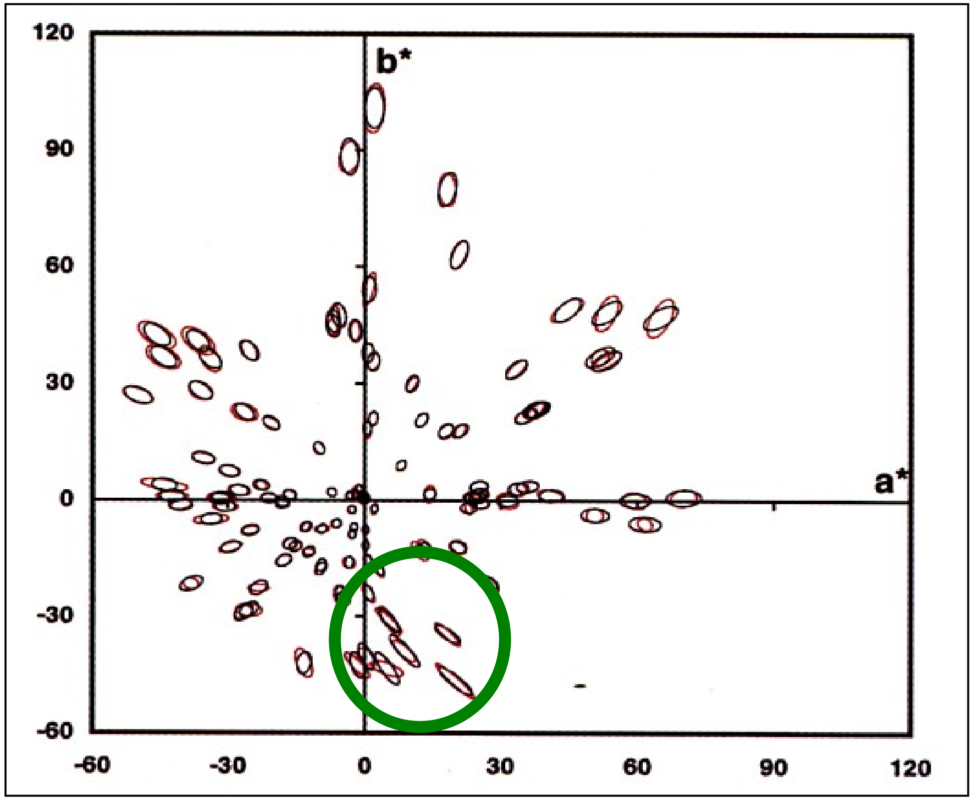
7.4. Color-difference formulas

CIEDE2000 color-difference formula: R_T

Experimental ellipses in the blue region are not in the radial direction, as assumed by CMC, CIE94, etc., but rotated counterclockwise

The BFD color-difference formula also tried to fit this tilt in the blue region.

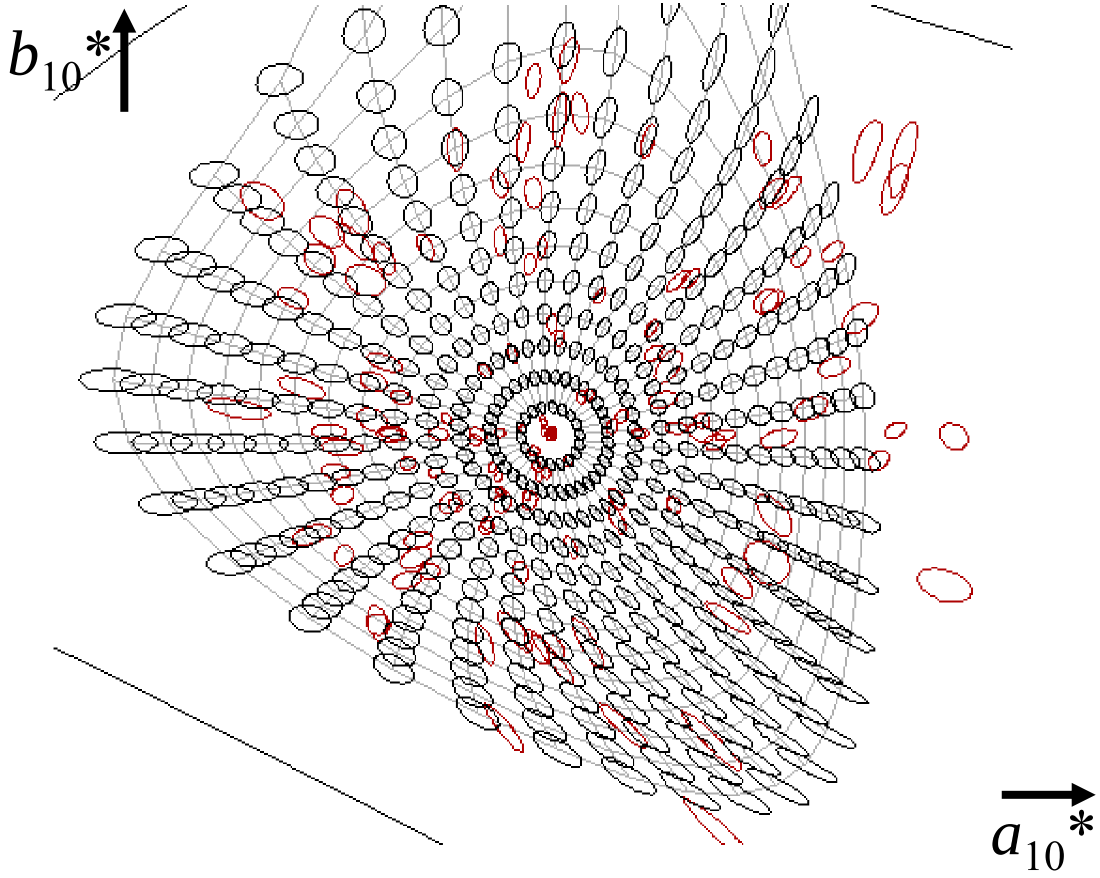
Note that the tilt happens at medium-high chroma at a hue-angle around 275º.



BFD and RIT-DuPont experimental ellipses (in red), and CIEDE2000 predicted ellipses (in black)

7.4. Color-difference formulas

CIEDE2000 color-difference formula: R_T



Red: Luo & Rigg 1986 ellipses.

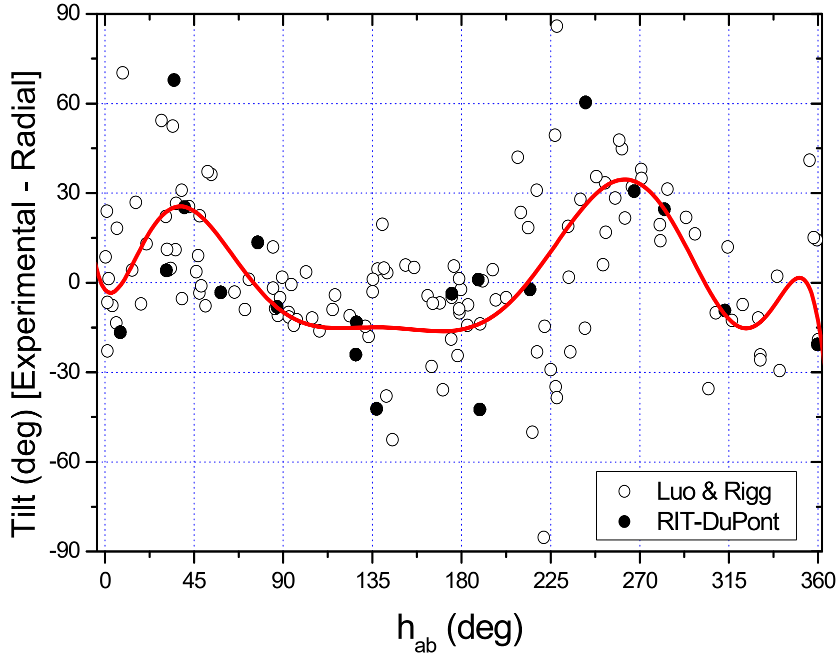
Black: CIEDE2000 predictions.

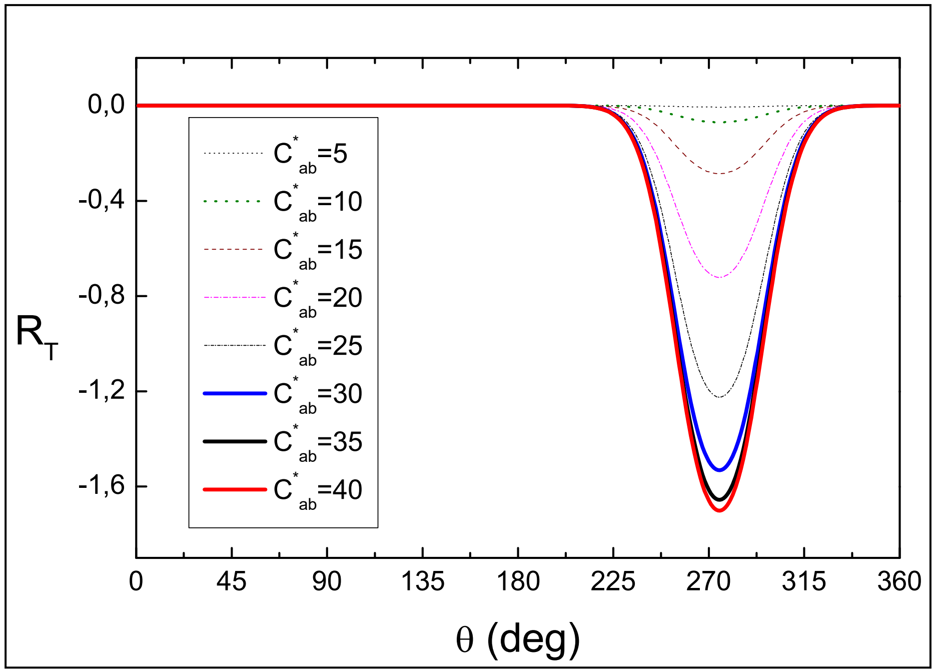
7.4. Color-difference formulas

CIEDE2000 color-difference formula: R_T

Deviation of radial orientation of different experimental ellipses in the a*b* plane (tilt).

Rotation term R_T proposed by CIEDE2000, as a function of both C^*_{ab} and h_{ab}, to account for experimental ellipses tilt in the CIELAB a*b* plane.



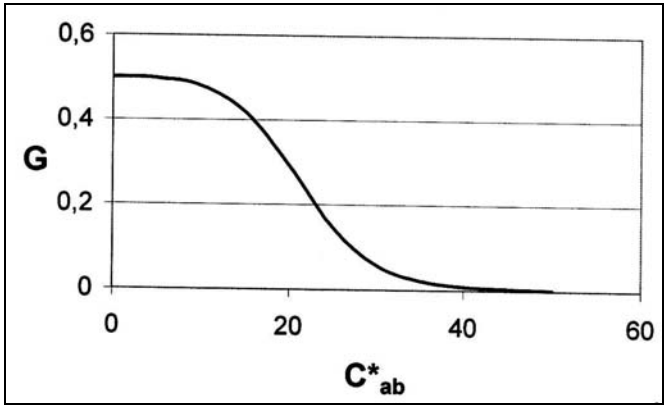


7.4. Color-difference formulas

CIEDE2000 color-difference formula: correction for neutral stimuli

$$a' = a^*(1 + G)$$

$$G = 0.5\left(1 - \sqrt{\frac{\bar{C}^{*7}}{\bar{C}^{*7} + 25^7}}\right)$$



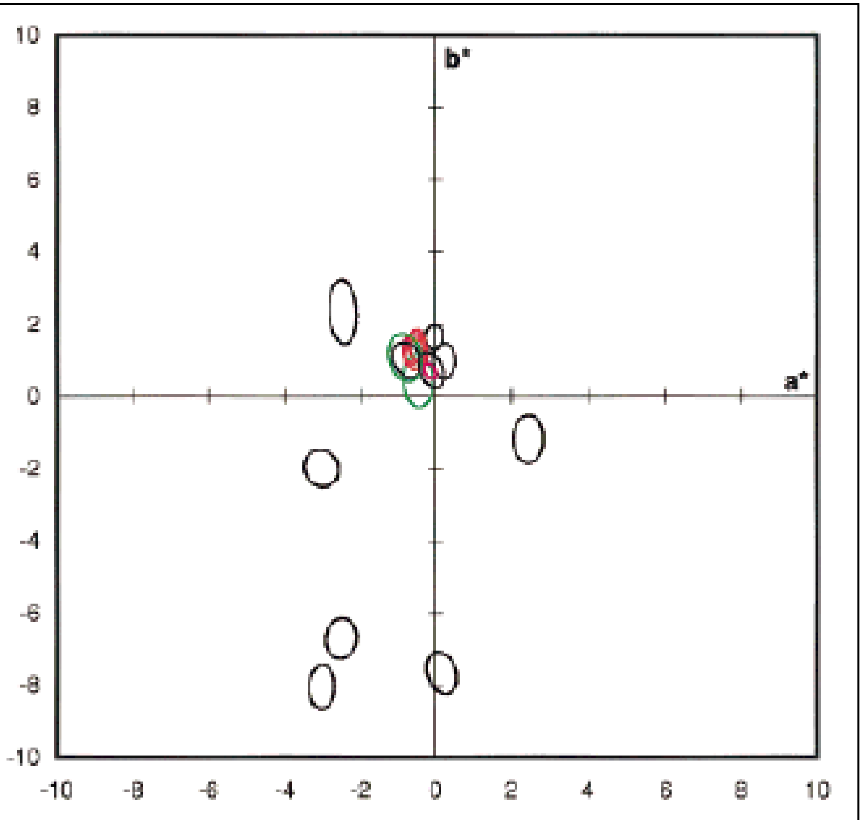


FIG. 3. Experimental ellipses close to the neutral axis plotted in a^* b^* diagram. The BFD, Leeds, RIT–DuPont, and Witt ellipses are plotted in black, red, green, and pink colours, respectively.

7.4. Color-difference formulas

CIEDE2000 color-difference formula: complex

$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T\left(\frac{\Delta C'}{k_C S_C}\right)\left(\frac{\Delta H'}{k_H S_H}\right)},$$

$$L' = L^*$$

$$a' = (1 + G)a^*$$

$$b' = b^*$$

$$C' = \sqrt{a'^2 + b'^2}$$

$$h' = \tan^{-1}(b'/a'),$$

where

$$G = 0.5\left(1 - \sqrt{\frac{\overline{C^*_{ab}}^7}{\overline{C^*_{ab}}^7 + 25^7}}\right),$$

where $\overline{C^*_{ab}}$ is the arithmetic mean of the C^*_{ab} values for a pair of samples.

where

$$S_L = 1 + \frac{0.015(\overline{L'} - 50)^2}{\sqrt{20 + (\overline{L'} - 50)^2}}$$

and

$$S_C = 1 + 0.045\overline{C'}$$

and

$$S_H = 1 + 0.015\overline{C'}T,$$

where

$$T = 1 - 0.17\cos(\overline{h'} - 30°) + 0.24\cos(2\overline{h'}) + 0.32\cos(3\overline{h'} + 6°) - 0.20\cos(4\overline{h'} - 63°)$$

and

$$R_T = -\sin(2\Delta\theta)R_C,$$

where

$$\Delta\theta = 30\exp\{-[(\overline{h'} - 275°)/25]^2\}$$

and

$$R_C = 2\sqrt{\frac{\overline{C'}^7}{\overline{C'}^7 + 25^7}}.$$

7.4. Color-difference formulas

CIEDE2000 color-difference formula

Experimental datasets employed at CIEDE2000 development:

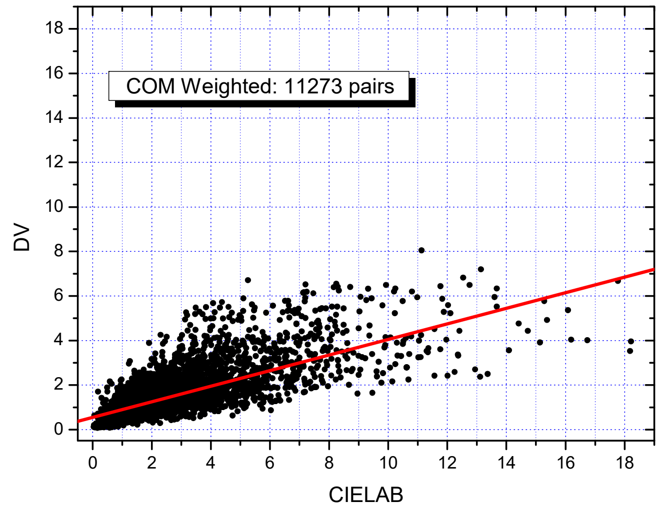
- ✓ **BFD-P** contains the 2776 perceptibility pairs used at the development of the BFD color-difference formula. The 1613 acceptability pairs (BFD-A), were discarded. BFD-P has 3 subsets with slightly different reference whites. Note that it includes very small (BFD-C), and very large (much more greater than 5.0 CIELAB units) color differences (BFD-D65).
- ✓ **Leeds** contains 307 pairs, 243 obtained using gray scale and 104 using anchor pair, used for the development of the LCD color-difference formula. Pairs were assessed by 10-15 normal observers.
- ✓ **RIT-DuPont** contains 312 color pairs (glossy paint samples) around 19 color centers, which were assessed against a neutral anchor pair with 1.02 CIELAB units, for CIE94 development. Surprisingly, this highly reliable dataset was wrongly used by CIE TC1-47.
- ✓ **Witt** contains 418 color pairs around the 5 CIE 1978 centers. The pairs were assessed by 10-15 observers using the gray scale method.

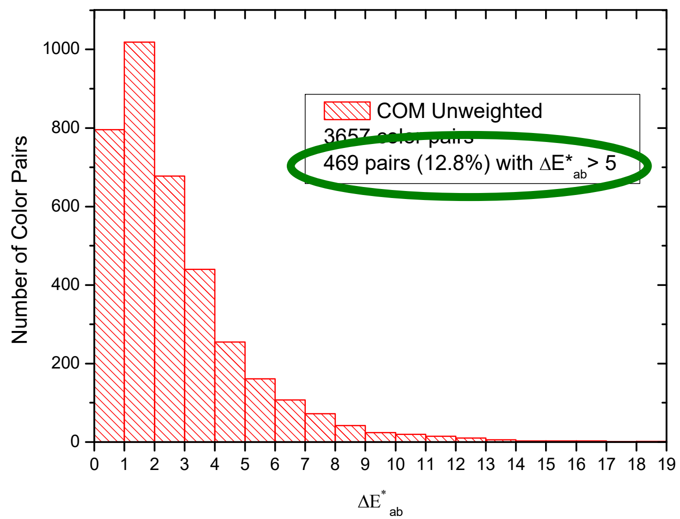
7.4. Color-difference formulas

CIEDE2000 color-difference formula

Recently, the use of a COM-Weighted dataset (BFD-P=1; Leeds=9; RIT-DuPont=9; Witt=7) has been questioned.

Datasets	Number of color pairs	CIELAB Color Differences		
		Max	Min	Average
COM-Weighted	11273	18.2	0.04	2.0
BFD-D65	2028	16.1	0.04	2.6
BFD-M	548	18.2	0.05	5.2
BFD-C	200	3.9	0.07	0.9
BFD-P	2776	18.2	0.04	3.0
Leeds	307	4.7	0.40	1.6
RIT-DuPont	312	4.4	0.78	1.4
Witt	418	10.6	0.12	1.9





7.4. Color-difference formulas

CIEDE2000 color-difference formula

k_L=k_C=k_H=1 under 'reference conditions' (usual practice):

- Illumination: D65 source.
- Illuminance: 1000 lx.
- Observer: Normal color vision.
- Background field: Uniform, neutral gray with L^*=50.
- Viewing mode: Object.
- Sample size: Greater than 4 degrees.
- Sample separation: Direct edge contact.
- Sample color-difference magnitude: Lower than 5.0 ΔE^*_{ab}.
- Sample structure: Homogeneous (without texture).

These reference conditions are the same proposed for CIE94

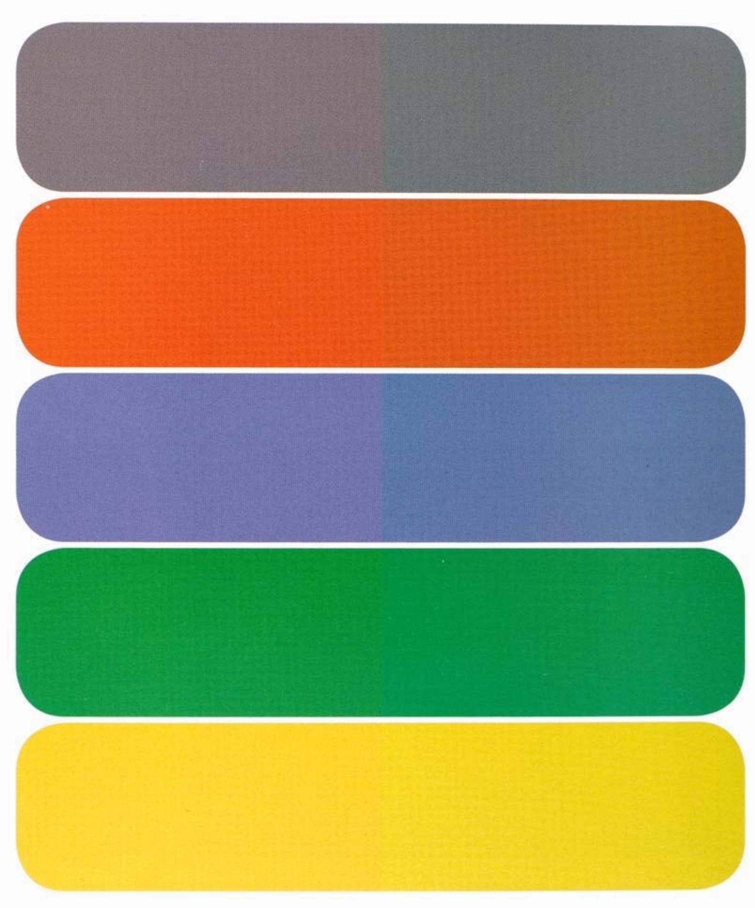
7.4. Color-difference formulas

CIE94 vs. CIEDE2000

- Both start from the widely accepted CIELAB color space.
- Both provide a significant improvement upon CIELAB.
- CIE94 was a simple and versatile formula. It was the first CIE recommended formula where parametric factors were included.
- CIE94 was a very conservative approach: only robust trends clearly shown by reliable experimental data were considered.
- CIEDE2000 is very complex, like the BFD formula.
- CIEDE2000 has not an associated color space (the same happening for CIE94).

7.4. Color-difference formulas

CIELAB vs. CIEDE2000

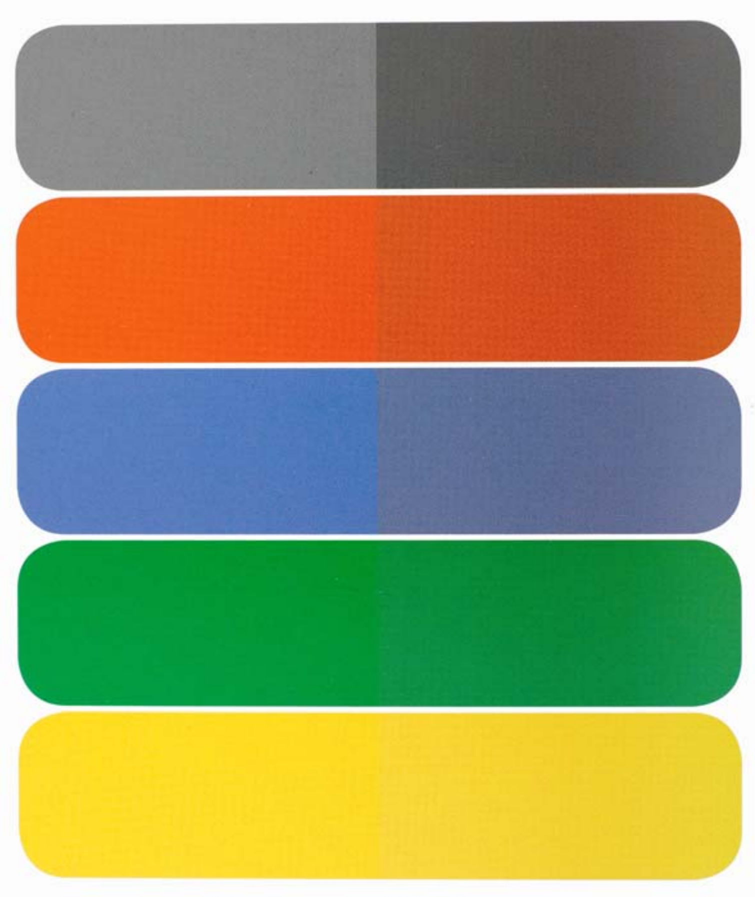


ΔE^*_{ab}	ΔE_{00}
5.5	7.9
5.4	2.6
5.6	5.1
3.9	2.0
4.1	2.4

From Test Targets 8.0, Prof. Bob Chung. Rochester Institute of Technology, NY, USA

7.4. Color-difference formulas

CIELAB vs. CIEDE2000



ΔE^*_{ab}	ΔE_{00}
9.9	9.9
10.8	3.2
11.6	5.0
10.3	3.5
8.8	2.1

From Test Targets 8.0, Prof. Bob Chung. Rochester Institute of Technology, NY, USA

7.4. Color-difference formulas

COMMUNICATIONS AND COMMENTS

CIEDE2000, Milestone or Final Answer?

R.G. Kuehni, Color Res. Appl. 27, 126-128, 2002.

"With CIEDE2000 the CIE is now recommending the fifth color difference formula since it began doing so in 1964. The formula continues to be based in CIELAB and is a modification of the BFD formula with more and more complex adjustment functions".

"This comment argues that CIEDE2000 is a milestone only and the real improvement is probably (depends a lot on what experimental data are used) very modest".

7.4. Color-difference formulas

CIEDE2000 has not an associated color space, and its complexity shows potential limitations of CIELAB.

DIN99d (*CR&A 27, 282-290, 2002*)

$$\Delta E_{99d} = \sqrt{(\Delta L_{99d})^2 + (\Delta a_{99d})^2 + (\Delta b_{99d})^2}$$

CAM02-SCD (*CR&A 31, 320-330, 2006*)

$$\Delta E_{CAM02-SCD} = \sqrt{(\Delta J')^2 + (\Delta a')^2 + (\Delta b')^2}$$

GP (Euclidea) (*JOSA A 26, 121-134, 2009*)

$$\Delta E_{GP,E} = \sqrt{\left(\Delta L_{OSA,E}\right)^2 + (\Delta G_E)^2 + (\Delta J_E)^2}$$

7.4. Color-difference formulas

DIN99 formula and color space

$$L_{99} = 105.51 \ln(1 + 0.0158L^*)$$

$$e = a^* \cos(16º) + b^* \sin(16º)$$

$$f = 0.7[-a^* \sin(16º) + b^* \cos(16º)]$$

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

Rotation of a*b* axis, and b* re-scaling

$$C_{99} = \frac{\ln(1 + 0.045G)}{0.045}$$

From CIE94 integration

$$h_{99} = \arctan(f/e)$$

$$a_{99} = C_{99} \cos(h_{99})$$

$$b_{99} = C_{99} \sin(h_{99})$$

$$\Delta E_{99} = \frac{1}{k_E}\sqrt{(\Delta L_{99})^2 + (\Delta a_{99})^2 + (\Delta b_{99})^2}$$

7.4. Color-difference formulas

DIN99d formula and color space (*Cui et al., 2002*)

$$X' = 1.12X - 0.12Z$$

$$L_{99d} = 325.22\ln(1 + 0.0036L^*)$$

$$e = a^*\cos(50º) + b^*\sin(50º)$$

$$f = 1.14[-a^*\sin(50º) + b^*\cos(50º)]$$

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

$$C_{99d} = 22.5\ln(1 + 0.06G)$$

$$h_{99d} = \arctan(f/e) + 50º$$

$$a_{99d} = C_{99d}\cos(h_{99d})$$

$$b_{99d} = C_{99d}\sin(h_{99d})$$

It starts from DIN99 (1999), but all coefficients are fitted to COM dataset.

The change of tristimulus value *X*, previously suggested by Kuehni, affects the blue region and 'replaces' the rotation term in CIEDE2000.

$$\Delta E_{99d} = \sqrt{(\Delta L_{99d})^2 + (\Delta a_{99d})^2 + (\Delta b_{99d})^2}$$

7.4. Color-difference formulas

Comparing CIELAB and DIN99d semi-polar coordinates

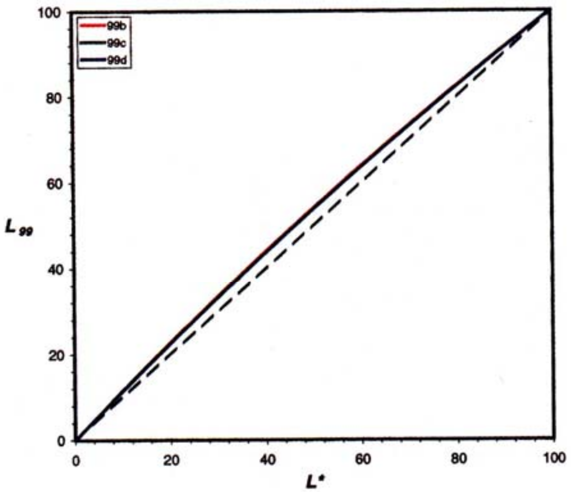


FIG. 6 The relationship between the lightness scales of the CIELAB and the DIN99b (red), DIN99c (green), and DIN99d (blue) formulas.

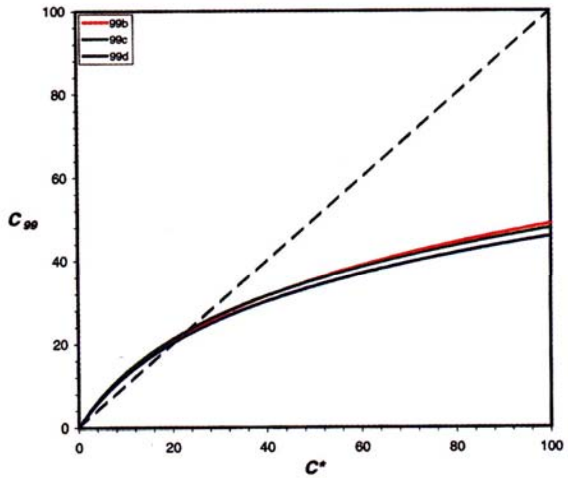


FIG. 7. The relationship between the chroma scales of the CIELAB and the DIN99b (red), DIN99c (green), and DIN99d (blue) formulas. (h_{ab} = 45°).

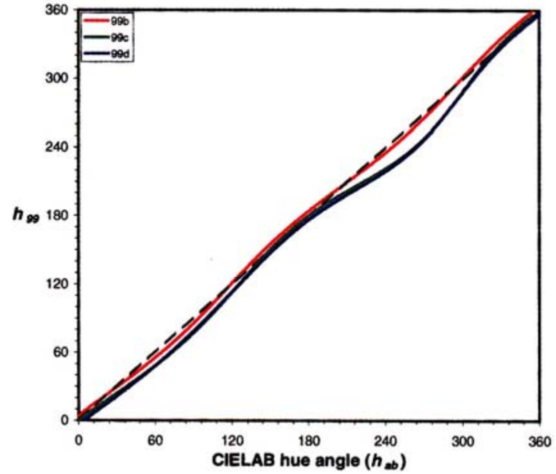


FIG. 8. The relationship between the hue angles of the CIELAB and the DIN99b (red), DIN99c (green) and DIN99d (blue) formulas. (C^* = 30).

Dashed lines indicate identical coordinates (CIELAB in x-axis)

Lightness is similar in both spaces, but chroma is strongly compressed in DIN99d space, and hue is also slightly different in the blue region.

7.4. Color-difference formulas

Comparing CIELAB and DIN99d semi-polar coordinates

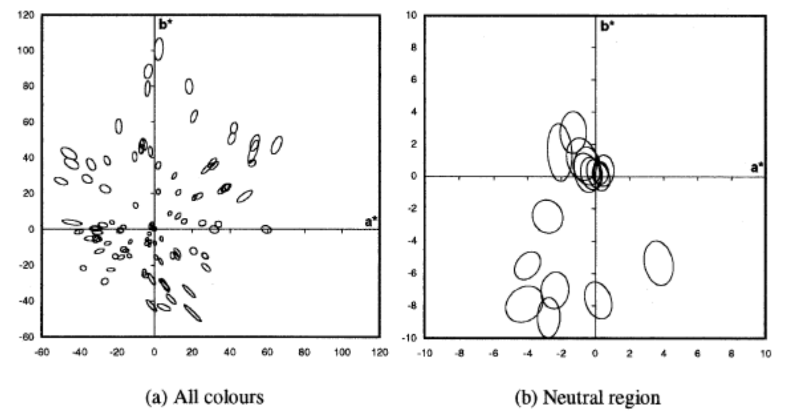


FIG. 1. The experimental ellipses from the BFD-P and RIT–DuPont data sets plotted in the CIELAB a^*b^* plane.

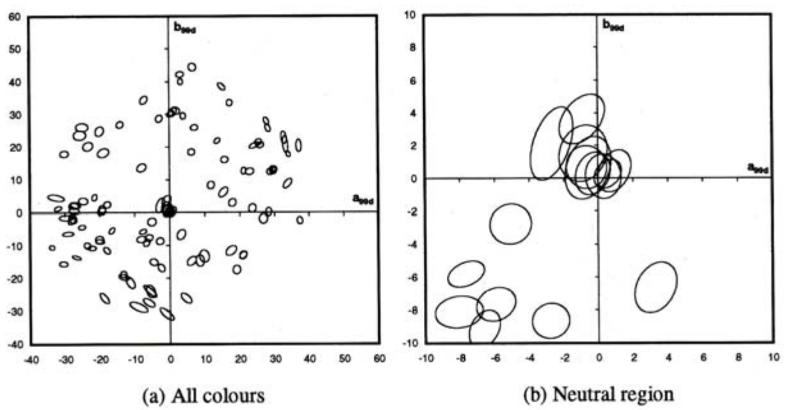


FIG. 5. The experimental ellipses from the BFD-P and RIT–DuPont data sets plotted in the DIN99d a_{99d} b_{99d} plane.

Ellipses in DIN99d space (bottom) are closer to circles than in CIELAB (top).

Reduction of the scale in a_{99d},b_{99d} plane with respect to a^*,b^* in CIELAB tries to make more similar the chromaticity and lightness scales.

7.4. Color-difference formulas

CAM02 formulas and color space

"Colour appearance models have been developed to predict colour appearance under different viewing conditions. They are also capable of evaluating colour differences because of their embedded uniform colour spaces" (*M.R. Luo et al., Color Res. Appl. 31, 320-330, 2006*)

The results show that CIECAM02 gives reasonable performance compared with the best available color difference formulas and color spaces. This is very encouraging, because unifies color-difference and color-appearance fields, considered separately over the years.

The same structure of color space, based on CIECAM02, may be used to predict small and large color differences (CAM02-SCD and CAM02-LCD color-difference formulas). It is also proposed a general CAM02-UCS formula.

The CAM02 formulas were satisfactorily tested for a dataset of color differences obtained under illuminant A. Currently, there is no CIE recommendation for calculating color differences under non-daylight illuminants.

7.4. Color-difference formulas

CAM02-LCD, CAM02-SCD and CAM02-UCS

Starting from CIECAM02 *J*, *M*, and *h* (lightness, colourfulnes, and hue angle, respectively), the PF/3 index was minimized for different experimental datasets, achieving:

$$J' = \frac{(1 + 100\ c_1)J}{1 + c_1 J} \quad ; \quad M' = \left(\frac{1}{c_2}\right)\ln(1 + c_2 M)$$

$$a' = M' \cos(h) \quad ; \quad b' = M' \sin(h)$$

	CAM02-LCD	CAM02-SCD	CAM02-UCS
k_L	0.77	1.24	1.00
c_1	0.007	0.007	0.007
c_2	0.0053	0.0363	0.0228

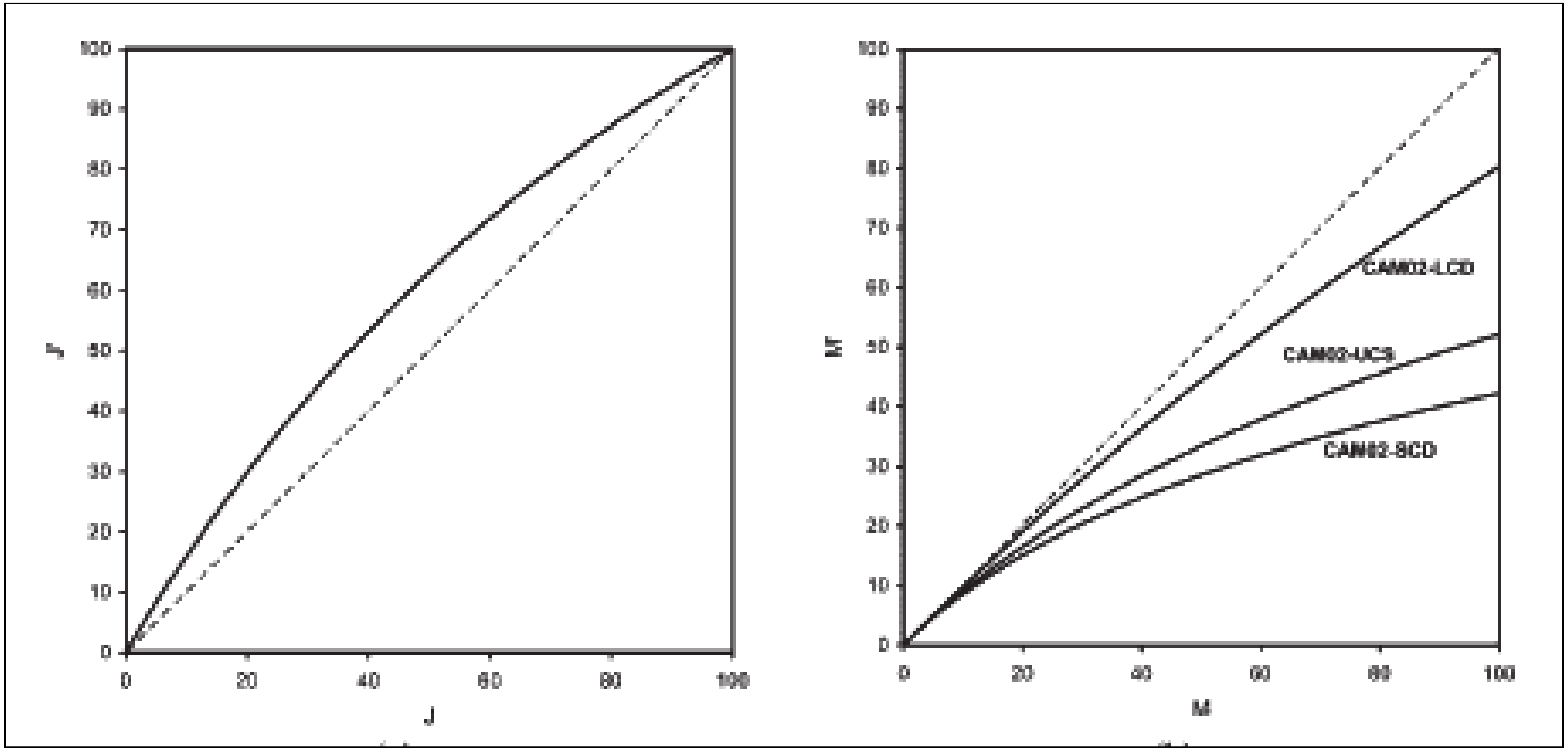
Note that *M’* is the typical CIE94 chroma integration.

$$\Delta E_{CAM02} = \sqrt{\left(\frac{\Delta J'}{k_L}\right)^2 + (\Delta a')^2 + (\Delta b')^2}$$

7.4. Color-difference formulas

CAM02-LCD, CAM02-SCD and CAM02-UCS

Relationship between *J* and *J'* (left) and *M* and *M'* (right)



The dashed line indicates perfect agreement.

7.4. Color-difference formulas

CAM02-LCD, CAM02-SCD and CAM02-UCS

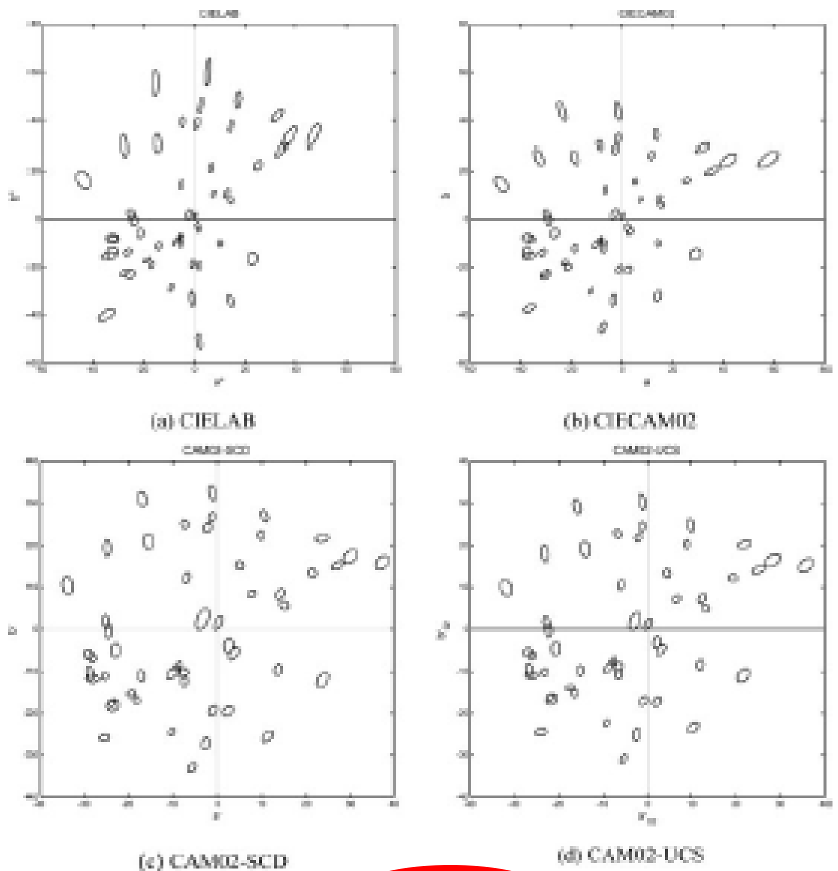


FIG. 4. Experimental chromatic discrimination ellipses under illuminant A plotted in (a) CIELAB, (b) CIECAM02, (c) CAM02-SCD, and (d) CAM02-UCS.

7.4. Color-difference formulas

OSA-UCS and GP (Granada-Parma) formulas

GP formulas are based on **OSA-UCS space**, not CIELAB.

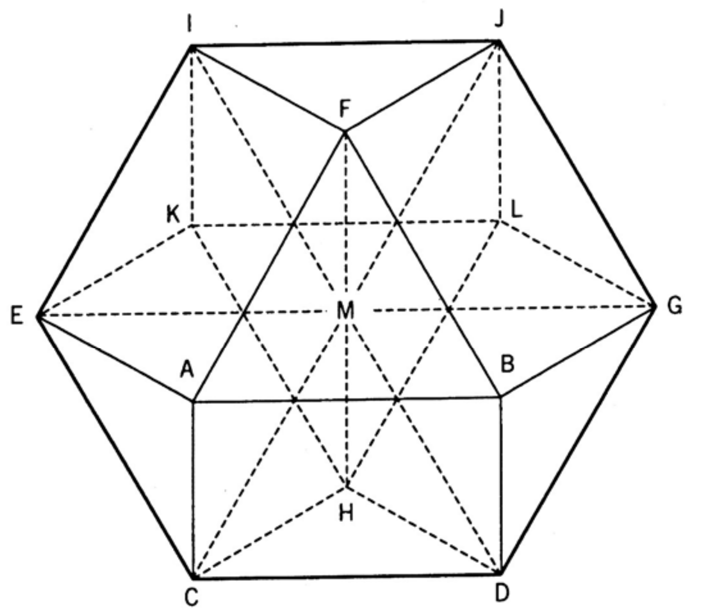


FIGURE 5.10 *Cubo-octahedron formed by the twelve nearest neighbors equidistant from the central color M.*

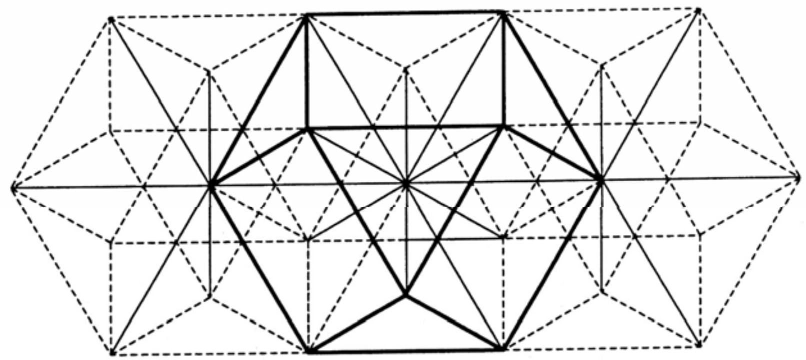


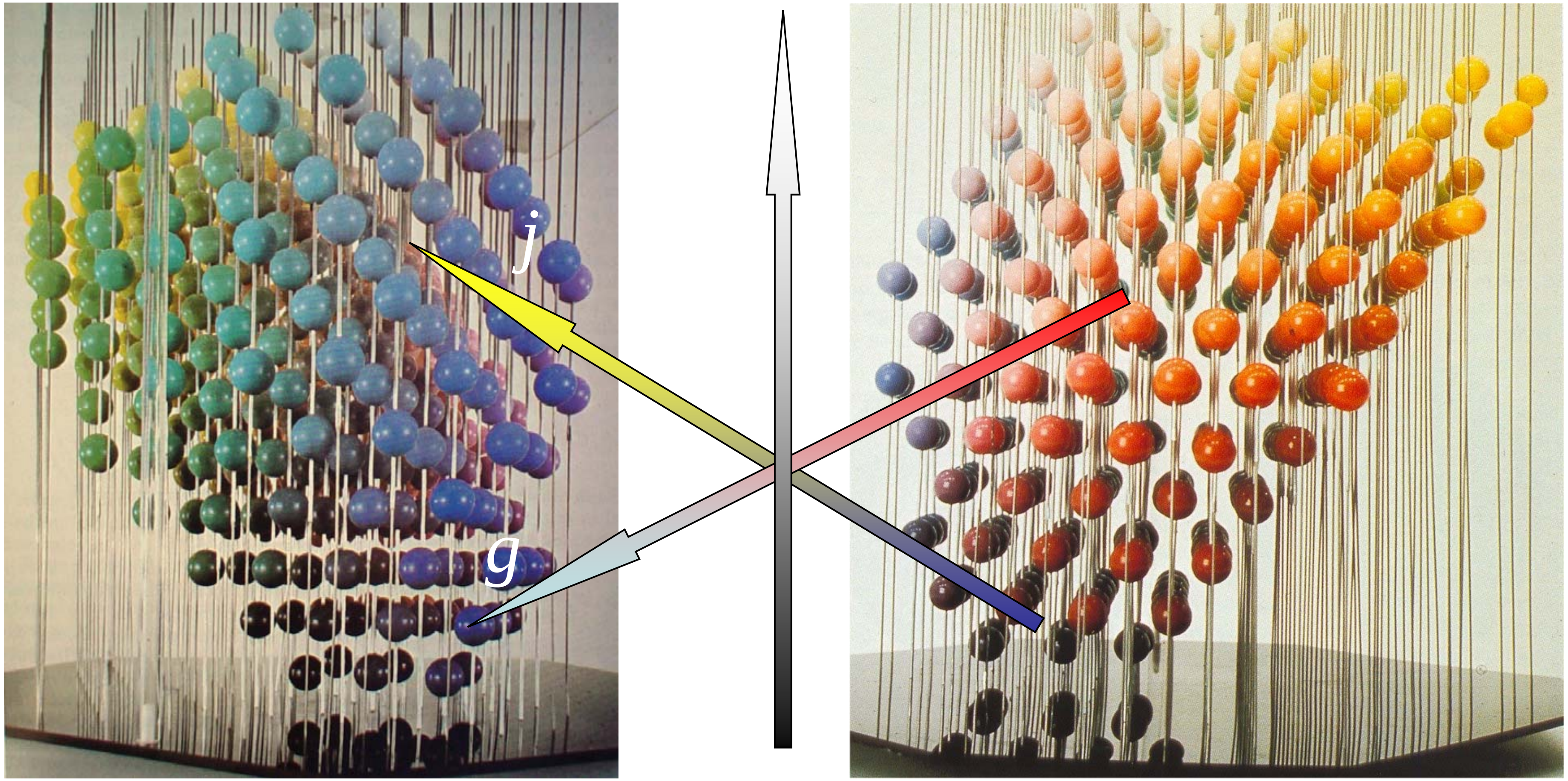
FIGURE 5.11 *Cubo-octahedron with two neighboring cubo-octahedra in the same horizontal plane.*

This geometry is considered one of the best to sample color space, in such a way that a random color by close to one of the fixed standards.

7.4. Color-difference formulas

OSA-UCS and GP (Granada-Parma) formulas

Space OSA-UCS (1947-1974)



7.4. Color-difference formulas

OSA-UCS and GP (Granada-Parma) formulas

References:

- R. Huertas et al. JOSA A 23, 2077-2084 (2006).
- C. Oleari et al. JOSA A 26, 121-134 (2009).

See references for definitions of L_{OSA}, C_{OSA}, H_{OSA}.

The format is analogous to the CIE94 one.

$$S_L = 2.499 + 0.007\left(10\overline{L_{OSA}}\right)$$

$$S_C = 1.235 + 0.058\left(10\overline{C_{OSA}}\right)$$

$$S_C = 1.392 + 0.017\left(10\overline{C_{OSA}}\right)$$

$$\Delta E_{GP} = \sqrt{\left(\frac{\Delta(10L_{OSA})}{S_L}\right)^2 + \left(\frac{\Delta(10C_{OSA})}{S_C}\right)^2 + \left(\frac{\Delta(10H_{OSA})}{S_H}\right)^2}$$

7.4. Color-difference formulas

OSA-UCS and GP (Granada-Parma) formulas

$$L_E = \left(\frac{1}{0.015}\right)\ln\left[1 + \frac{0.015}{2.890}(10L_{OSA})\right]$$

$$C_E = \left(\frac{1}{0.050}\right)\ln\left[1 + \frac{0.050}{1.256}(10C_{OSA})\right]$$

$$h = \arctan\left(\frac{-J}{G}\right)$$

$$G_E = -C_E\cos(h)$$

$$J_E = C_E\sin(h)$$

Note that G_E axis is green-red, just opposite to CIELAB a* axis.

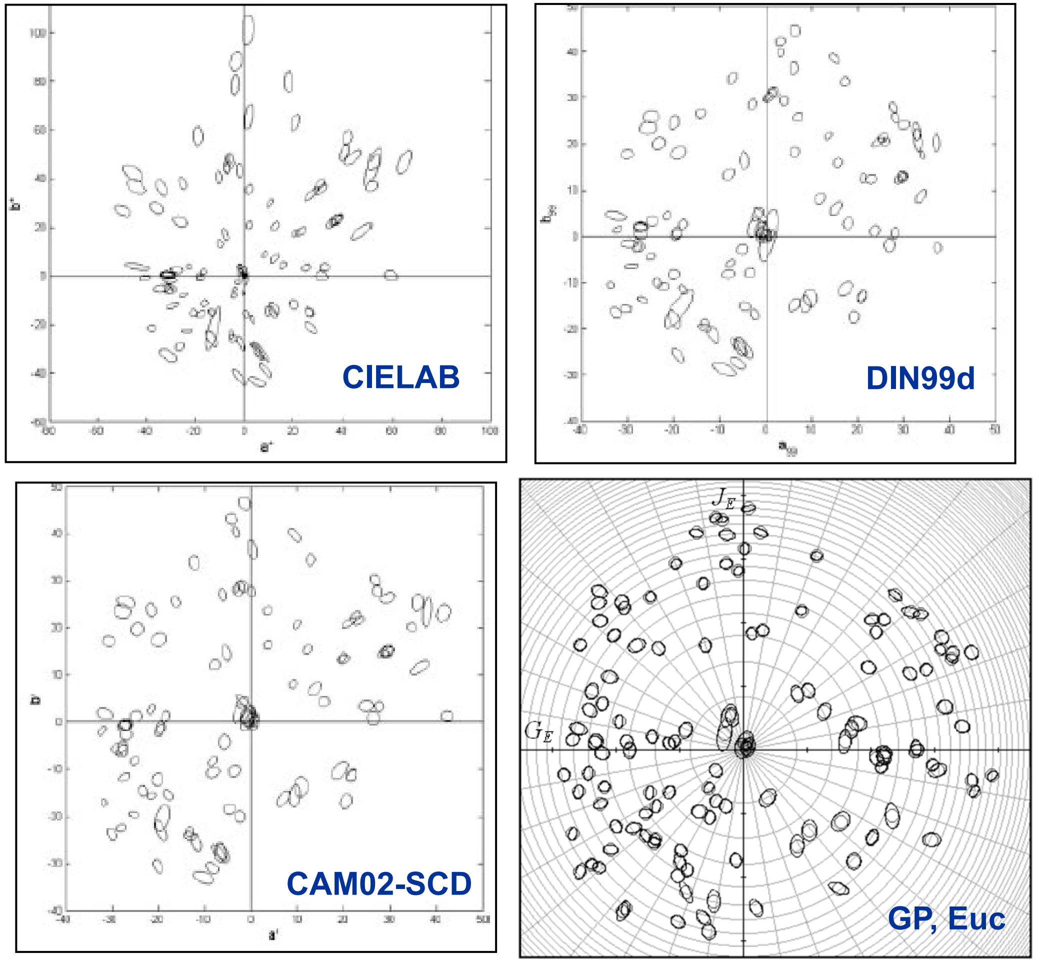
Compression is used in the chroma equation (very important), and also in lightness (less important).

$$\Delta E_{GP,E} = \sqrt{\left(\Delta L_{OSA,E}\right)^2 + (\Delta G_E)^2 + (\Delta J_E)^2}$$

Similar STRESS% than CIEDE2000, but simpler and physiologically based.

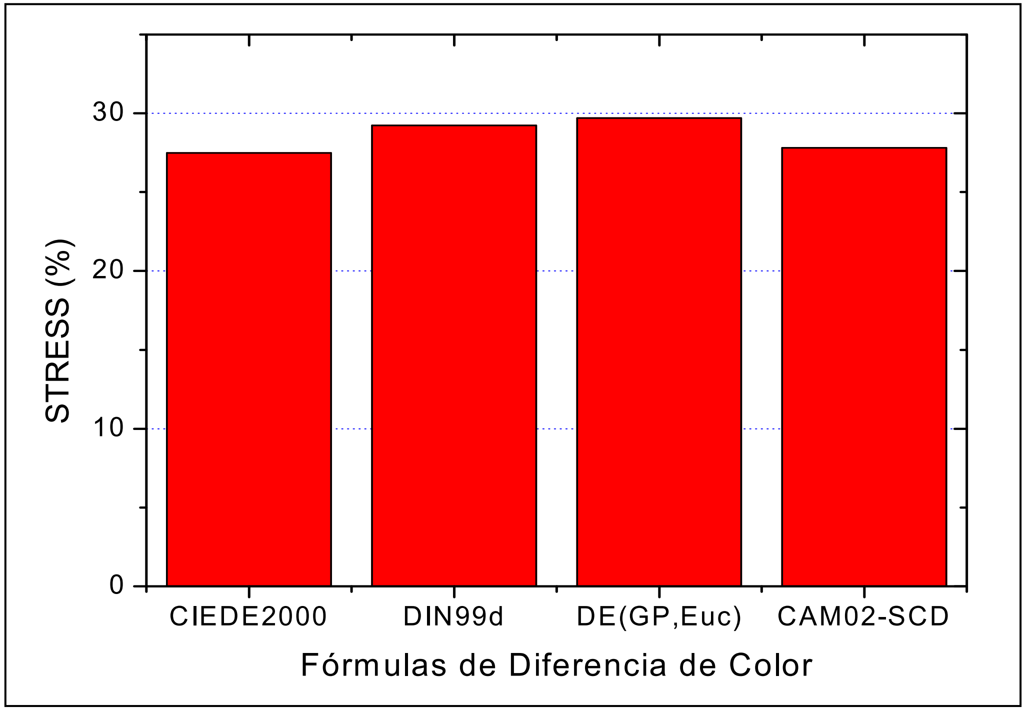
7.4. Color-difference formulas

DIN99d, CAM02, and GP color-difference formulas



7.4. Color-difference formulas

DIN99d, CAM02, and GP color-difference formulas



STRESS results are very close to those of CIEDE2000, and new formulas are both simpler (Euclidean) and increasingly based on physiology.

Anyway a ~25% STRESS is an “unsatisfactory state of affairs” (R. Kuehni, CR&A, 2008), and new reliable experimental data are required.

7.4. Color-difference formulas

Outlook

The CIELAB formula has achieved an important 'uniformity of use' amongst industries around the world. To keep this important property, looking for a strong relationship between ΔV and ΔE, the use of CIEDE2000 (not CMC, CIE94 or other previous formulae) is strongly recommended. However if you are not close to some of the established 'reference conditions' you may continue using CIELAB.

The CIEDE2000 formula is not at all a last step in color-difference evaluation. Currently new Euclidean formulas, and formulas based on CIECAM02, are being successfully tested. CIE TC's 1-55, 1-63 and 8-02 are involved in these works. New reliable experimental data are desired. It seems that CIE TC 8-02 is not going to recommend any particular formula, but guidelines of good practices in this field.

The influence of different parametric factors (CIE Publ. 101-1993) like texture, size of color difference, etc. must be better understood (basic research).

Contents

7.5. Parametric effects in color-difference evaluation

Reference conditions for CIE94 and CIEDE2000

$k_L = k_C = k_H = 1$ under 'reference conditions' (usual practice):

- Illumination: D65 source.
- Illuminance: 1000 lx.
- Observer: Normal color vision.
- Background field: Uniform, neutral gray with L^*=50.
- Viewing mode: Object.
- Sample size: Greater than 4 degrees.
- Sample separation: Direct edge contact.
- Sample color-difference magnitude: Lower than 5.0 ΔE^*_{ab}.
- Sample structure: Homogeneous (without texture).

7.5. Parametric effects in color-difference evaluation

"Parametric effects in color difference evaluation" (A. R. Robertson, Die Farbe 29, 273-296, 1981; CIE Publication 101-1993; K. Witt, CR&A 20, 399-403, 1995)

Observer variability (non-defective observers)

It seems most likely that this is a significant factor. Better than replications by just one observer (as in MacAdam's pioneer experiment), it is preferable a large number of observers (not lower than 10). Recent experiments have reported results from 564.480 estimations (Wang and Xu, JOSA A 25, 2908-2917, 2008). Anyway observers' fatigue must be always prevented.

Intra-observer variability seems lower than inter-observer variability. Both can be evaluated using STRESS(%).

UFL and LFL (or confidence intervals) of median tolerances (T50) are highly appreciated in modern experiments. Monte Carlo simulation has been used to analyze variability of fitted ellipses / ellipsoids.

7.5. Parametric effects in color-difference evaluation

Samples size

Retina is not uniform, and two Standard Observers have been defined by CIE. In general, color discrimination improves with greater field sizes.

Visual tolerances in chromaticity are greater for a small field size (2º) than for a large field (10º): approximately, a factor 2.0 for related colors and white background, and a factor 1.4 for unrelated colors and black background.

Samples separation

It has long been known that the width of the dividing line between two samples (gap) can have a significant effect on the discrimination of their color differences (particularly if they are small). Lightness differences seem more affected than chromaticity differences by this effect, which is lower when the size of the samples increases.

With respect to hairline separation, a gap greater than 0.5º increases tolerances in a factor in the range 1.6-2.6 approximately. This effect is more pronounced for small than for large (Munsell) color differences.

7.5. Parametric effects in color-difference evaluation

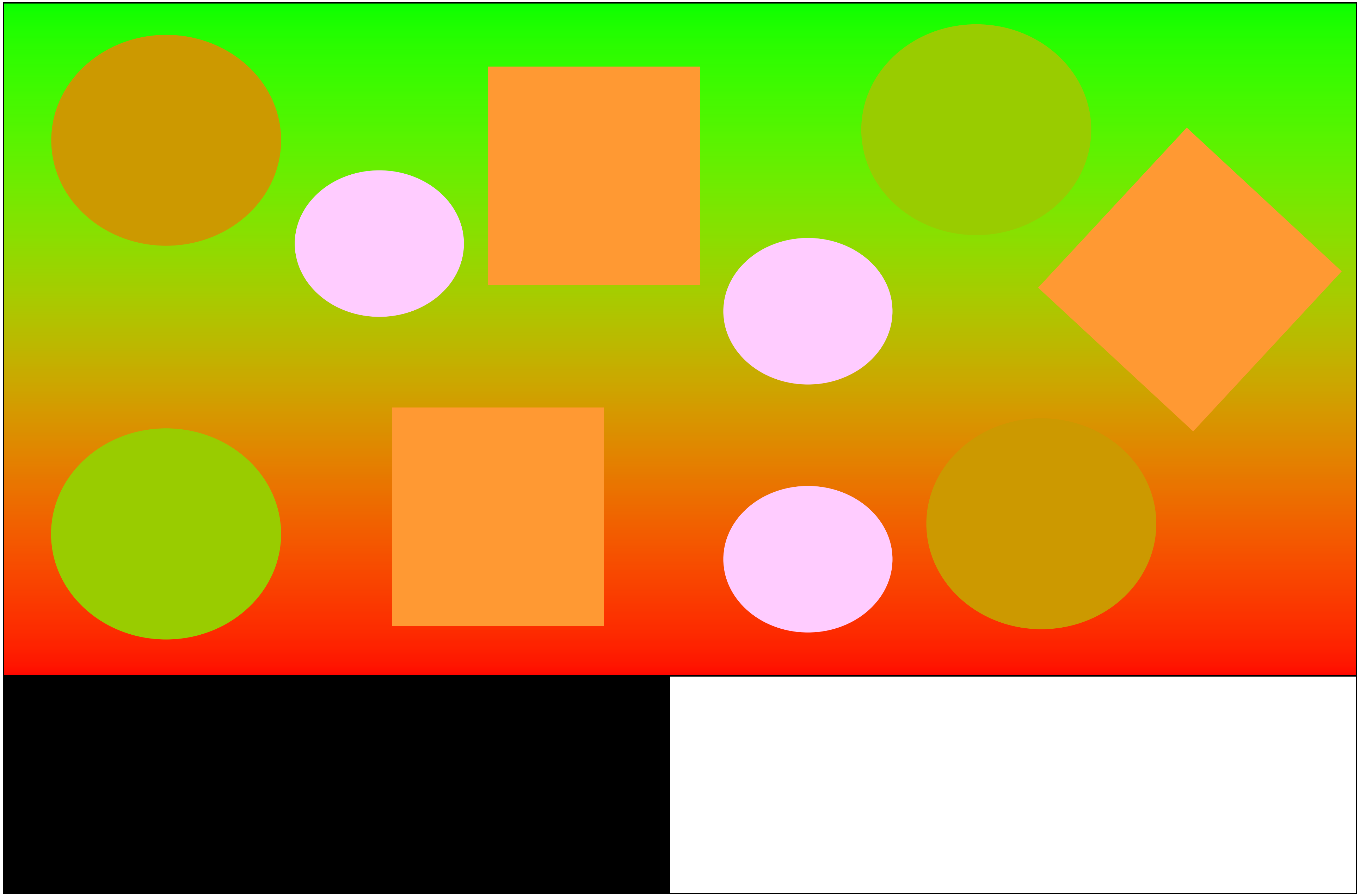
Background

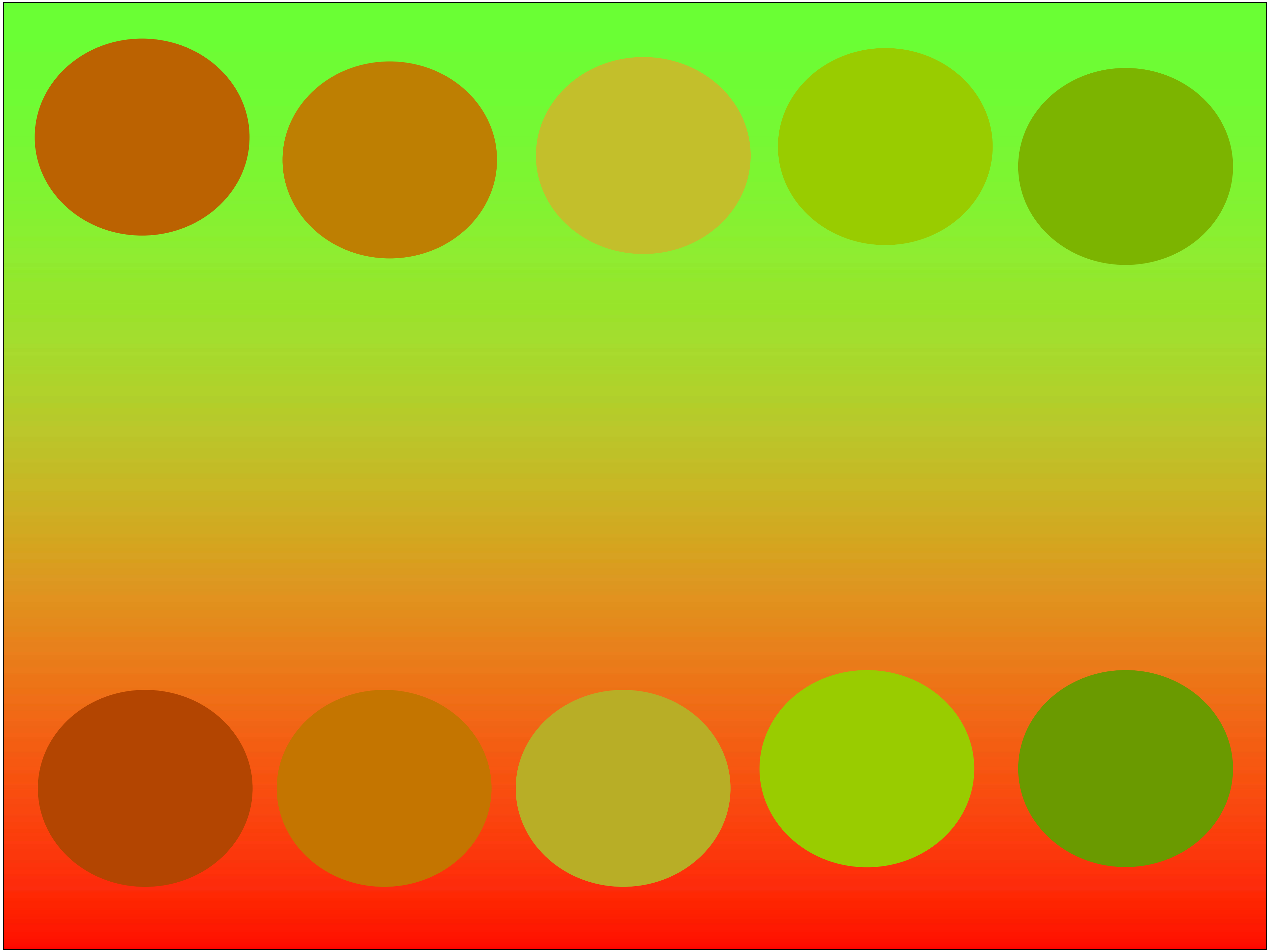
The effect of the background may be one of the most important parametric effects.

There is possible connection with sample size: increasing the sample size of a color-difference pair may decrease the effect of the background parameter.

If non-neutral background are investigated, the effect of changing the background on chromatic adaptation should be considered.

Simultaneous contrast or induction
(J. Albers, 1975)





7.5. Parametric effects in color-difference evaluation

Adaptation

Observer's adaptation may be determined by the sample pair/s, the background, the surround, which respective relative sizes are relevant. The chromaticity of the light source also influences. Chromatic adaptation transforms and color appearance models account for these effects.

Discrimination improves when the luminance and chromaticity of the background is close to the one of the sample pair: "crispening effect" (C. C. Semmelroth, Appl. Opt 10, 14-17, 1971).

Mode of appearance

Depending of the relative luminance of the stimuli and the background, and of various other clues such as dust, reflected highlights, lack of texture, etc. the stimuli take on the appearance either of an "aperture color" (unrelated color), or of a "surface color" (related color).

It seems unlikely that discrimination would be influenced by the mode of appearance (M. Melgosa et al., Appl. Opt. 35, 176-187, 1996).

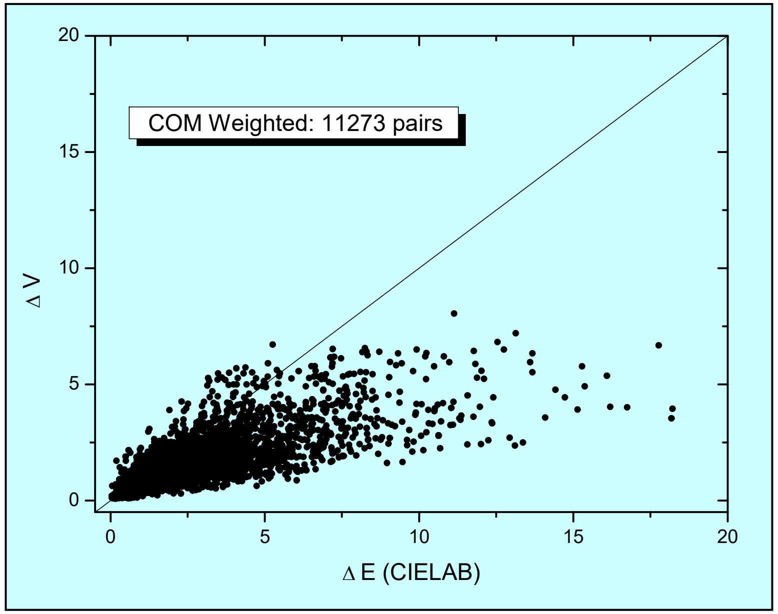
7.5. Parametric effects in color-difference evaluation

Color-difference size

There is no fundamental reason to suppose that the discriminability of small color differences is in any way related to the scaling of larger color differences. It is unknown whether this transition occurs and whether it occurs smoothly or not.

Large color-differences (ΔE^*_{ab}>10) are also important in color image reproduction and industrial design.

Color-difference formulas have been proposed for large color-difference datasets: GLAB (CR&A 24, 344-355, 1999), CAM02-LCD (CR&A 31, 320-330, 2006), etc.



$$\Delta E_{GLAB} = \left(\left(\frac{\Delta L^*}{W_L}\right)^2 + \left(\frac{\Delta C^*_{ab}}{W_C}\right)^2 + \left(\frac{\Delta H^*_{ab}}{W_H}\right)^2\right)^{1/2}$$

$$W_L = 0.76; \quad W_C = 1 + 0.016 C_{sb}; \quad W_H = 1.0$$

$$C_{sb} = \left(C^*_{ab,Std} C^*_{ab,Bat}\right)^{1/2}$$

7.5. Parametric effects in color-difference evaluation

Luminance level

For small luminance changes about the range 30 to 100 cd/m^2 the discrimination doesn't change. However taking as reference a luminance of 100 cd/m^2 a change to 1000 cd/m^2 improves discrimination in a factor $k_E \approx 0.7$

Acceptability vs. perceptibility

In many of the pass/fail studies using object samples, the question posed to the observer has been of the form "Is this an acceptable color match?" For threshold differences acceptability and perceptibility may be equivalent, but not for medium and large color differences.

To avoid the use of different acceptability criteria in different experiments, only perceptibility experimental data were used at the development of CIE94 and CIEDE2000 color-difference formulas.

7.5. Parametric effects in color-difference evaluation

Texture

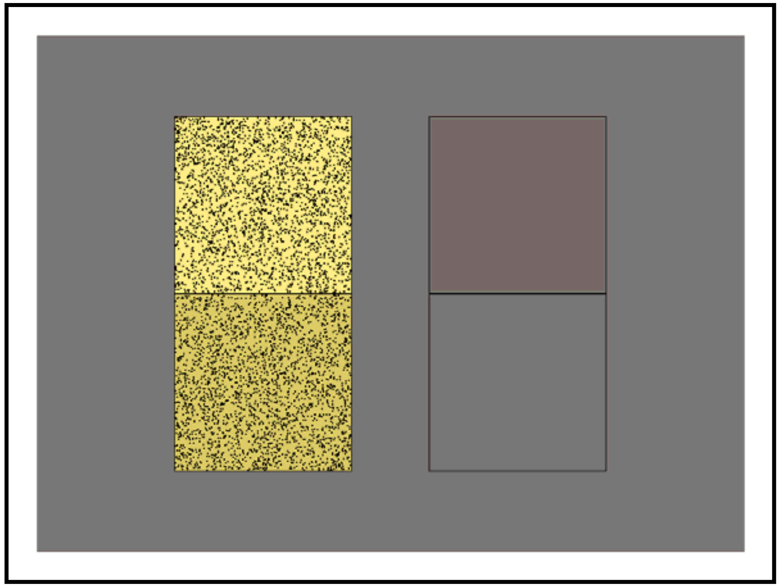
It is considered an important parametric factor in some industries, particularly in textiles.

CIE 101-1993: No recommendation for textures is given.

It is suspected that the recommendation k_L=2 ; k_C=k_H=1 in textiles (CIE Pubs. 116-1995 and 142-2001) may be related to the presence of textures.

Few research works had been carried out on this topic. Our approach:

- Simulated textures in a CRT. Obviously it is easier to control gradual changes of texture using CRT than using real object samples.
- Random dots texture. It is a realistic texture, which can be defined by only a few parameters, this leading to a reasonable number of observations (R. Huertas, Ph.D. Dissertation, University of Granada, 2004).



7.5. Parametric effects in color-difference evaluation

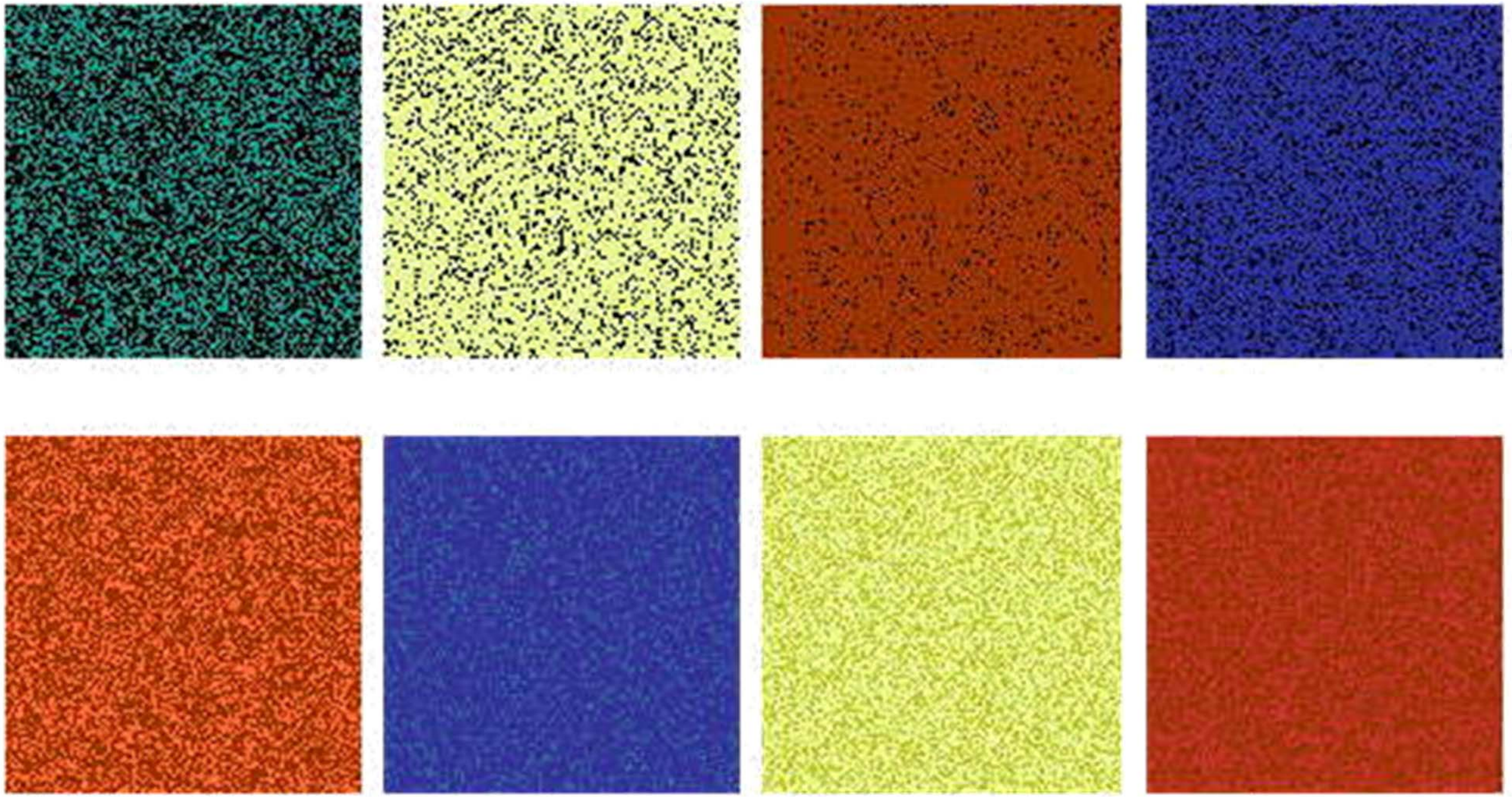
Texture

Textures employed. General criteria: textures visually detectable and acceptable at the established observation distance (Method: trial & error). Possibility of a gradual change in texture parameters, leading to a reasonable number of visual assessments (e.g. to study only the 5 CIE 1978 centres).

Distribution	Random dots	
Thickness	1 y 4 pixels	
Type	*Relative*	A: +10 units in L* B: -10 units in L* C: +15 units in C* D: -15 units in C*
	Absolute	E: Black Dots
Surface	5%, 20%, 50% (and 80% in E)	

7.5. Parametric effects in color-difference evaluation

Texture



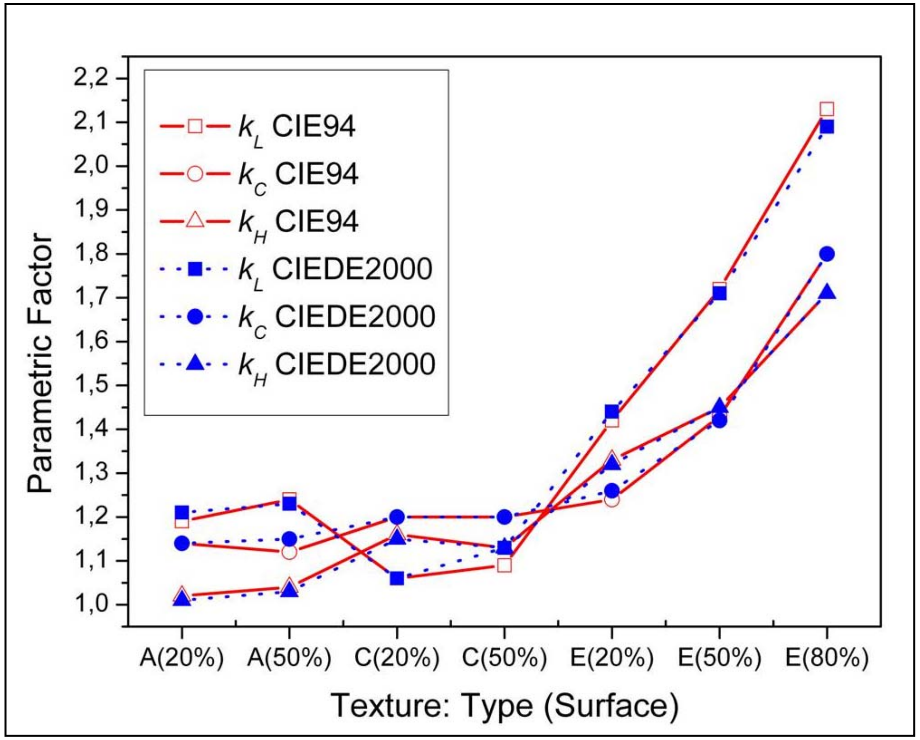
7.5. Parametric effects in color-difference evaluation

Texture

Parametric factors in CIE94 and CIEDE2000 have similar values.

Lightness texture (A) mainly affects k_L while Chroma texture (C) affects k_C.

Black-dots textures (E) with increasing percentages of covered surface strongly increase k_L k_C k_H (not only k_L).



7.5. Parametric effects in color-difference evaluation

Texture

Performance of CIE color-difference formulas.

Formula	$PF/3^b$	$PF/3^c$
CIEDE2000 (k_L:k_C:k_H)[a]	26.0	28.0
CIEDE2000 (1:1:1)	35.0	33.7
CIEDE2000 (2:1:1)	47.4	43.8
CIE94 (k_L:k_C:k_H)[a]	26.3	28.5
CIE94 (1:1:1)	35.7	34.5
CIE94 (2:1:1)	47.8	44.0

[a] Parametric factors fitted for each specific texture.
[b] Textures A (20%), A (50%), C (20%), C (50%), E (20%), E (50%), and E (80%).
[c] Textures E (20%), E (50%), and E (80%).

Appropriate parametric factors may considerably improve the performance of CIE94 and CIEDE2000 color-difference formulas.

Only a parametric factor k_L=*2* (textiles) is not appropriate in our case.

To achieve sound conclusions, much more additional research should be necessary in this field, mainly focused on the needs of specific industries.

7.5. Parametric effects in color-difference evaluation

"Performance Comparison for Image Threshold Data" (Don Gyou Lee, Ph.d. Color Science Department; Leeds, UK)

Models	K_L	CV
CIELAB	1	46.32
CIELAB	4	29.72
CMC	1	56.97
CMC	4	32.11
CIE94	1	54.02
CIE94	5	22.36
CIEDE2000	1	46.32
CIEDE2000	4	20.32
CAM02-UCS	1	32.56
CAM02-UCS	3	15.73
CICDM1	1	15.08
CICDM2	1	15.36
CICDM3	1	15.07

Parametric factor K_L strongly improves color difference formulas' performance where K_C=K_H=1.

Contents

7.6. Relationships between perceived and measured color differences

PF/3 (*Luo et. al., 1999*)

$$V_{AB} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\frac{(\Delta E_i - F\Delta V_i)^2}{\Delta E_i F \Delta V_i}} \qquad F = \sqrt{\frac{\sum_{i=1}^{N}\Delta E_i/\Delta V_i}{\sum_{i=1}^{N}\Delta V_i/\Delta E_i}}$$

$$CV = 100\sqrt{\frac{1}{N}\sum_{i=1}^{N}\frac{(\Delta E_i - f\Delta V_i)^2}{\left(\overline{\Delta E}\right)^2}} \qquad f = \frac{\sum_{i=1}^{N}\Delta E_i \Delta V_i}{\sum_{i=1}^{N}\Delta V_i^2}$$

$$\log_{10}(\gamma) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[\log_{10}\left(\frac{\Delta E_i}{\Delta V_i}\right) - \overline{\log_{10}\left(\frac{\Delta E_i}{\Delta V_i}\right)}\right]^2}$$

$$PF/3 = \frac{100[(\gamma - 1) + V_{AB}] + CV}{3}$$

Perfect Agreement:

$\gamma = 1$

$V_{AB} = 0$

$CV = 0$

$PF/3 = 0$

7.6. Relationships between perceived and measured color differences

PF/3: properties and shortcomings

- ✓ A PF/3 of 30 roughly indicates an average disagreement of 30% between visual and computed differences.
- ✓ Initially a PF/4 index was proposed (*Luo et al. 1982*), considering also the linear correlation coefficient *r*. However *r* values were not in agreement with Gamma, V_{AB} and *CV* values, and therefore it was suppressed.
- ✓ PF/3 was generated because applying the Gamma, V_{AB} and *CV* indices, different conclusions were achieved for different experimental datasets.
- ✓ Obviously, because PF/3 is an eclectic index, a flaw in any one of its 3 components (Gamma, V_{AB} and *CV*) is translated to PF/3.
- ✓ PF/3 index is not a standard statistical index. Therefore it cannot inform us about the statistical significance of the differences between two formulas with similar PF/3 values.
- ✓ For industry a new standardized color-difference formula must compensate costs of retraining and software changes, being statistically significant better than the previous adopted formulas.

7.6. Relationships between perceived and measured color differences

Alman's V_M function used at CIEDE2000 development

$$\boxed{V_M = \frac{\sum(\Delta V_i - a_M \Delta E_i)^2}{N-1}}$$

$$a_M = \frac{\sum \Delta E_i \Delta V_i}{\sum \Delta E_i{}^2}$$

where the sums go thorough the *i*=1,…N color pairs, a_M is a scale factor trying to put ΔE_i and ΔV_i in the same scale, and *M* refer to a color-difference formula.

It is important to note that the ratio V_A/V_B follows an *F* distribution if the residuals are normally distributed and unbiased. In our case the V_A/V_B ratio can be used for statistical inferences, because a_M corrects bias and the residuals do not show strong skew. (*cfr. M. Melgosa, R. Huertas, R. Berns, J. Opt. Soc. Am. A 25, p.1829, 2008*).

7.6. Relationships between perceived and measured color differences

STRESS (*P.A. García et. Al. JOSA A, 24, 1823-1829, 2007*)

$$STRESS = 100 \left(\frac{\sum (\Delta V_i - F \Delta E_i)^2}{\sum \Delta V_i^2} \right)^{1/2}$$

$$F = \frac{\sum \Delta E_i \Delta V_i}{\sum \Delta E_i{}^2}$$

$0 \leq STRESS \leq 100$

Ideal value: $STRESS = 0$

STRESS index (Kruskal's STRESS): STandardized REsidual Sum of Squares.

Statistical inference:

$$F = \frac{V_A}{V_B} = \frac{STRESS_A^2}{STRESS_B^2}$$

Assuming the same set of ΔV_i (i=1…N) data

- $F < F_C \Rightarrow$ A is significantly better than B
- $F > 1/F_C \Rightarrow$ A is significantly poorer than B
- $F_C \leq F < 1 \Rightarrow$ A is insignificantly better than B
- $1 < F \leq 1/F_C \Rightarrow$ A is insignificantly poorer than B
- $F = 1 \Rightarrow$ A is equal to B

7.6. Relationships between perceived and measured color differences

Summary of properties of the different indices

	Symmetry[a]	Range	Sensitivity to scale factors[b]	Possibility of F tests
γ	Yes	[1,+∞]	No	No
V_{AB}	Yes	[0,+∞]	No	No
CV	No	[0,+∞]	No	No
$PF/3$	No	[0,+∞]	No	No
V_M	No	[0,+∞]	No for ΔE_i but yes for ΔV_i	Yes
$STRESS$	Yes	[0,100]	No	Yes

[a] Exchange of ΔE_i and ΔV_i (i=1, N color pairs) values.

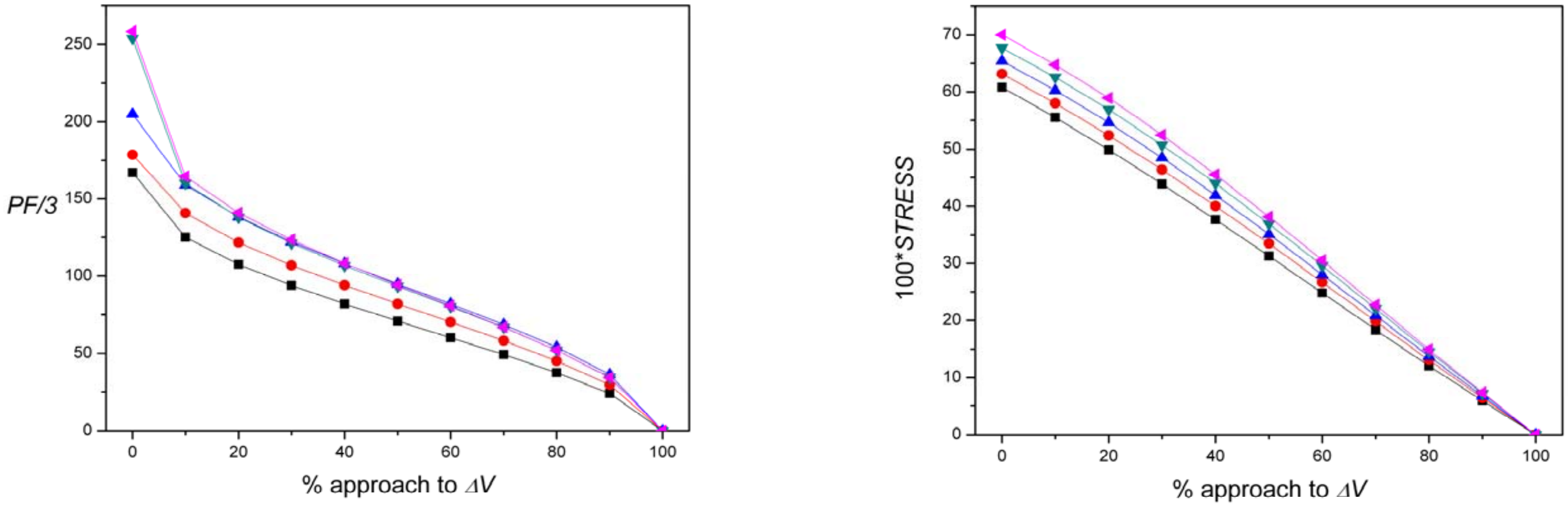
[b] Change of the scales of ΔE_i (or ΔV_i) multiplying by a constant factor.

As an average PF/3 will incorporate flaws in any one of its 3 components: γ, V_{AB}, CV.

7.6. Relationships between perceived and measured color differences

Linearity of PF/3 and STRESS when ΔE_i approach to ΔV_i

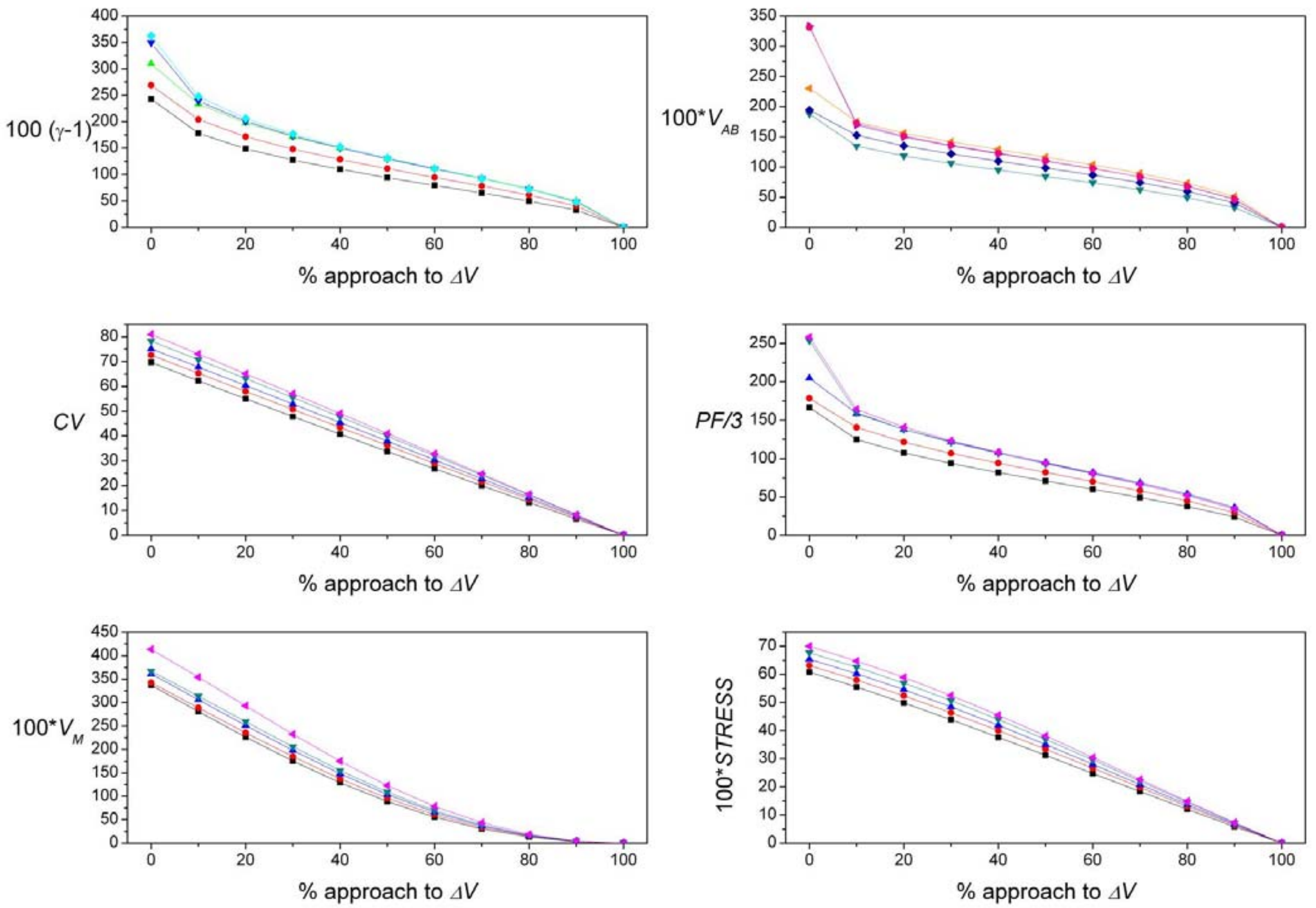
$$\Delta E_i(20\%) = \begin{matrix} \Delta E_i(0\%) + |\Delta E_i(0\%) - \Delta V_i| \cdot (20/100) & \text{if } \Delta E_i < \Delta V_i \\ \Delta E_i(0\%) - |\Delta E_i(0\%) - \Delta V_i| \cdot (20/100) & \text{if } \Delta E_i > \Delta V_i \end{matrix}$$



Each curve corresponds to a different set of 500 pairs of random ΔE_i and ΔV_i (i=1,…,N) values in the range 0 to 5.

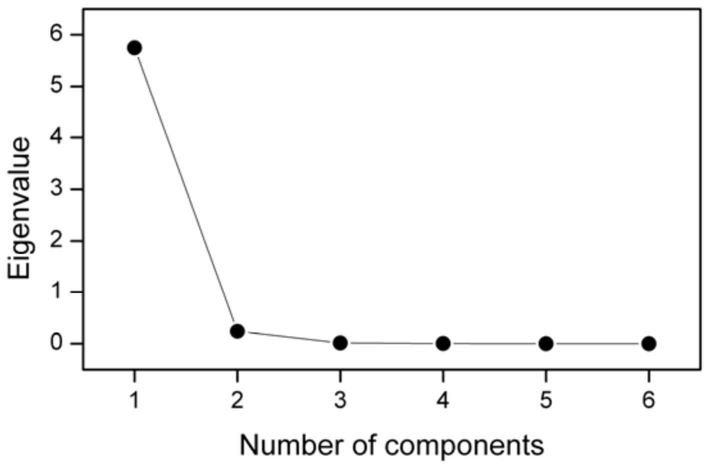
7.6. Relationships between perceived and measured color differences

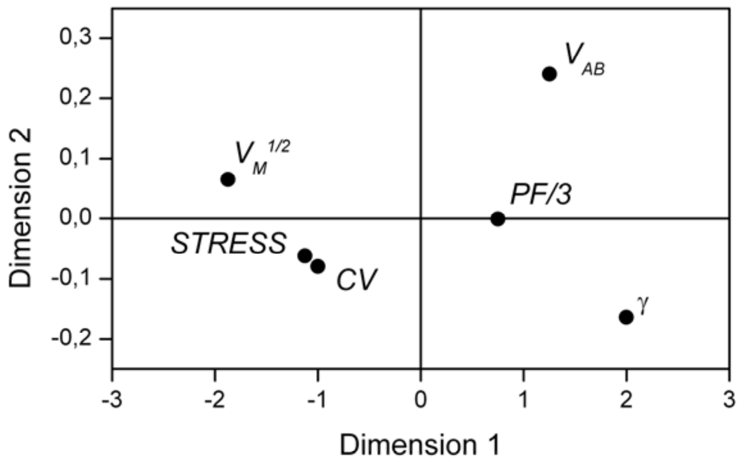
The CV index is not in the appropriate scale



7.6. Relationships between perceived and measured color differences

Results of PCA and MDS from 50 random datasets

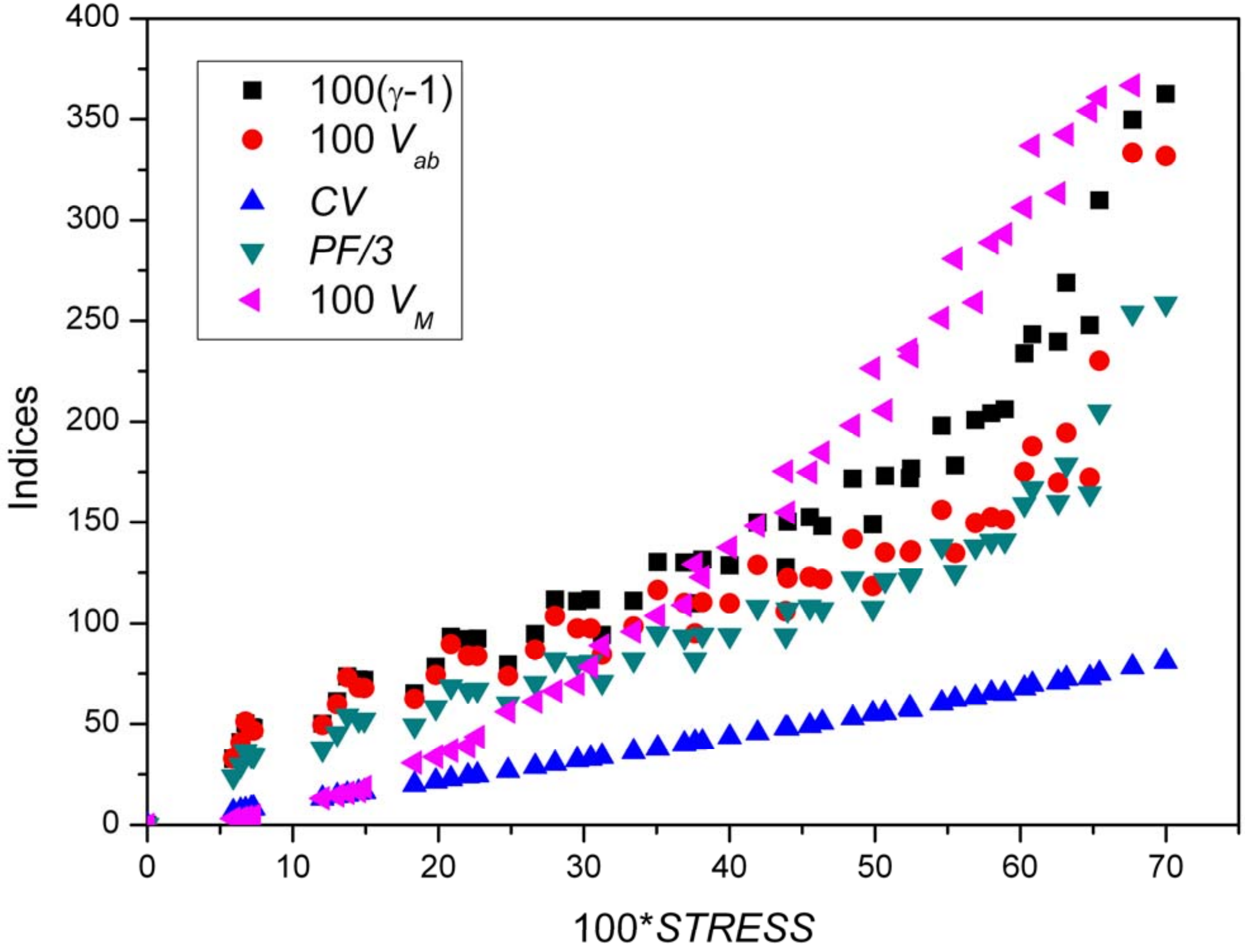




- ✓ 5 random datasets x 10 %approach = 50 datasets.
- ✓ The six indices are not independent. In particular, CV and STRESS are very similar indices.

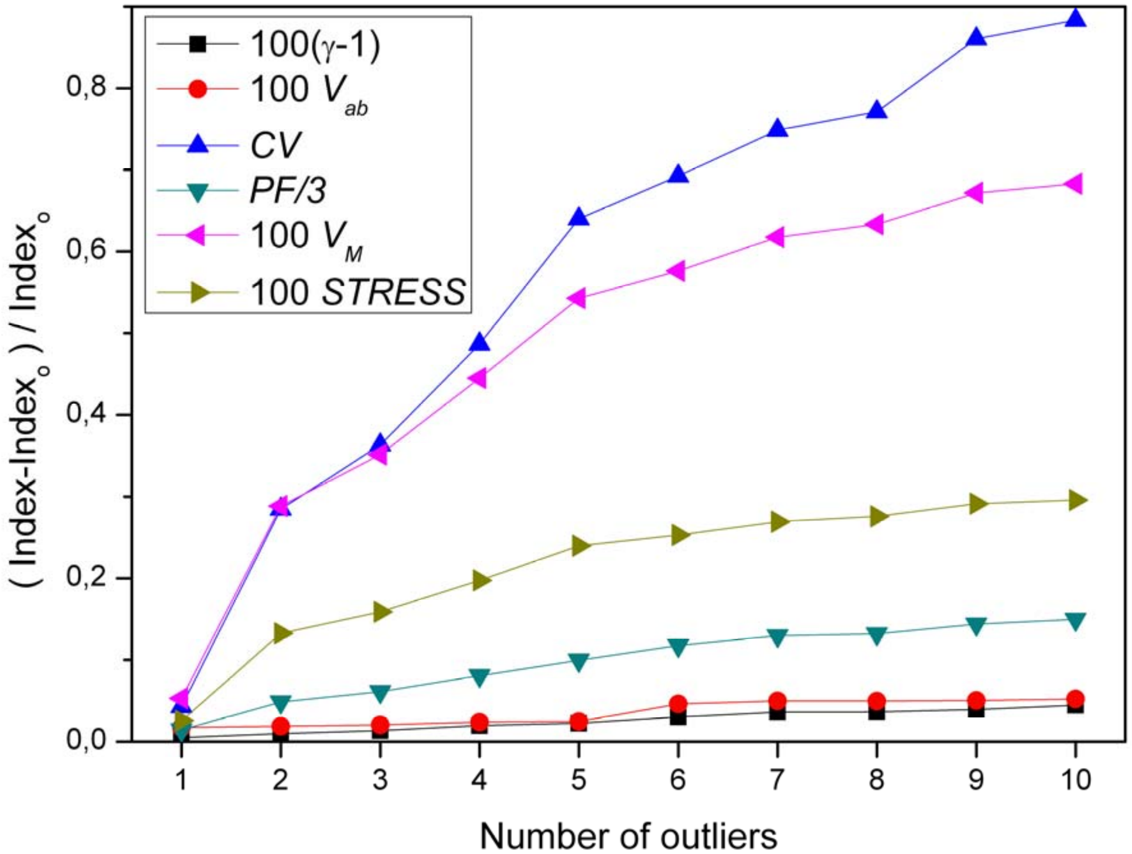
7.6. Relationships between perceived and measured color differences

Relationship between STRESS(%) and the other 5 indices



7.6. Relationships between perceived and measured color differences

Influence of the number of outliers (x10 factors) in the 5 datasets

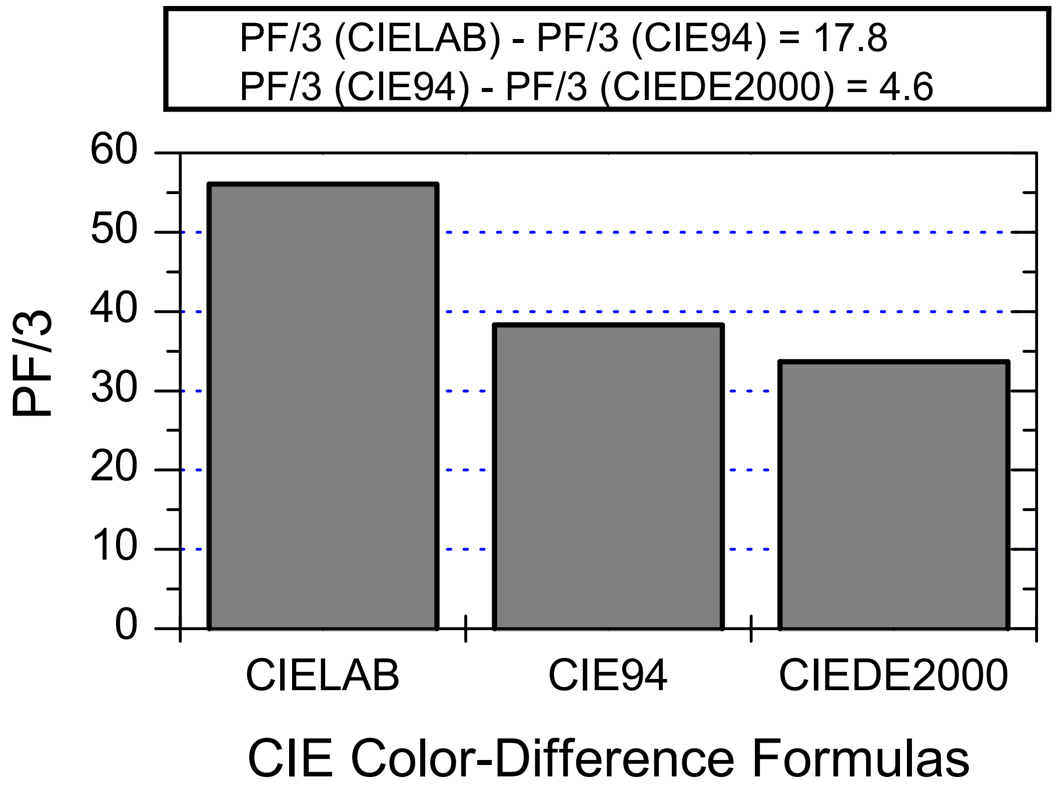


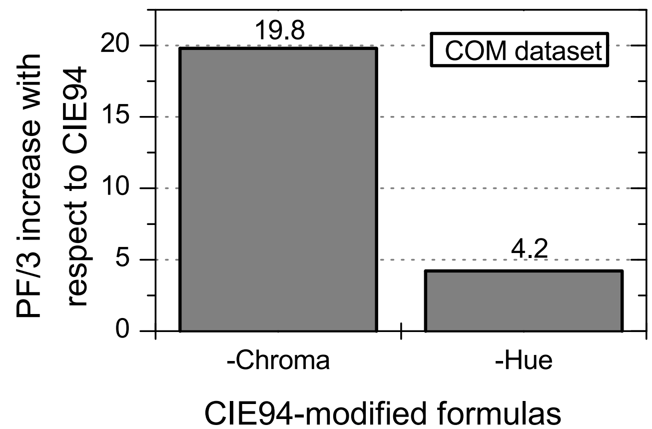
On the "y" axis Index and Index$_0$ mean the values of any of the indices with and without the presence of outliers, respectively.

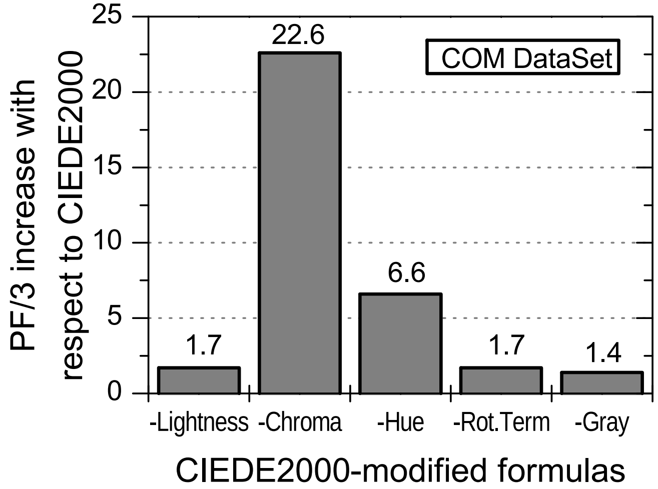
While STRESS(%) has an intermediate sensitivity, CV has the highest sensitivity to outliers.

7.6. Relationships between perceived and measured color differences

PF/3 for CIE recommended formulas and COM Weighted dataset

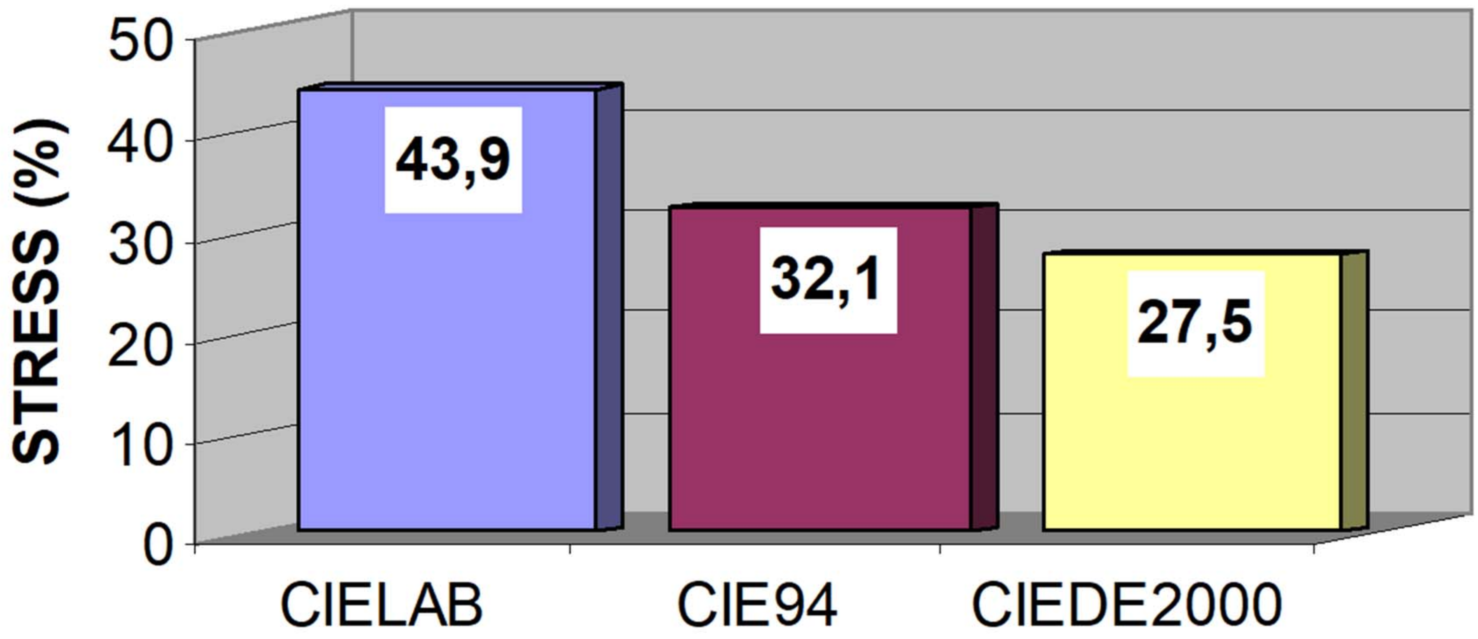






7.6. Relationships between perceived and measured color differences

STRESS (%) for CIE recommended formulas and COM Weighted dataset

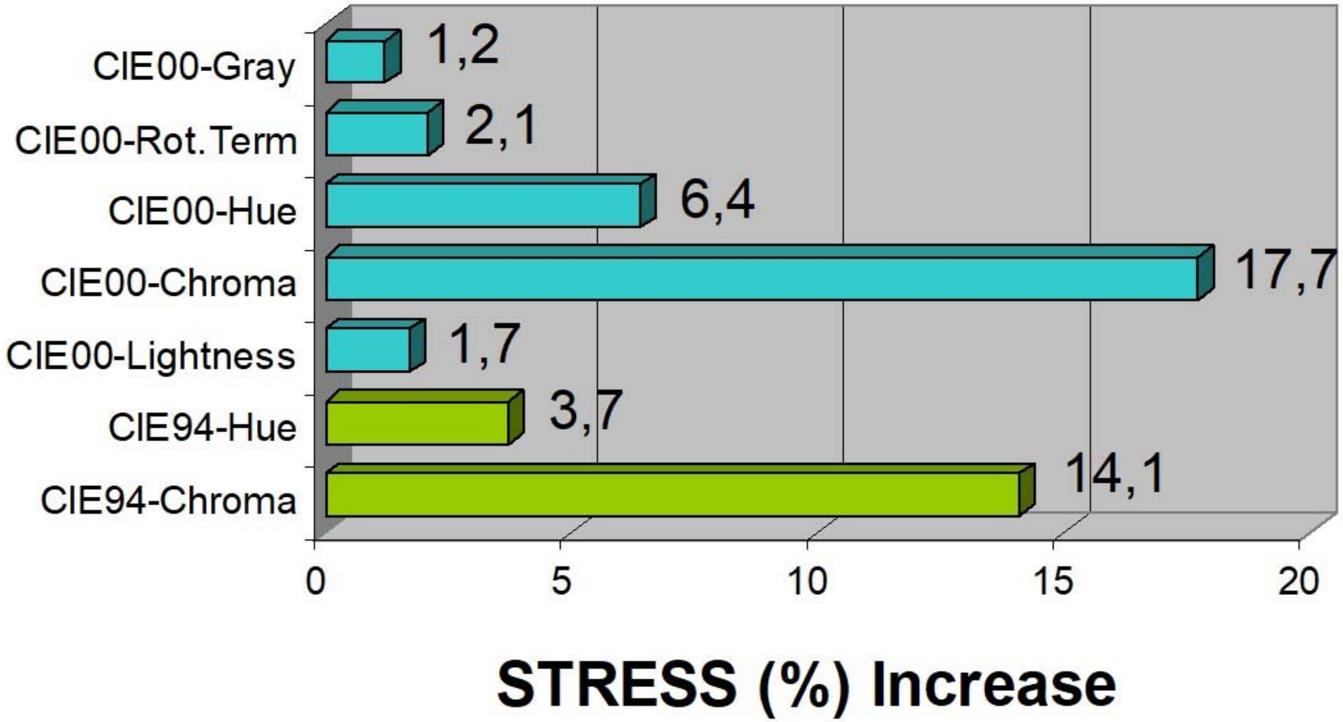


From CIELAB to CIE94 *STRESS* decreased **11.8** units.

From CIE94 to CIEDE2000 *STRESS* decreased **4.6** units (2.5 times lower).

7.6. Relationships between perceived and measured color differences

STRESS (%) increase for reduced models & COM Weighted

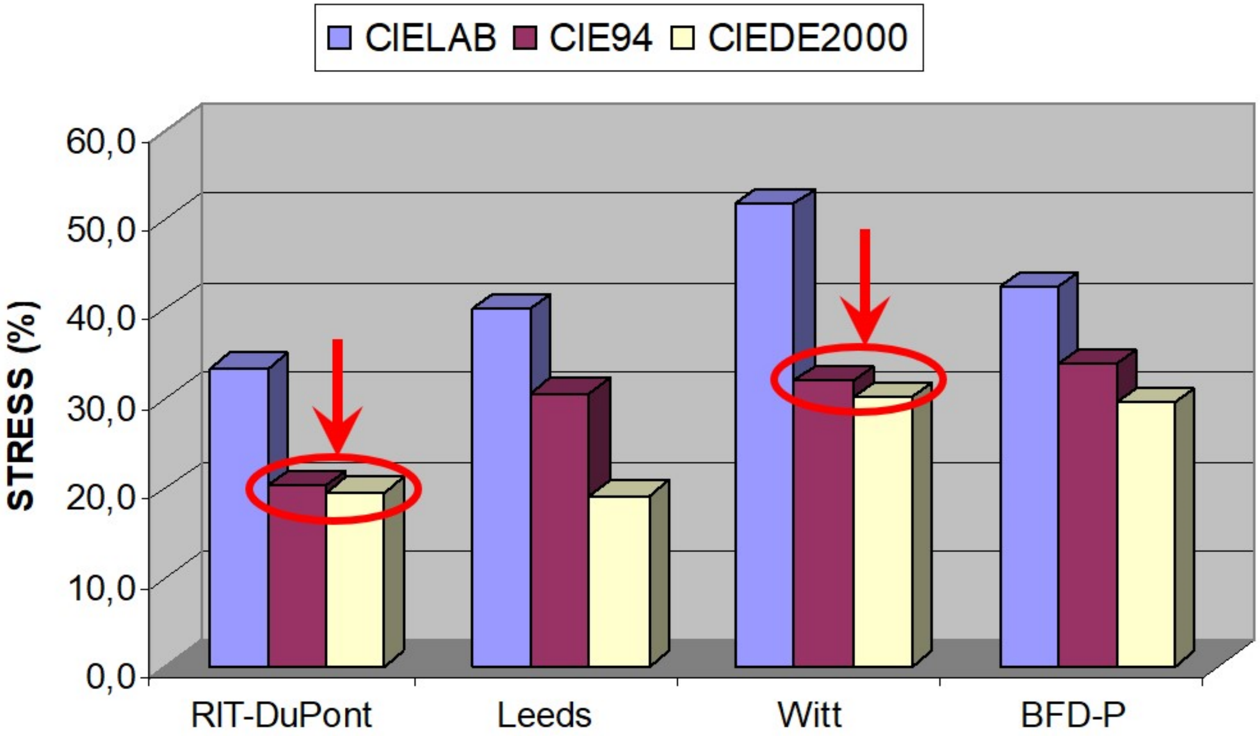


For COM Weighted each one of corrections proposed by CIEDE2000 or CIE94 were found statistically significant at 95% confidence level.

CIEDE2000 (but not CIE94) significantly improves CMC.

7.6. Relationships between perceived and measured color differences

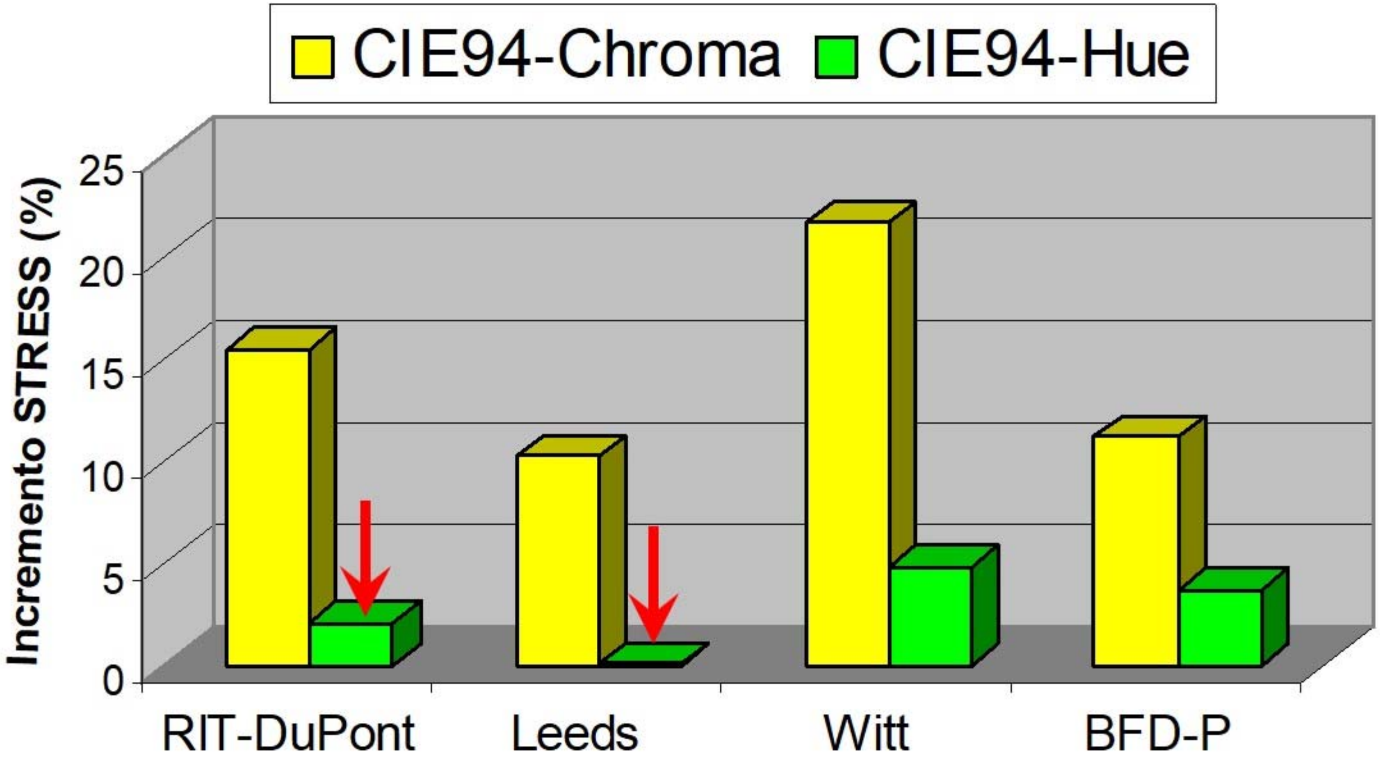
STRESS (%) for individual datasets in COM



Surprisingly CIEDE2000 is not significantly better than CIE94 for the RIT-DuPont and Witt's datasets. In addition, it has been reported that the RIT-DuPont dataset was wrongly used at CIEDE2000 development.

7.6. Relationships between perceived and measured color differences

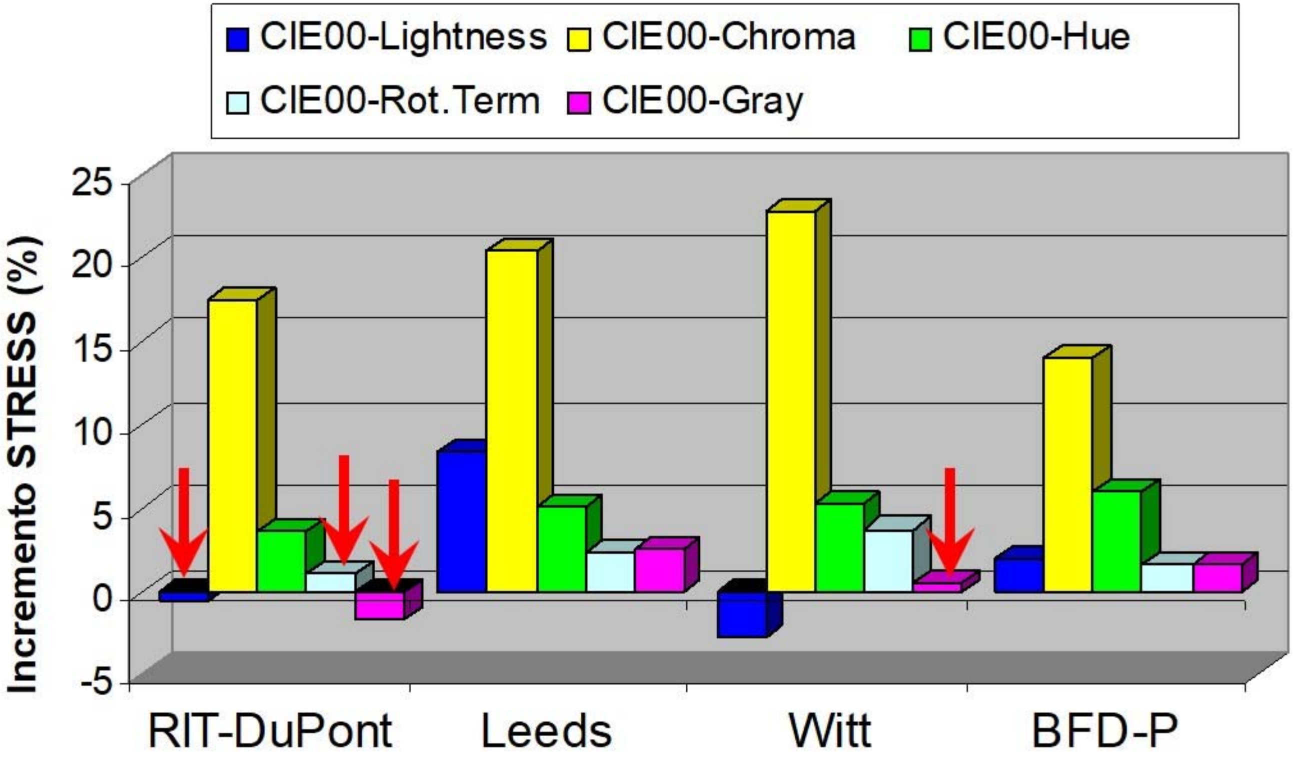
Reduced CIE94 models for 4 datasets in COM



Surprisingly the hue correction in CIE94 is not statistically significant in RIT-DuPont and Leeds datasets.

7.6. Relationships between perceived and measured color differences

Reduced CIEDE2000 models for 4 datasets in COM



Surprisingly the gray correction in CIEDE2000 is not statistically significant in RIT-DuPont and Witt datasets.

7.6. Relationships between perceived and measured color differences

Combined Weighted Datasets?

TABLE I. A summary of RIT–DuPont, Witt, Leeds, BFD-P, and COM data sets.

Data sets	No. of pairs	Mean ΔE^*_{ab}	Weighting factor	Adjustment factor for ΔV	Material
RIT–DuPont	156	1.0	18	0.93	Glossy paint
Witt	418	1.9	7	0.43	Glossy paint
Leeds	307	1.6	9	0.79 and 0.93	Glossy paint
BFD-P	2 776	3.0	1	1.00	Various materials but relative scales of individual sets adjusted using textile samples
COM	3 657	2.6		—	All of above
Weighted COM	11 273				

- ✓ A way to have a large number of color pairs in all regions of color space, avoiding a general formula be biased by data from a specific laboratory. Obviously, all data were put in a common scale before combination.
- ✓ A ‘political’ (or ‘polite’) way to consider all the laboratories equally important, avoiding conflicts among them.
- ✓ A wrong way because it is not based on scientific reasons (e.g. degree of accuracy on visual determinations, etc.).
- ✓ A wrong way because experimental conditions, or fitting techniques, or both, may be not the same in all reported experimental data.

7.6. Relationships between perceived and measured color differences

Combined Weighted Datasets?

Request for Existing Experimental Datasets on Color Differences

Received 6 October 2006; accepted 13 October 2006

Abstract: The Technical Committee 1-55 of the International Commission on Illumination on "Uniform color space for industrial color difference evaluation" is requesting the submission of datasets for use in developing a new approximately uniform color space for industrial use. The data should be submitted to the TC Chair, Dr. Manuel Melgosa at the University of Granada. © 2007 Wiley Periodicals, Inc. Col Res Appl, 32, 159, 2007; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/col.20300

Key words: color difference; CIE; CIEDE2000; uniform color space

The Technical Committee 1-55 of the International Commission on Illumination (CIE TC 1-55) on "Uniform color space for industrial color difference evaluation" is looking for existing experimental datasets on color differences complementing those employed during the development of the CIEDE2000 color-difference formula (Color Res Appl 2001;26:340–350). Reliable experimental datasets (that is, color pairs assessed by a considerable number of observers with nondefective color vision, under well controlled experimental conditions and using proper experimental methods) are requested. These datasets will be used to develop/test new color spaces with Euclidean color-difference formulas which may be useful for industrial applications. Not only surface specimens (object color), but also color pairs assessed using visual displays (e.g., CRT) can be considered. Experimental results obtained under illuminating/viewing conditions close to the "reference conditions" suggested for the CIEDE2000 color-difference formula (CIE Publication 142-2001) are particularly useful. Exact experimental conditions including the spectral power distribution of the viewing environment and the spectral reflectance factors or spectral radiance factors of the specimens are preferred. Researchers interested in having their experimental datasets considered by CIE TC 1-55 are kindly invited to contact the chairman of this TC. Please provide detailed information on the data: color coordinates and visual differences for color pairs (with their corresponding uncertainties or confidence limits, if possible), and a detailed description of the experimental conditions and method employed. Decisions as to the applicability of submitted data for the purposes of the work of the committee will be made by CIE TC 1-55.

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Color appearance vs. color differences

5 colors

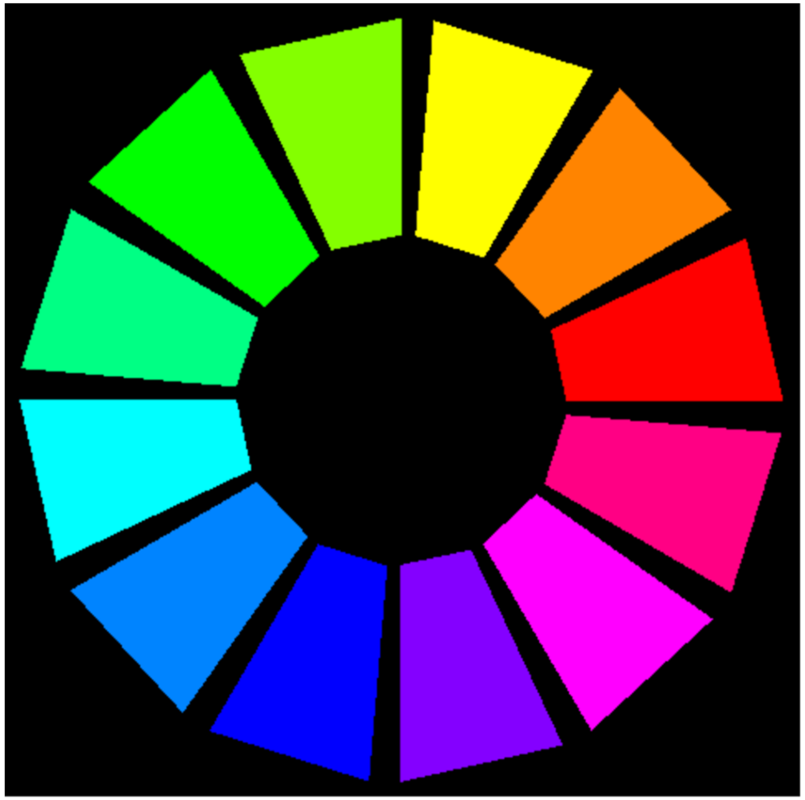
8 color appearances

Paul Green-Armitage
(Color Res Appl. 31, 253, 2006)

7.7. Color differences in images

Color-Differences in images (CIE TC 8-2): s-CIELAB, iCAM, etc.

CIE94 and CIEDE2000 were not developed to compare 2 images.



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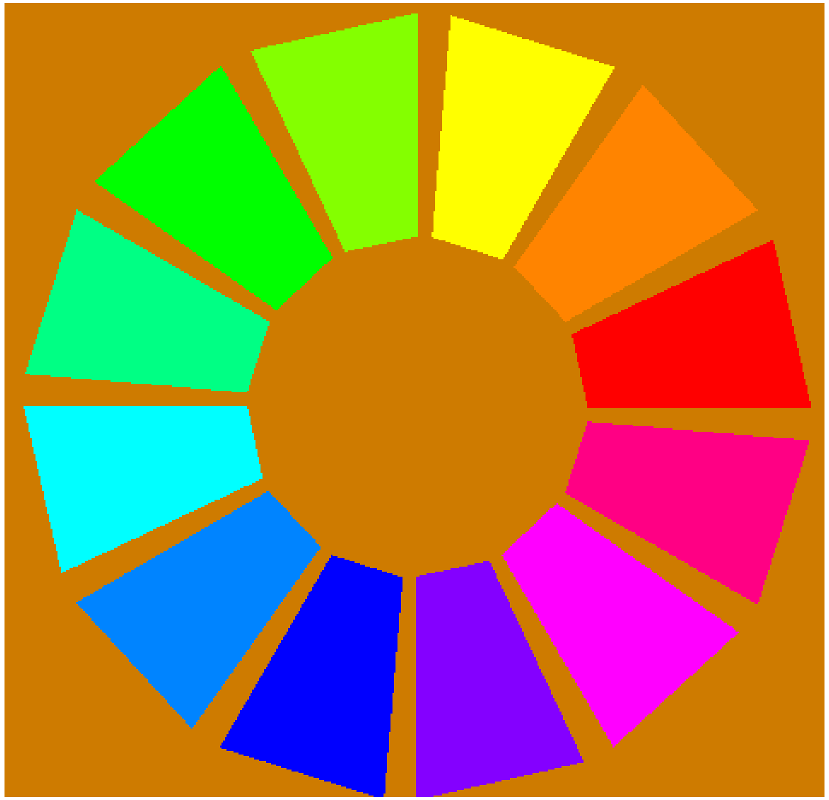
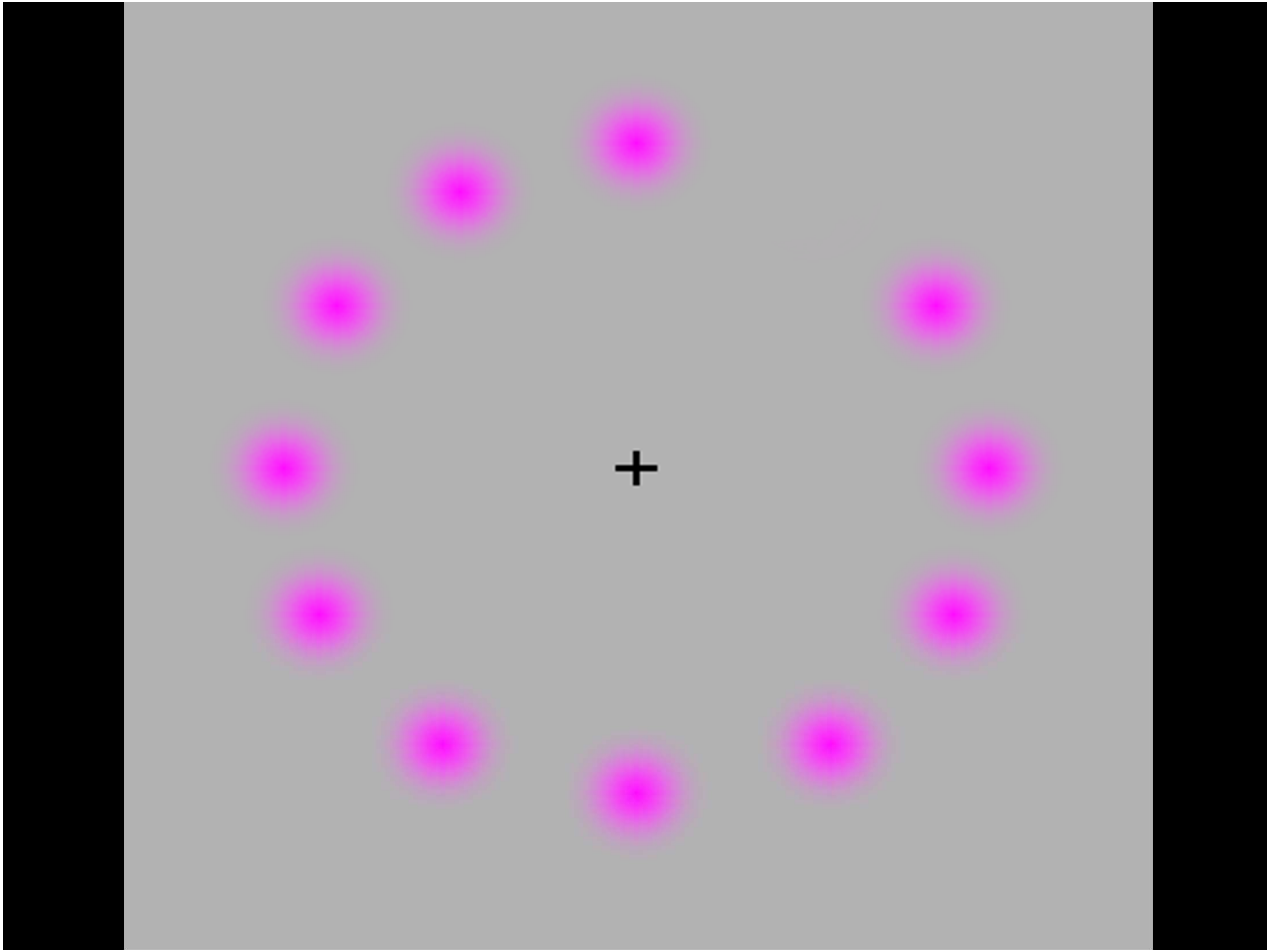


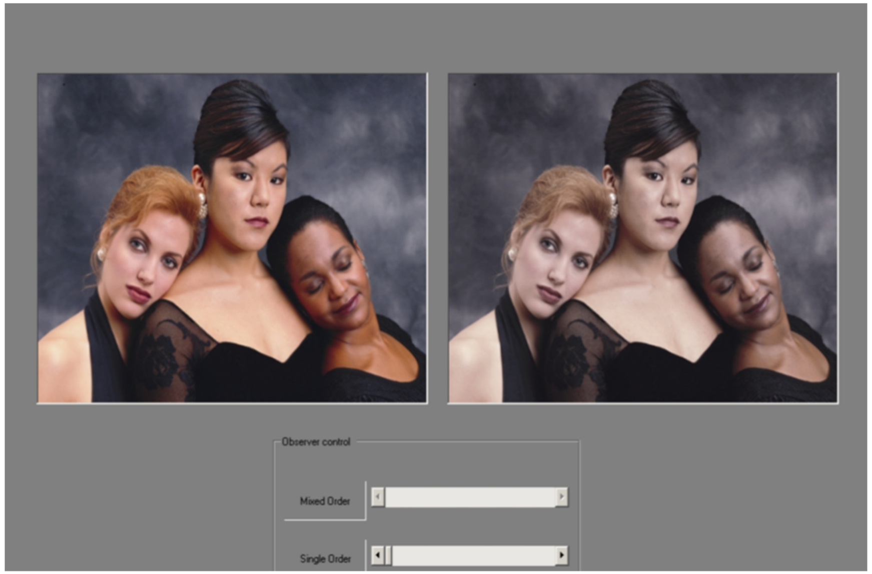


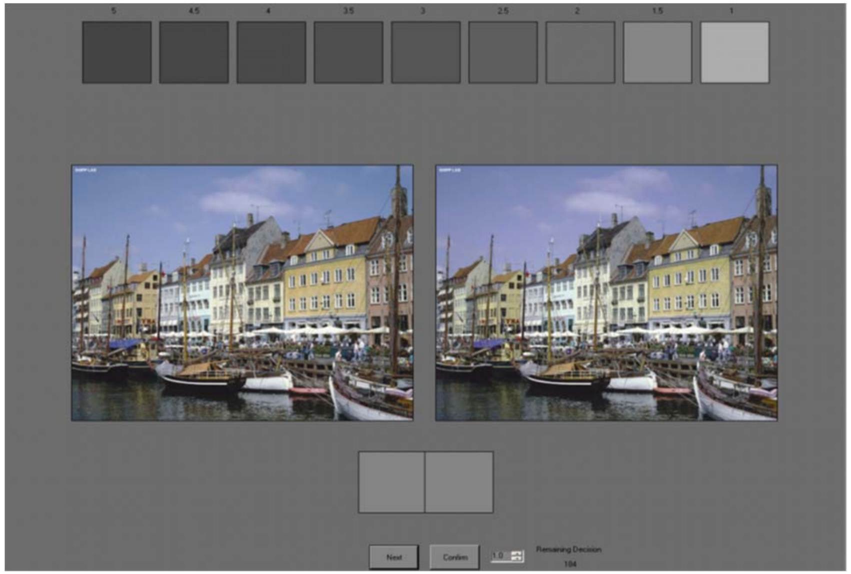

http://www.johnsadowski.com/big_spanish_castle.php

7.7. Color differences in images

Color-Differences in images (CIE TC 8-2): s-CIELAB, iCAM, etc.

Are useful for complex images the color-difference formulas developed for uniform patches? (Leeds, UK)





$$\overline{\Delta E_{ij}} = \frac{\sum_{j=1}^{x}\sum_{i=1}^{y}\sqrt{\left(\frac{\Delta L_{ij}^*}{1+0.12L_m^*}\right)^2+\left(\frac{\Delta C_{ij}^*}{1+0.09C_m^*}\right)^2+\left(\frac{\Delta H_{ij}^*}{1+0.06C_m^*}\right)^2}}{x\times y}$$

Don Gyou Lee et al., CGIV 2008.

7.7. Color differences in images

Color-Differences in images (CIE TC 8-2): s-CIELAB, iCAM, etc.

Don Gyou Lee, PhD (Color Science Department, University of Leeds, UK).

Approximately 2000 images were rendered based on 11 ‘original’ images.

Threshold and supra-threshold experiments between original and rendered images.

(a) 3-Ladies (b) Picnic (c) Harbour (d) Lady (e) Fruit (f) Barn

Pictorial Images used in this study

(a) Pi (b) Auto (c) 3D-Trend (d) Trend and bar (e) 3D-Bar

Business graphic Images used in this study

7.7. Color differences in images

Color-Differences in images (CIE TC 8-2): s-CIELAB, iCAM, etc.

Color metrics proposed by Leeds team (CGIV'08)

$$\overline{\Delta E_{ij}}(CICDM1) = \frac{\sum_{1}^{j}\sum_{1}^{i}\sqrt{\left(\frac{\Delta L^*_{ij}}{K_L I_L}\right)^2 + \left(\frac{\Delta C^*_{ij}}{K_C I_C}\right)^2 + \left(\frac{\Delta H^*_{ij}}{K_H I_H}\right)^2}}{i \times j}$$

$where,\ K_L, K_C\ and\ K_H = 1$

$i = horizontal\ \ pixel\ \ number$

$j = vertical\ \ pixel\ \ number$

$$I_L = 1 + W_L \cdot L_m$$
$$I_C = 1 + W_C \cdot C_m$$
$$I_H = 1 + W_H \cdot C_m$$

$and\quad W_L = 0.12,\quad W_C = 0.09\quad W_H = 0.06$

$$\overline{\Delta E_{ij}} = \frac{\sum_{1}^{j}\sum_{1}^{i}\sqrt{\left(\frac{\Delta J^*_{ij}}{K_L I_L}\right)^2 + \left(\frac{\Delta C^*_{ij}}{K_C I_C}\right)^2 + \left(\frac{\Delta H^*_{ij}}{K_H I_H}\right)^2}}{i \times j}$$

$K_L, K_C\ and\ K_H = 1$

$i = horizontal\ \ pixel\ \ number$

$j = vertical\ \ pixel\ \ number$

$$I_L = 1 + W_L \cdot L_m$$
$$I_C = 1 + W_C \cdot C_m$$
$$I_H = 1 + W_H \cdot C_m$$

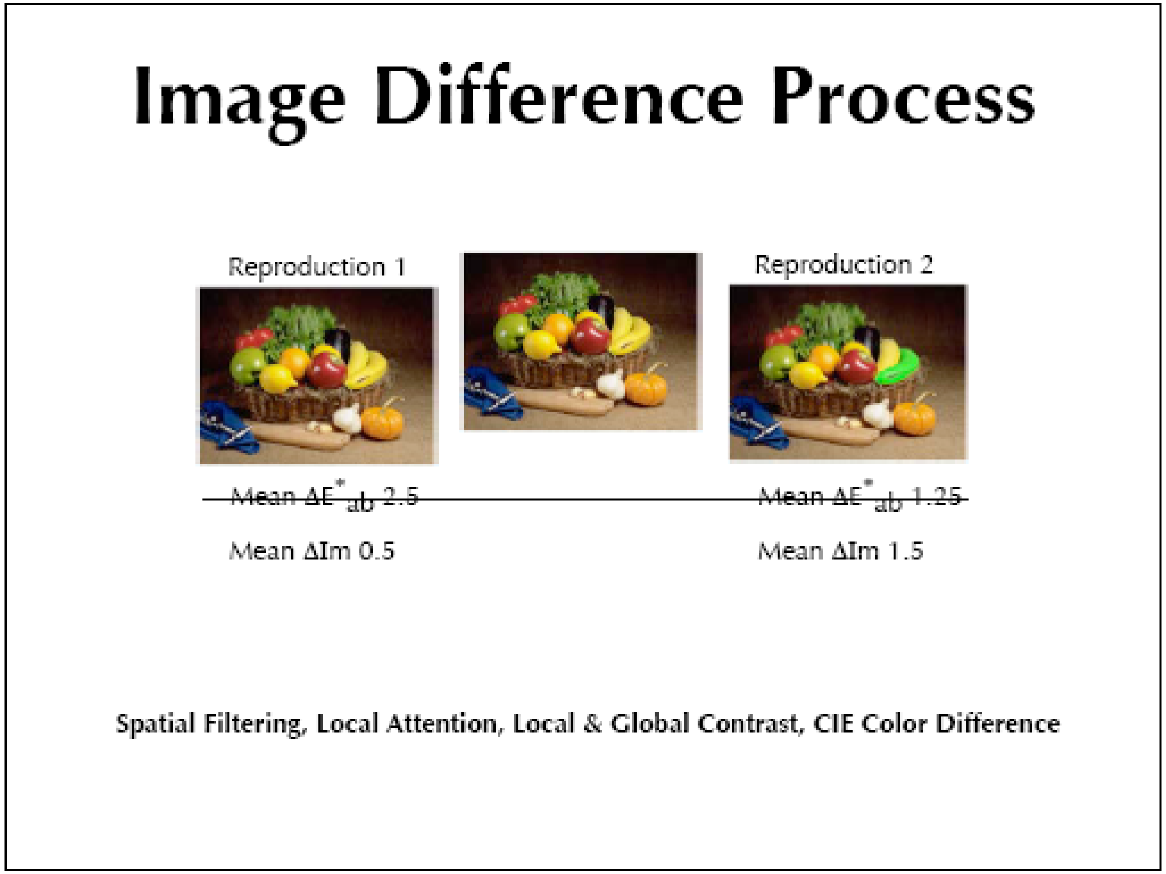
$W_L = 0.05,\quad W_C = 0.005\quad W_H = 0.013$

It seems that weighting functions are dependent of the experiment (threshold/supratheshold) or even the image tested…

7.7. Color differences in images

Color-Differences in images (CIE TC 8-2): s-CIELAB, iCAM, etc.

Pixel by pixel color-differences?



7.7. Color differences in images

S-CIELAB (*Zhang, Wandell, 1996*)

“S-CIELAB metric is a ‘perceptual color fidelity’ metric. It measures how accurate the reproduction of a color is to the original when viewed by a human observer. The S-CIELAB metric extends the CIELAB ΔE^*_{ab} to color images”

“Color discrimination and appearance is a function of spatial pattern. In general, as the spatial frequency of the target goes up (finer variations in space), color differences become harder to see, especially differences along the blue-yellow direction”. So if we want to apply the CIE L*a*b* Delta E metric to color images, the patterns of the image have to be taken into account”.

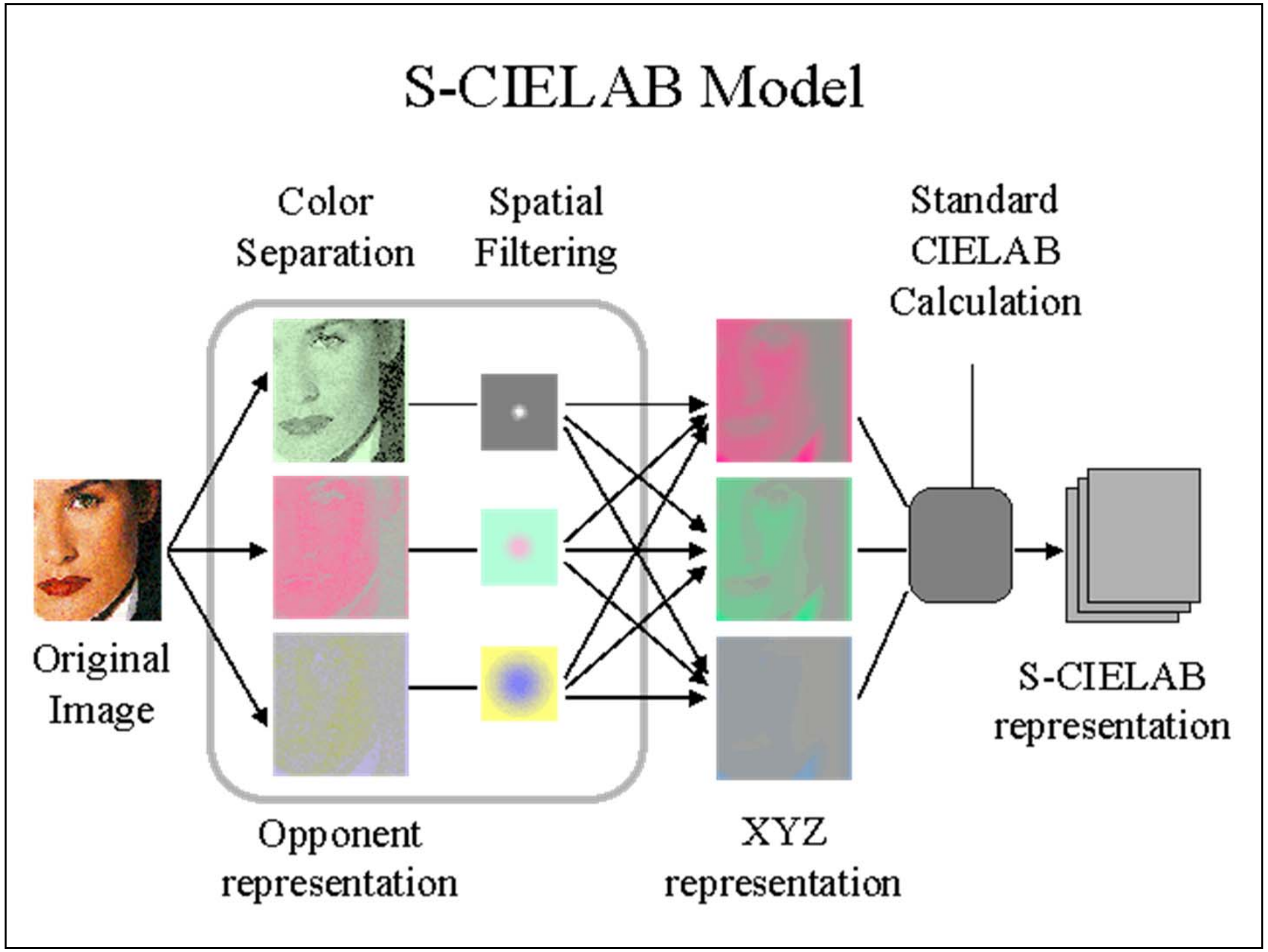
“The goal of the S-CIELAB metric is to add a spatial pre-processing step to the standard CIELAB Delta E metric to account for spatial-color sensitivity of the human eye”.

Rafael Huertas Roa
Javier Hernández Andrés
Eva Valero Benito

7.7. Color differences in images

S-CIELAB (*Zhang, Wandell, 1996*)

The key components are the color transformation and the spatial filtering steps before the standard CIELAB Delta E calculations.



7.7. Color differences in images

Performance comparison using Supra-Threshold Experiment data

Original Models	CV	Spatial Models	CV
CIELAB(1:1:1)	50.31	S-CIELAB(1:1:1)	67.52
CIELAB(2:1:1)	46.87	S-CIELAB(4:1:1)	65.51
CMC(1:1:1)	61.38	S-CMC(1:1:1)	75.95
CMC(3:1:1)	32.76	S-CMC(6:1:1)	42.08
CIE94(1:1:1)	63.31	S-CIE94(1:1:1)	79.73
CIE94(3:1:1)	29.65	S-CIE94(6:1:1)	37.85
CAM02_UCS(1:1:1)	44.32	S-CAM02_UCS(1:1:1)	53.83
CAM02_UCS(2:1:1)	28.26	S-CAM02_UCS(3:1:1)	37.18
CIEDE2000(1:1:1)	51.59	S-CIEDE2000(1:1:1)	76.1
CIEDE2000(3:1:1)	25.54	S-CIEDE2000(6:1:1)	33.63
CICDM1	23.85	S-CICDM1	34.4
CICDM2	24.32	S-CICDM2	36.64
CICDM3	20.55	S-CICDM3	29.88

Don Gyou Lee, PhD (Color Science Department, University of Leeds, UK): Pictorial and Business graphic Images.

Testing the performance of the original and the optimized K_L color-difference model (Including Spatial color-difference model).

Spatial color-difference models do not report improvement. Future work: to consider more viewing conditions and the spatial filtering.