CIE Division 1
Vision and Colour

ISO Technical Committee 130
Graphic Technology

CIE/ISO new standard: CIEDE2000

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University of Leeds (UK), 4 July 2013 (10:15 – 10:30)

Outline

1. Introduction
2. CIEDE2000 General Structure
3. CIEDE2000 Performance
4. CIEDE2000, Milestone or Final Answer?

1. Introduction

History of CIE Colour-Difference Formulas

1964: CIE 1964 (U*V*W*)
1976: CIE 1976 (L*u*v*) ≡ CIELUV
1976: CIE 1976 (L*a*b*) ≡ CIELAB
1995: CIE94
2000: CIEDE2000

CIE TC 1-57 "Standards in Colorimetry" (Chair: A. Robertson):

- ISO 11664-4:2008(E) / CIE S 014-4 E:2007. Joint ISO/CIE Standard: CIE Colorimetry – Part 4: 1976 L*a*b* Colour Space.
- ISO 11664-5:2009(E) / CIE S 014-5 E:2009. Joint ISO/CIE Standard: CIE Colorimetry – Part 5: CIE 1976 L*u*v* Colour Space and u',v' Uniform Chromaticity Diagram.
- CIE DS 014-6/E:2012, "Colorimetry - Part 6: CIEDE2000 colour-difference formula," CIE Central Bureau, Vienna (2012).

“Industrial Colour-Difference Evaluation”

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

To replace visual <u>subjective</u> judgments (ΔV) by instrumental <u>objective</u> measurements (ΔE)

CIELAB-Based Colour-Difference Formulas

CIEDE2000 was first proposed by CIE TC 1-47 (Chair: David H. Alman) in CIE Publ. 142-2001, and discussed by Luo, Cui & Rigg CR&A 26, 340-350 (2001). Latter in 2013 CIE TC 1-57 (Chair: Alan Robertson) proposed it as a Standard.

CIE S 014-6/E:2013

International Standard

Colorimetry – Part 6: CIEDE2000 Colour-Difference Formula

Colorimétrie – Partie 6: Formule d'écart de couleur CIEDE2000

Farbmessung – Teil 6: CIEDE2000-Farbabstandsformel

CIE Central Bureau, Vienna
Kegelgasse 27, A-1030 Vienna, Austria

CIE S 014-6/E:2013

UDC: 535.65:006
535.643.2

Descriptor: Standardisation of colour measurement
Standard colorimetric systems

* The chairperson of this TC was A.R. Robertson (CA), members were: P.J. Alessi (US), M. Brill (US), J. Campos Acosta (ES), E. Carter (US), R. Connelly (US), J.-F. Decarreau (FR), R. Harold (US), R. Hirschler (HU), B. Jordan (CA), C. Kim (KR), D. McDowell (US), P. McGinley (AU), M. Melgosa (ES), Y. Ohno (US), M.R. Pointer (GB), K. Richter (DE), G. Rösler † (DE), J.D. Schanda (HU), R. Sève (FR), K. Witt (DE), H. Yaguchi (JP), J. Zwinkels (CA).

CONTENTS

2. CIEDE2000 General Structure (CIE Publ. 142-2001, CIE S 014-6/E:2013)

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

- **Weighting Functions: S_L, S_C, S_H, R_T, Neutral.**

  Positional corrections to the lack of uniformity of CIELAB.

- **Parametric Factors: k_L, k_C, k_H**

  Corrections accounting for the influence of experimental viewing conditions.

Weighting Functions in CIEDE2000

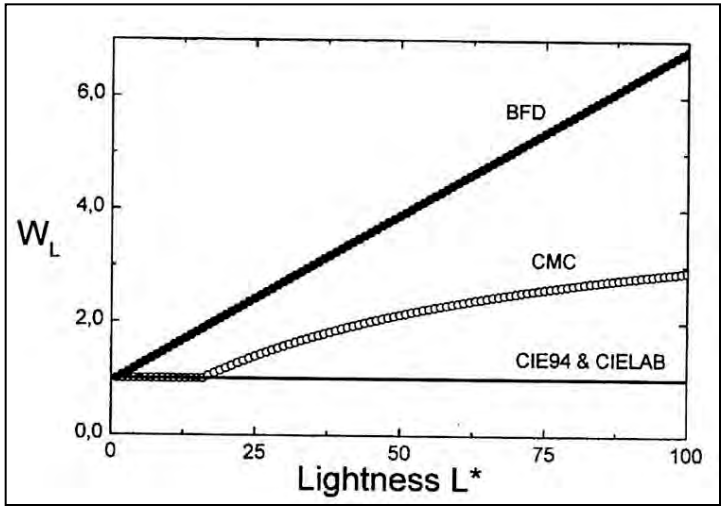
$$\Delta E_{00} = \left(\left(\frac{\Delta L^*}{S_L} \right)^2 + \left(\frac{\Delta C'}{S_C} \right)^2 + \left(\frac{\Delta H'}{S_H} \right)^2 + R_T \left(\frac{\Delta C' \Delta H'}{S_C S_H} \right) \right)^{1/2}$$

Five positional corrections to CIELAB are introduced in CIEDE2000:

- 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}
- Rotation term R_T
- New a* scale (only for color-difference purposes)

The S_L weighting function in CIEDE2000

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



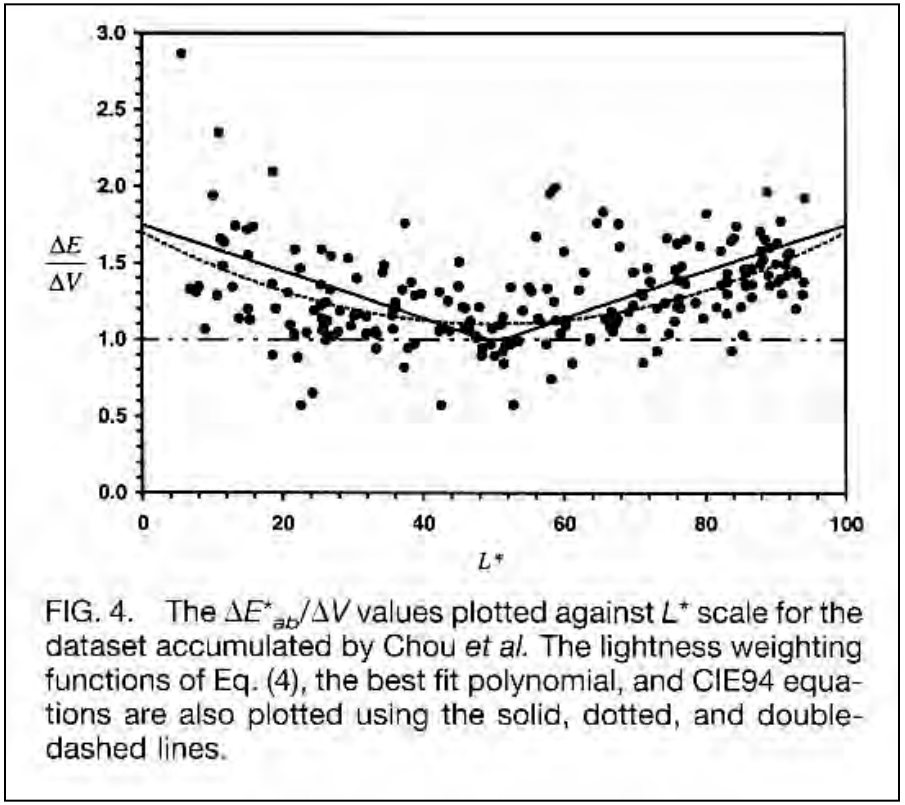
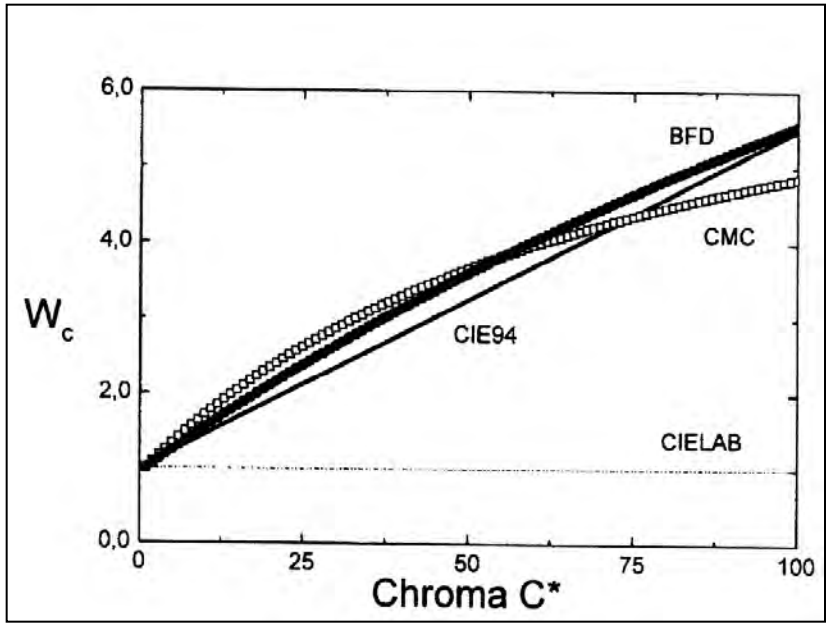
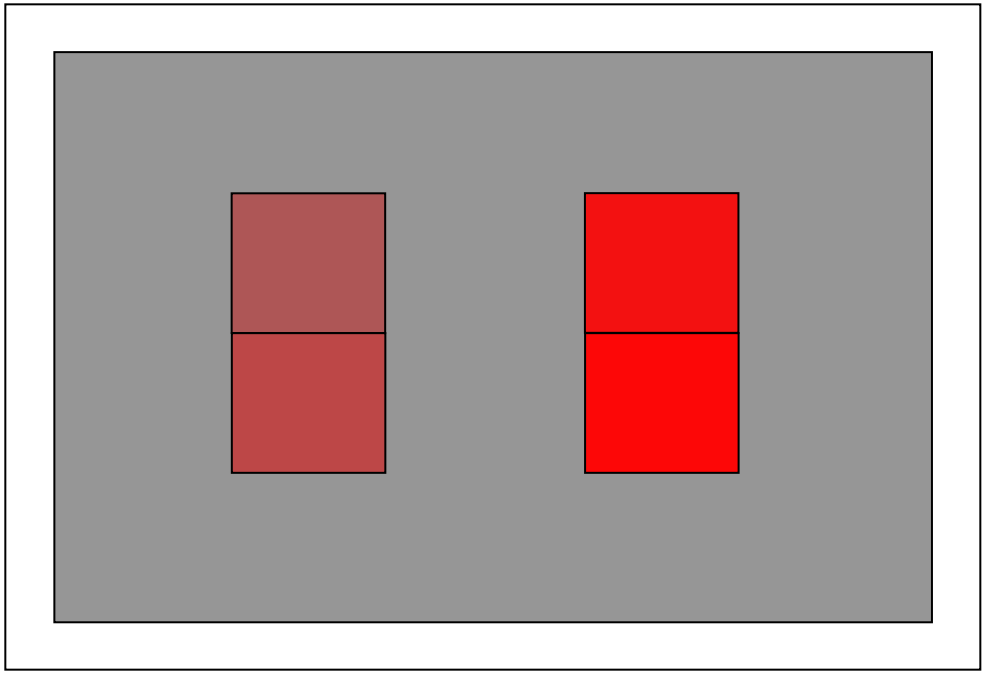


FIG. 4. The $\Delta E^*_{ab}/\Delta V$ values plotted against L^* scale for the dataset accumulated by Chou *et al.* The lightness weighting functions of Eq. (4), the best fit polynomial, and CIE94 equations are also plotted using the solid, dotted, and double-dashed lines.

- Results from Nobbs et al. (1997) moved the CIE to propose for CIEDE200 a V-shaped S_L function assuming a background with L*=50, considering also its relationship with the so-called 'crispening effect'.
- One of the major differences between CMC, BFD and CIE94 was the S_L function.

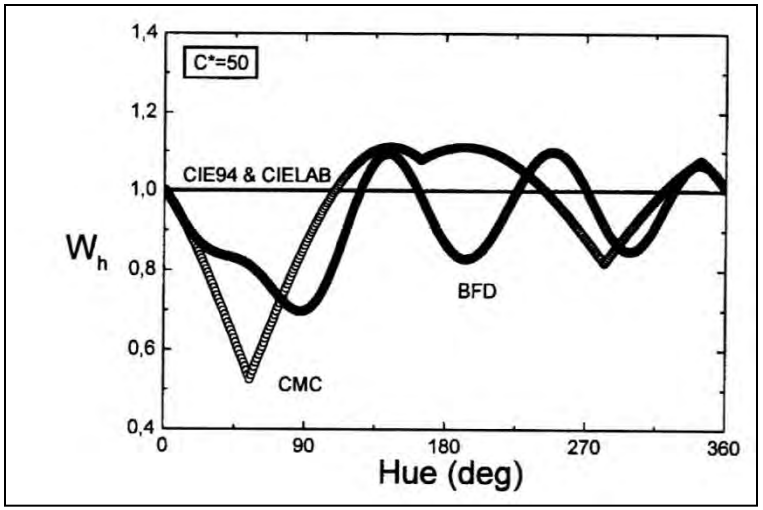
The S_C weighting function in CIEDE2000

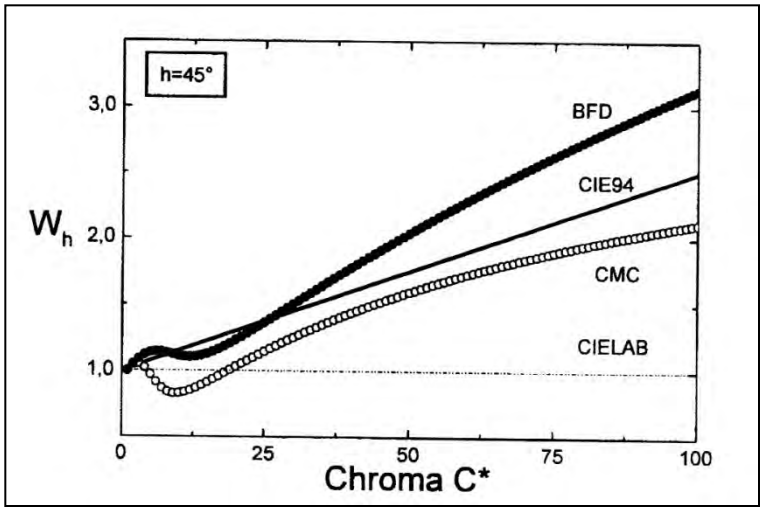




- This is the most important positional correction to CIELAB, as earlier reported by McDonald in 1974. The S_C proposed by CMC, BFD and CIE94 formulas were very similar, and CIE94 adopted the simplest (linear) dependence.

The S_H weighting function in CIEDE2000





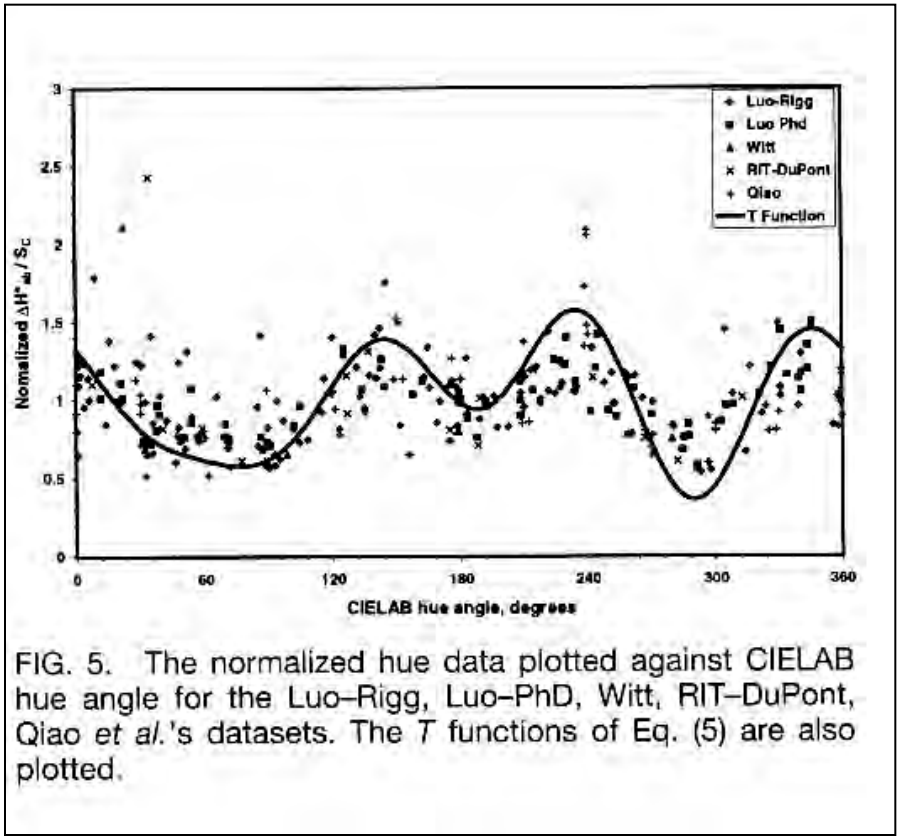
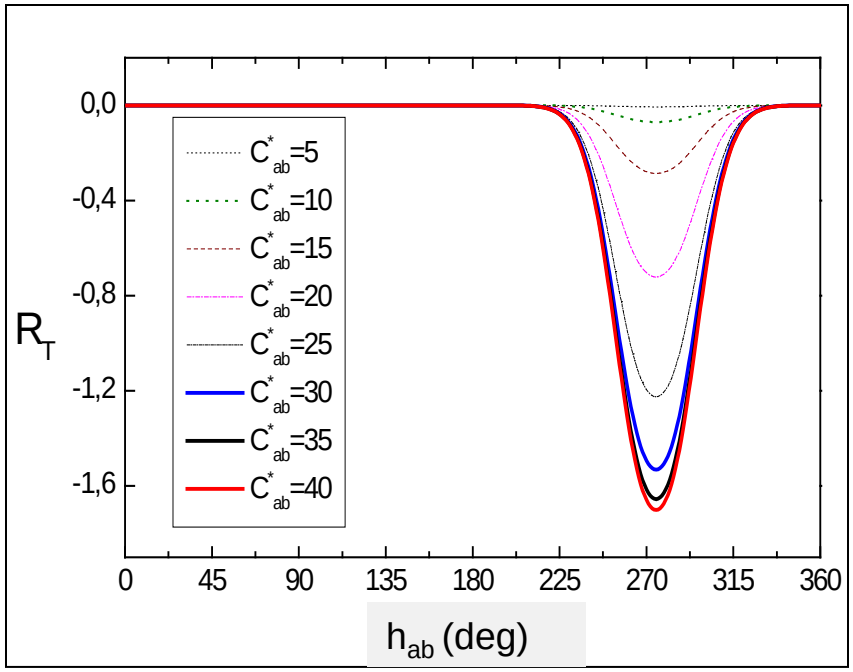
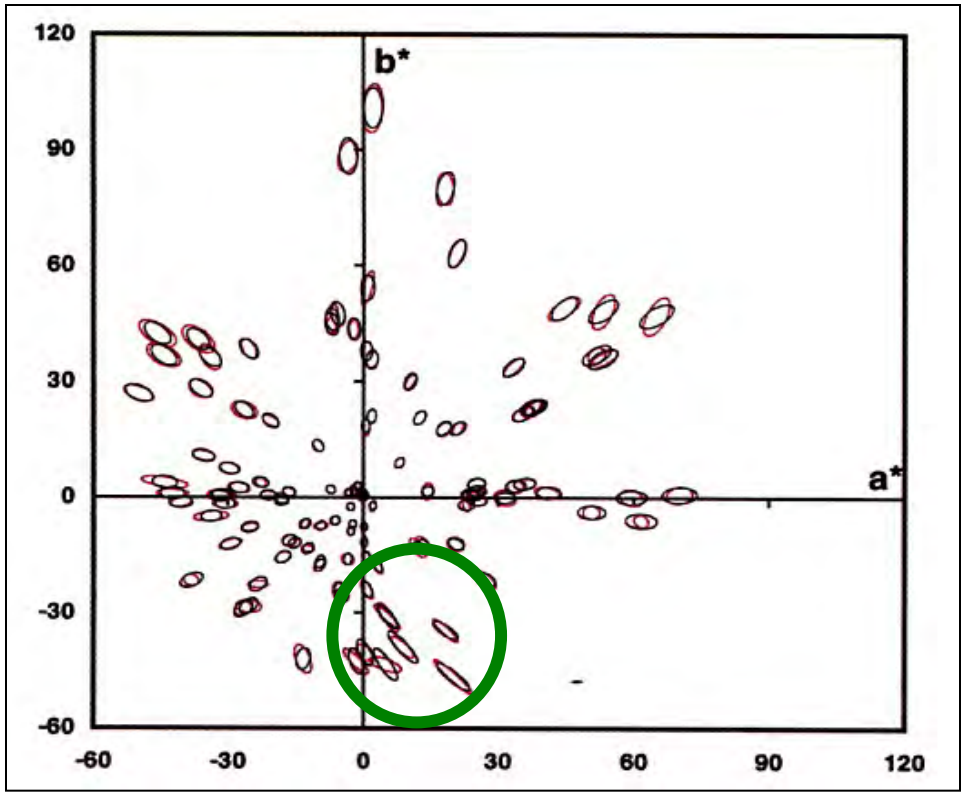


FIG. 5. The normalized hue data plotted against CIELAB hue angle for the Luo–Rigg, Luo–PhD, Witt, RIT–DuPont, Qiao *et al.*'s datasets. The *T* functions of Eq. (5) are also plotted.

- Experiments by Quiao et al. at RIT (1998) led to a hue-angle dependence in the S_H function of the CIEDE2000 formula in addition to the C^*_{ab} dependence in CIE94.

The Rotation Term R_T in CIEDE2000



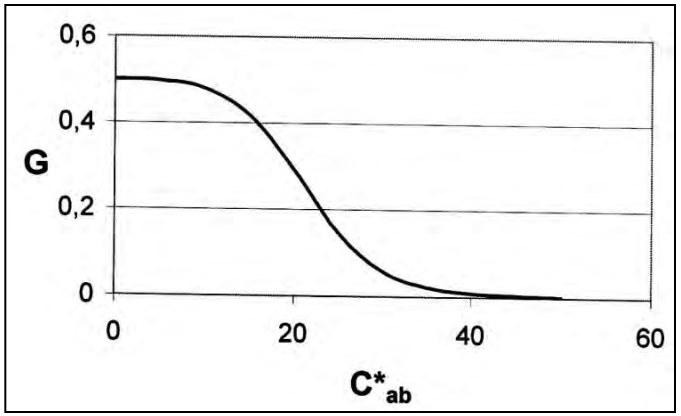


BFD and RIT-DuPont experimental ellipses (in red), and CIEDE2000 predicted ellipses (in black)

- As earlier considered by the BFD formula, the experimental ellipses in the medium-high chroma of the blue region are not in the radial direction in a*b* (as assumed by CMC or CIE94), but rotated counterclockwise.

The neutral colours correction in CIEDE2000

$$a' = a^*\left(1 + G\right)$$



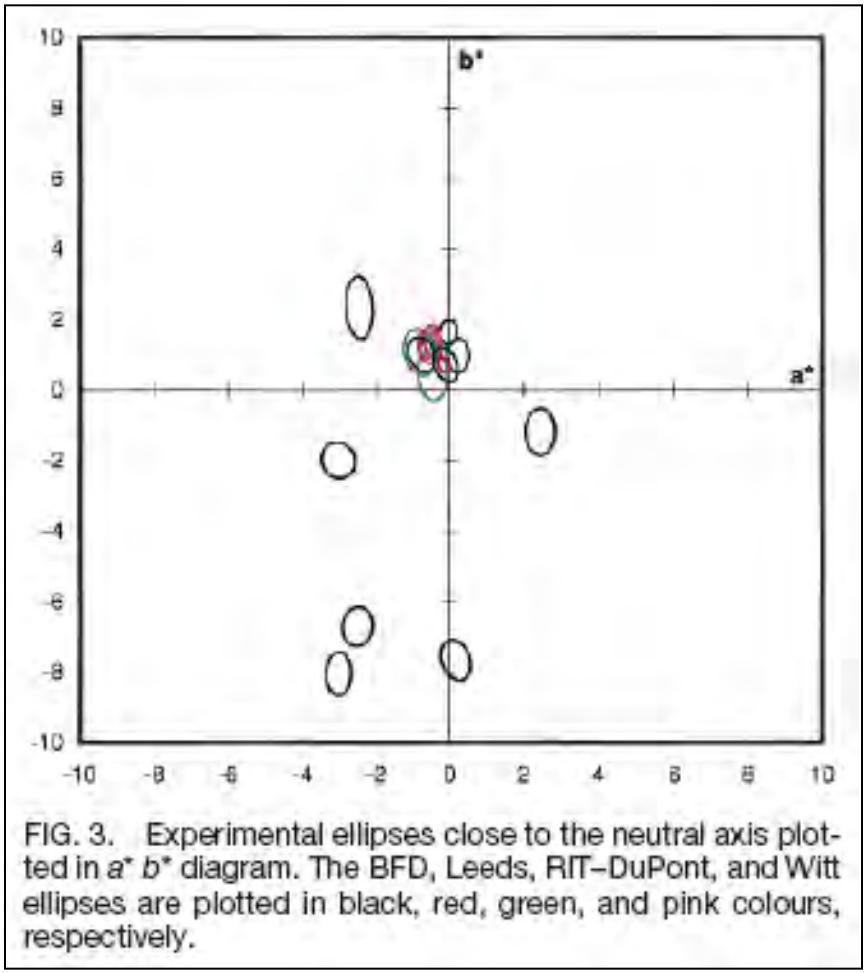


FIG. 3. Experimental ellipses close to the neutral axis plotted in a^* b^* diagram. The BFD, Leeds, RIT–DuPont, and Witt ellipses are plotted in black, red, green, and pink colours, respectively.

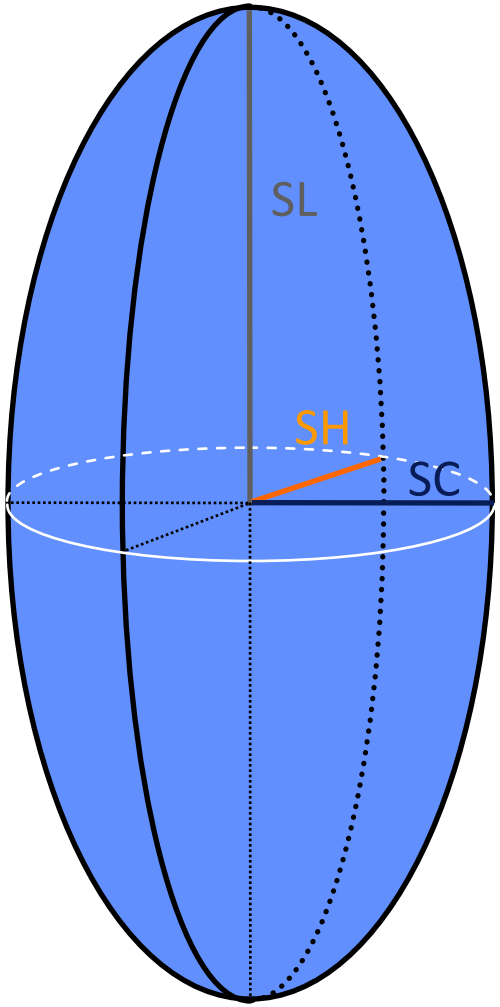
- Experimental discrimination contours in the neutral area are not circles, but ellipses vertically oriented. This modification of a* is only proposed for the specific purpose of colour-difference evaluation.

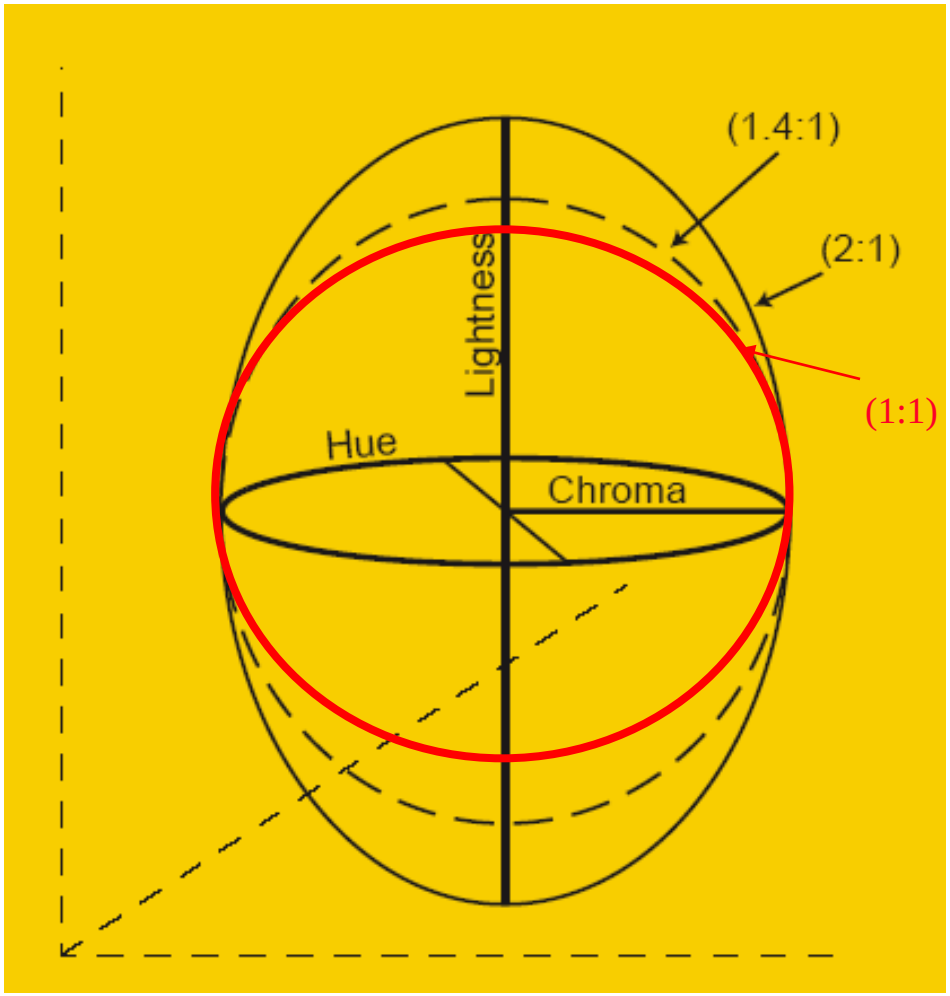
Parametric Factors using CIEDE2000

k_L=k_C=k_H=1 under 'reference conditions':

- **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 $\Delta E^*_{ab.}$**
- **Sample structure: Homogeneous (without texture)**

✓In textile industry it is common practice to use k_L=2.0





The weighting functions S_L, S_C, S_H (or the parametric factors k_L, k_C, k_H) can be interpreted as the semi-axis lengths of colour discrimination ellipsoids in CIELAB colour space.

The complexity of CIEDE2000: Is this a problem? CIEDE2000 has not an associated color space

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

$$L' = L^*$$

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

$$b' = b^*$$

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

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

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

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

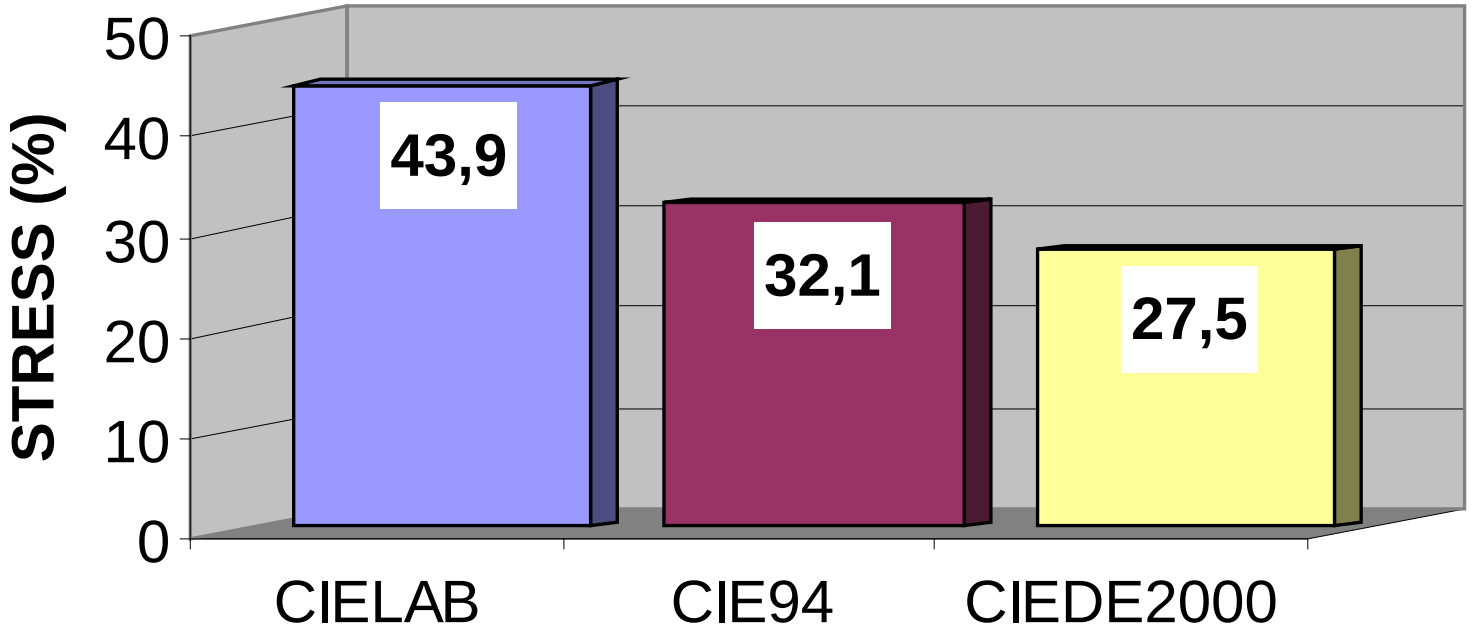
and

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

3. CIEDE2000 Performance

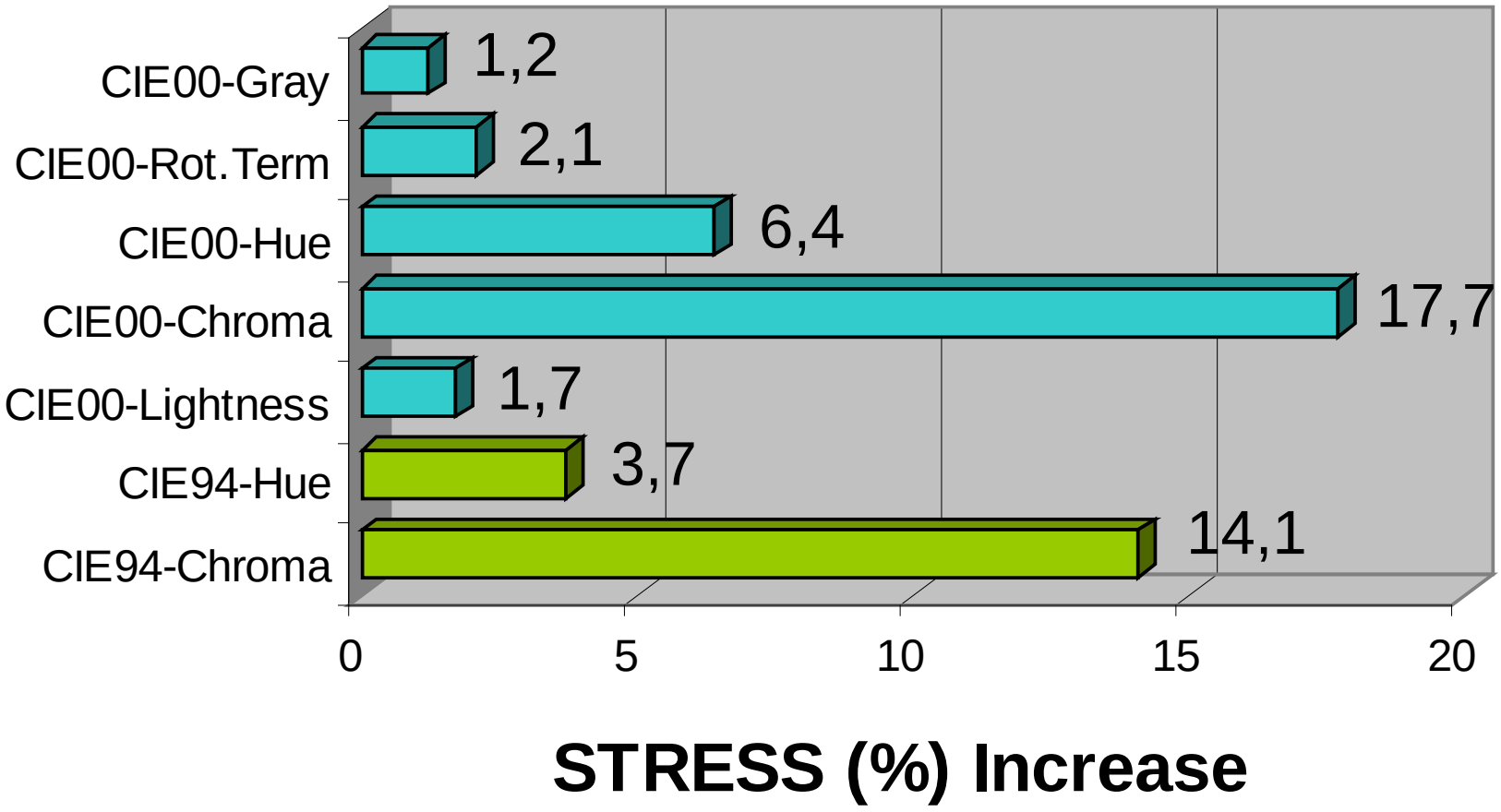
STRESS (%) for the three last CIE-recommended formulas

COM Weighted (11273 color pairs)



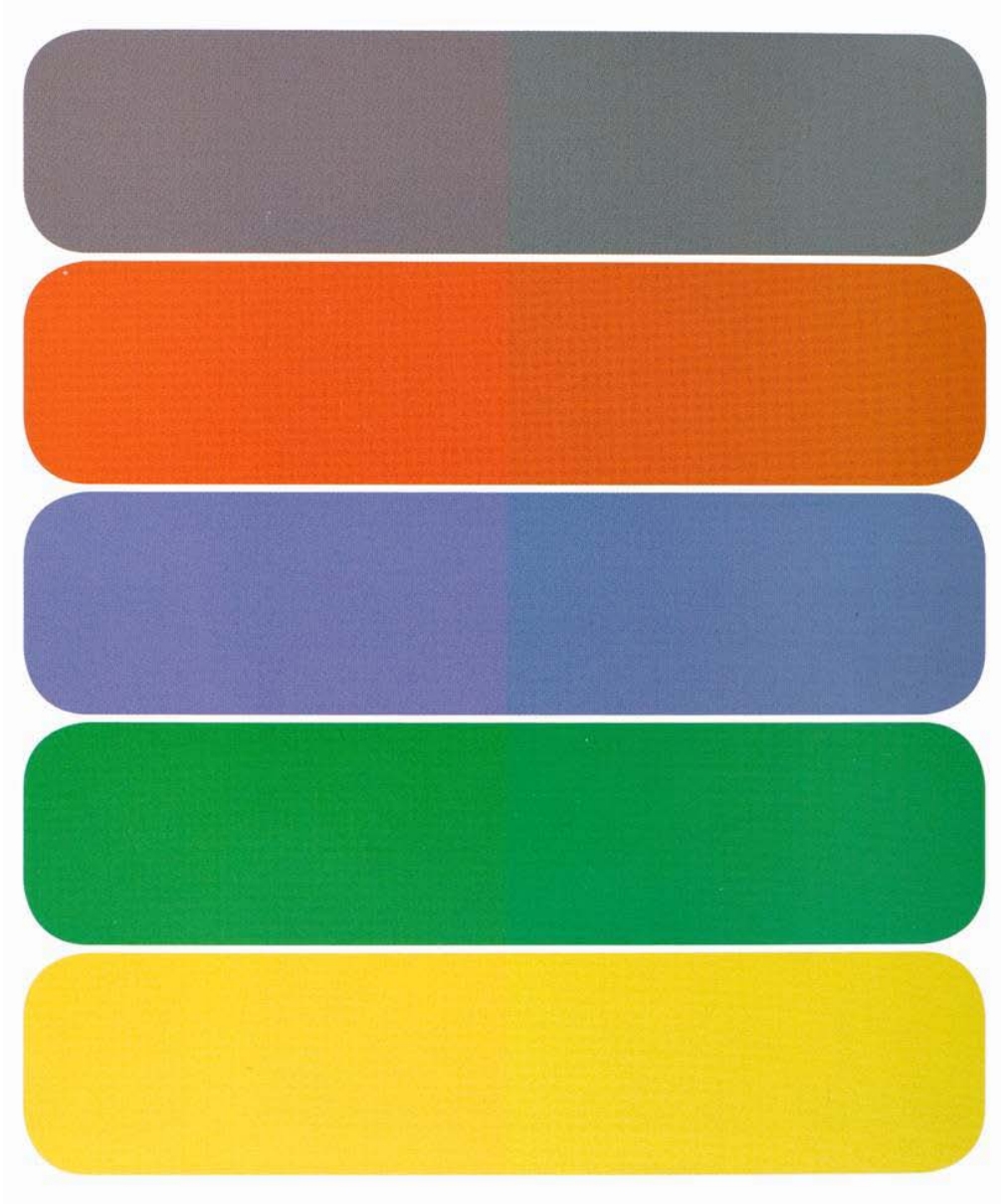
From CIELAB to CIE94 *STRESS* decreased **11.8** units.
From CIE94 to CIEDE2000 *STRESS* decreased **4.6** units (2.5 times lower).

STRESS (%) increase for reduced models & COM Weighted



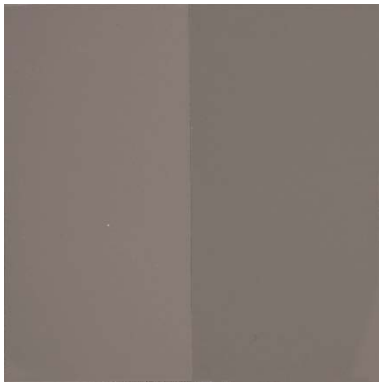
For the COM Weighted dataset each one of the corrections proposed by CIEDE2000 or CIE94 were found statistically significant at 95% confidence level.

CIEDE2000 (but not CIE94) significantly improves CMC



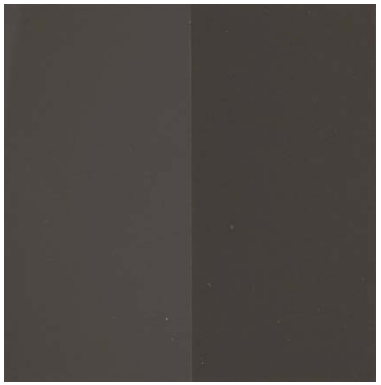
ΔE^*_{ab}	ΔE_{00}
5.5	7.9
5.4	2.6
5.6	5.1
3.9	2.0
4.1	2.4

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



#1

#2



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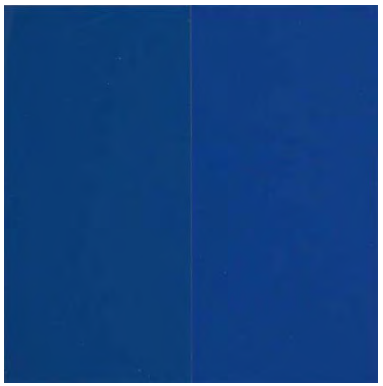

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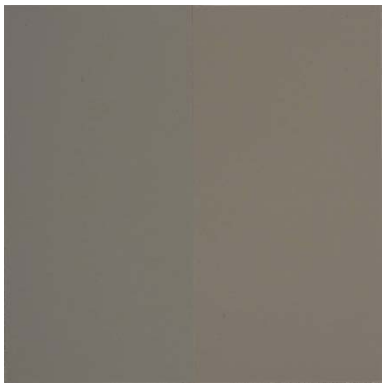

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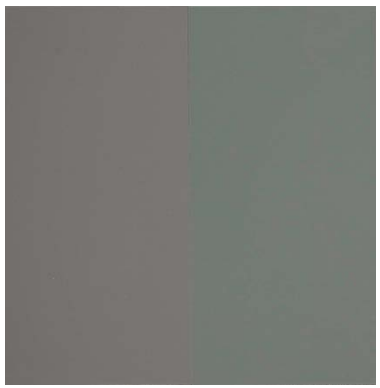
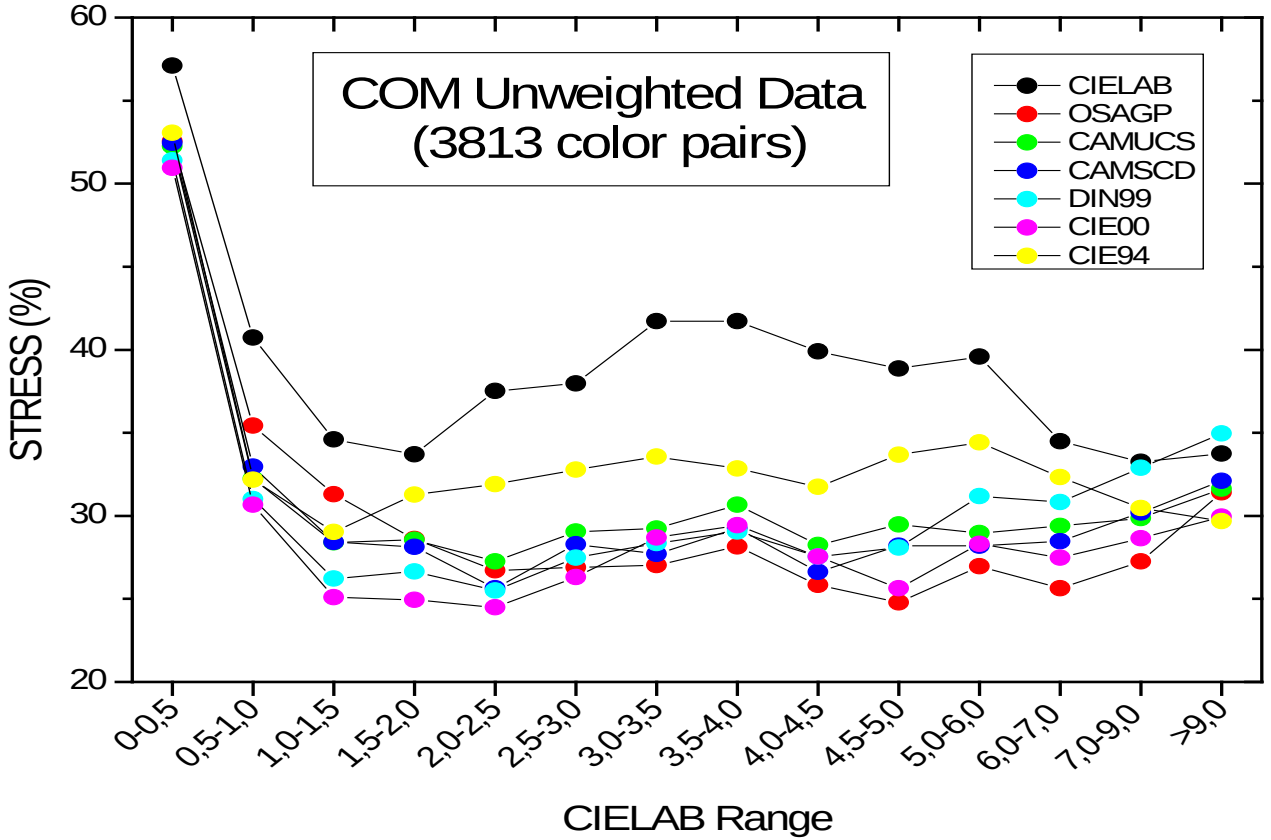


#10

10 Color Pairs produced by Dr. David H. Alman (DuPont, USA)

M. Melgosa et al. “Practical demonstration of the CIEDE2000 corrections to CIELAB using a small set of sample pairs”, Color Res. Appl. DOI 10.1002/col.21751

4. CIEDE2000, Milestone or Final Answer?



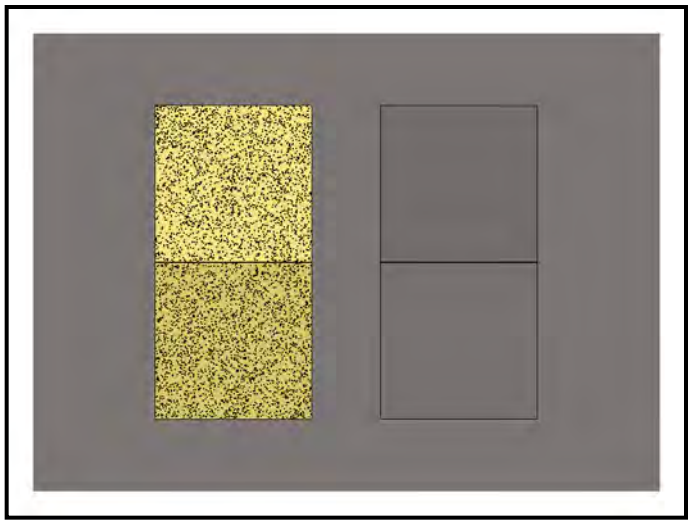
CIE TC's 1- 63 and 1-81

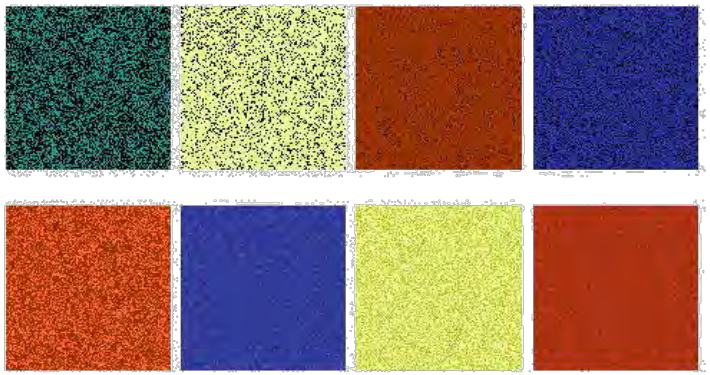
✓ The performance of all formulas strongly deteriorates below 1.0 CIELAB unit.

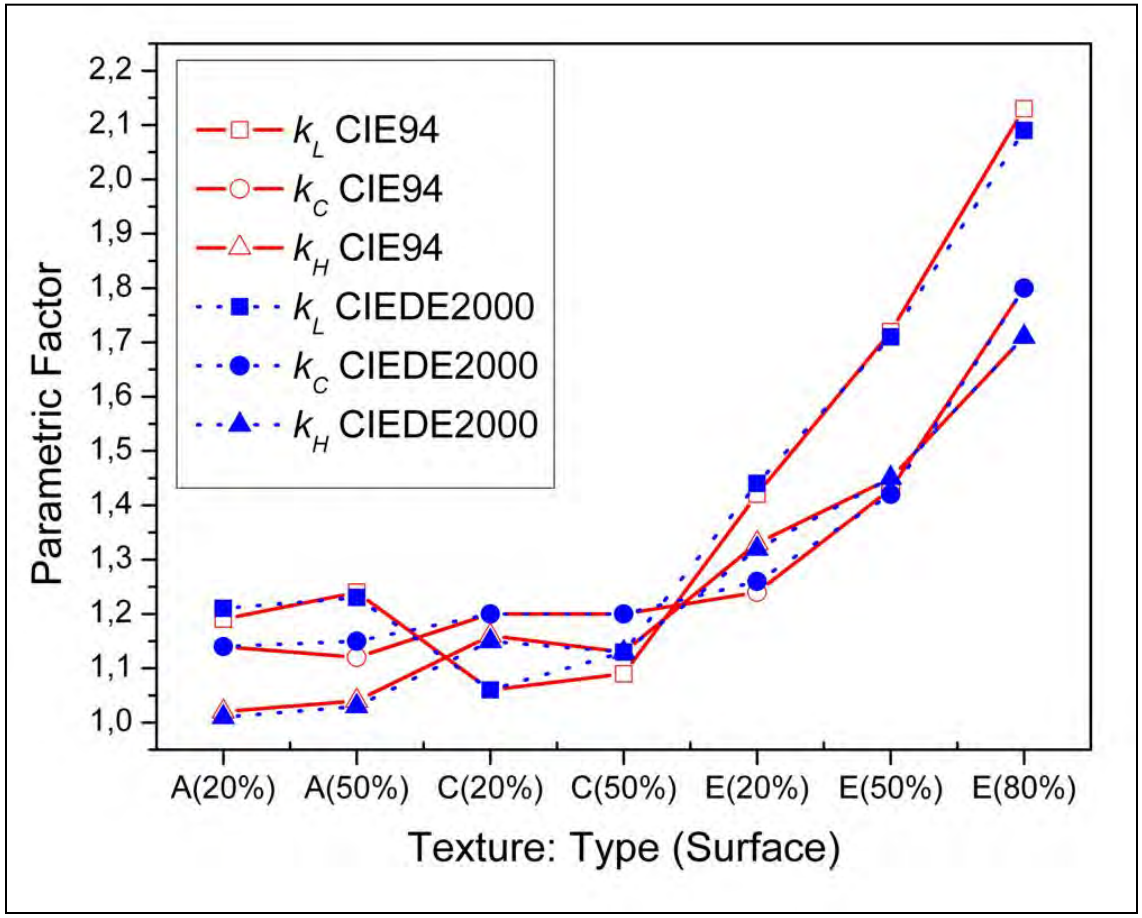
✓ At highest ranges all formulas are slightly worse (except CIELAB and CIE94).

CIE TC 1-55: Currently, we have no candidate color space (e.g. DIN99, CAM02, OSA-GP, etc.) providing statistically significant improvement upon CIEDE2000.

R. Huertas, M. Melgosa, E. Hita, “Influence of random dot textures on perception of suprathreshold color differences,” JOSA A 23, 2067-2076 (2006)







- 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).

CIE TC 8-02 and CIE Publ. 199:2011: Either CIEDE2000 (2:1:1) or CIELAB (2:1:1) is recommended for future investigation. A version of S-CIELAB is also recommended, specially for dealing with halftone or compressed images.

J. Opt. Soc. Am A. 30, 616 -626 (2013):

Color-difference evaluation for digital images using a categorical judgment method

Haoxue Liu,[1] Min Huang,[1] Guihua Cui,[2,*] M. Ronnier Luo,[3,4] and Manuel Melgosa[5]

[1]School of Printing & Packaging Engineering, Beijing Institute of Graphic Communication, Beijing 102600, China
[2]Wenzhou University, Wenzhou 325035, China
[3]Colour, Imaging and Design Research Centre, University of Leeds, Leeds LS2 9JT, UK
[4]State Key Laboratory of Modern Optical Instrumentation, Zhejiang University, Hangzhou 310027, China
[5]Departamento de Óptica, Facultad de Ciencias (Edificio Mecenas), Universidad de Granada, Granada 18071, Spain
*Corresponding author: guihua.cui@gmail.com

Specifically, CIEDE2000(2.3:1) performed the best, with a satisfactory average *STRESS* value of 25.8, which is very similar to the 27.5 value that was found from the CIEDE2000(1:1) formula for the combined weighted dataset of homogeneous color samples employed at the development of this formula [J. Opt. Soc. Am. A **25**, 1828 (2008),

Color Res. Appl. 28, 425-435 (2003):

A Top Down Description of S-CIELAB and CIEDE2000

Garrett M. Johnson,* Mark D. Fairchild

Munsell Color Science Laboratory, Chester F. Carlson Center for Imaging Science, Rochester Institute of Technology, Rochester, NY 14623

Color Res. Appl. 27, 126-128 (2002)

COMMUNICATIONS AND COMMENTS

ROLF G. KUEHNI
4112 Blaydes Court
Charlotte, NC 28226
DOI 10.1002/col.10035

CIEDE2000, Milestone or Final Answer?

Further Comments on CIEDE2000

M. R. LUO, G. CUI, AND B. RIGG
DOI 10.1002.col.10043

"The CIEDE2000 formula may not be the final word with respect to a colour difference formula for small colour differences for industry... The experimental data on which the formula is based are far from perfect… However, at the present time the formula represents the best that can be achieved… In our view, CIEDE2000 is timely because there are two different formulae (CMC and CIE94) being widely used at present. This is clearly unsatisfactory. The new formula offers significant improvements over both… **Progress on unresolved questions requires different viewpoints being put forward to stimulate new ideas."**

Thank you!

Manuel Melgosa, Department of Optics, University of Granada (Spain)

Email: mmelgosa@ugr.es

Acknowledgment: Research Project FIS2010-19839

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