Colour in the CIE

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Department of Colour Science
University of Leeds
Colour and the CIE

- The CIE – Introduction
- The CIE – Past Achievements
- The CIE – Future Goals
Origin of the CIE

- Commission Internationale de Photométrie
- International Gas Congress, Paris, 1900
- 400 gas engineers
- … methods of measuring light given by incandescent gas lamps
- … the unification of screw threads of gas fittings!
- Next met in Zurich in 1903
- … and then in Zurich in 1907
Origin of the CIE

• … and then in Zurich in 1911!
• … if the radiation from a source were weighted in accordance with the sensitivity of the eye it would provide a measure of the light from the source …
• … but it was necessary to determine the sensitivity of the eye
• … led to a widening of the scope of the CIP
Origin of the CIE

• Commission Internationale de l’Eclairage
• International Commission on Illumination
• First met in Berlin in 1913
• … matters relating to science, technology and art in the fields of light and lighting …
• … embraces such fundamental subjects as vision, photometry and colorimetry …
Origin of the CIE

• ... met in Geneva in 1924 ...
• ... the relative luminous efficiency of radiation, $V(\lambda)$
• ... leading to the standard photometric observer
CIE Photopic Spectral Luminous Efficiency Function $V(\lambda) - 1924$
1. Vision and colour
2. Measurement of light and radiation
3. Interior environment and lighting design
4. Lighting and signalling for transport
5. Exterior lighting
6. Photobiology and photochemistry
7. General aspects
8. Image technology
CIE Division 1

• D1 Vision & Colour
  • To study visual responses to light and to establish standards … relevant to photometry, colorimetry, colour rendering, visual performance and visual assessment of light and lighting.
  • 33 member countries
  • 24 technical committees
  • 12 reporters
CIE Division 1 - Meetings

- 2007: Beijing, China
- 2008: Stockholm, Sweden
- 2009: Budapest, Hungary
- 2010: ?
- 2011: Sun City, South Africa
CIE Division 1 - People

- Director: Prof M Ronnier Luo
- AD Colour: Dr Ellen Carter
- AD Vision: Prof Miyoshi Ayama
- Secretary: Dr Mike Pointer
Colour and the CIE

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CIE 1924

6th Session, Geneva, 1924
Set up a Study Group on Colorimetry

… in response to industry’s need of a unified system for colour measurement
1. Standard observer functions
2. Standard sources: A, B, C
3. Illuminating and viewing conditions, $45^\circ:0^\circ$
4. Primaries of X,Y,Z system
CIE 2° Observer

- John Guild
  The National Physical Laboratory

- W David Wright
  Imperial College of Science & Technology
CIE 2° Standard Observer $x, y, z$ Colour Matching Functions - 1932

![Graph showing the relative value of $x$, $y$, and $z$ functions over different wavelengths. The graph displays three curves: $x$ bar 2, $y$ bar 2, and $z$ bar 2.]
CIE (Standard) Sources

Full radiator
@ 2856 K

Direct sunlight
@ 4874 K

Average daylight
@ 6774 K
CIE Colorimetric System

\[ P(\lambda) \quad R(\lambda) \quad \bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda) \]
CIE Colorimetric System

\[ X = k \int P(\lambda) R(\lambda) \bar{x}(\lambda) d\lambda \]
\[ Y = k \int P(\lambda) R(\lambda) \bar{y}(\lambda) d\lambda \]
\[ Z = k \int P(\lambda) R(\lambda) \bar{z}(\lambda) d\lambda \]
Earliest application:

- CIE 1935, Berlin
- Signal lights for road, rail, aviation
CIE Scotopic Spectral Luminous Efficiency Function $V'(\lambda)$ - 1951

- Maximum at 505 nm
- Purkinje Shift
- Relative Sensitivity
- Wavelength (nm)
CIE 1957

- CIE Publication 1.1: 1957
- International Lighting Vocabulary
- English, French, German
1941 W D Wright 1942 D L MacAdam

**Fig. 56.** Subjectively equal colour steps plotted in the C.I.E. chromaticity chart. The lines represent a colour difference about three times greater than the just noticeable difference for a 2° field (Wright)

**Fig. 57.** Sensitivity to chromaticity differences expressed in terms of the standard deviations of colour matching. The ellipses represent the standard deviations multiplied by a factor of 10. Results are for one observer (After MacAdam)

CIE 1959

14th Session, Brussels, Belgium, 1959

- $u,v$ chromaticity system
CIE 1963

15th Session, Vienna, Austria, 1963
Supplementary standard observer –
the 10° observer
CIE 10° Standard Observer $x, y, z$ Colour Matching Functions - 1964
\[ W^* = 25 \ Y^{1/3} \]
\[ U^* = 13 \ W^* \ (u - u_0) \]
\[ V^* = 13 \ W^* \ (v - v_0) \]

\[ \Delta E^* = (\Delta U^*^2 + \Delta V^*^2 + \Delta W^*^2)^{1/2} \]
CIE Standard Illuminant D65

The graph shows the relative spectral power distribution of the CIE Standard Illuminant D65. The x-axis represents wavelength in nanometers, ranging from 350 to 800 nm. The y-axis represents relative spectral power. Two curves are plotted: D65 (blue) and SC (green).
CIE 1965

CIE Colour Rendering Index

3000 K  3500 K  4100 K  5000K
SON  HMI  SOX  Tungsten
CIE 1965

CIE Colour Rendering Index

Special Index

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

General Index

$$CRI = \frac{1}{8} \sum (\Delta R_i)$$
• CIE Document 15, *Colorimetry*, 1971
CIE 1975


$u'$, $v'$ uniform chromaticity diagram
CIE 1975

CIELAB, CIELUV uniform colour spaces
Associated colour-difference formulae

\[ \Delta E_{ab}^* = \sqrt{\left(\Delta L^*\right)^2 + \left(\Delta a^*\right)^2 + \left(\Delta b^*\right)^2} \]

\[ \Delta E_{uv}^* = \sqrt{\left(\Delta L^*\right)^2 + \left(\Delta u^*\right)^2 + \left(\Delta v^*\right)^2} \]
20th Session, Amsterdam, Netherlands, 1983

CIE Division structure established:

Technical committees

Reporters
CIE 1986

• CIE Document 15, *Colorimetry*, 1972
• CIE Document 15.2, *Colorimetry*, 1986
CIE 94 Colour Difference Formula

\[ \Delta E^* = \sqrt{\left( \frac{\Delta L^*}{k LS_L} \right)^2 + \left( \frac{\Delta C_{ab}^*}{k CS_C} \right)^2 + \left( \frac{\Delta H_{ab}^*}{k HS_H} \right)^2} \]
CIECAM97s

Chromatic adaptation

Cone response

Surround induction

Sample $X, Y, Z$

CIECAM Model

White $X_w, Y_w, Z_w$

Surround $Y_b$

Source $L_A$

Correlates of:
- redness/greenness, $a$
- yellowness/blueness, $b$
- brightness, $Q$
- lightness, $J$
- colourfulness, $M$
- chroma, $C$
- saturation, $s$
- hue angle, $h$
- hue composition, $H$
CIE 2000

CIE DE2000 Colour Difference Formula

\[ \Delta E^* = \sqrt{\left(\frac{\Delta L^*}{k_L S_L}\right)^2 + \left(\frac{\Delta C_{ab}^*}{k_C S_C}\right)^2 + \left(\frac{\Delta H_{ab}^*}{k_H S_H}\right)^2 + \left(\frac{\Delta C_{ab}^* \Delta H_{ab}^*}{k_{CH} S_{CH}}\right)^2}\]
• CIE Document 15, \textit{Colorimetry}, 1972
• CIE Document 15.2, \textit{Colorimetry}, 1986
• CIE Document 15:2004, \textit{Colorimetry}
CIE 15:2004 Colorimetry

- CIE illuminants
- CIE geometry
- CIE standard observer
- Calculation of tristimulus values
- Uniform colour spaces
- Colour difference equations
- Tables of data for lamps
  - Fluorescent
  - High pressure
CIE $10^\circ$ Photopic Spectral Luminous Efficiency Function $V_{10}(\lambda)$ - 2005

Maximum at 555 nm
CIE
COMMISSION INTERNATIONALE DE L'ECLAIRAGE
INTERNATIONAL COMMISSION ON ILLUMINATION
INTERNATIONALE BELEUCHTUNGSKOMMISSION

TECHNICAL REPORT
A FRAMEWORK FOR THE MEASUREMENT OF VISUAL APPEARANCE

CIE 175:2006
GDC: 612.64
Descriptor: Physiological optics, vision
Colour and the CIE

• The CIE – Introduction
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Uniform Colour Spaces

\[
L = f(Y / Y_n)
\]

\[
a = f(X / X_n, Y / Y_n)
\]

\[
b = f(Y / Y_n, Z / Z_n)
\]
Colour Categorisation

FIG. 5. Predicted elemental hue sensations plotted on the radial lines of the Munsell hues of $V = 4$, 6, and 8 for 1000, 1, and 0.1 lx, respectively.
LED Colour Rendering

Incandescent lamp

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>CRI</th>
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<tbody>
<tr>
<td>2779</td>
<td>98.8</td>
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Tri-band fluorescent

<table>
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<tr>
<th>Temperature (K)</th>
<th>CRI</th>
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<tr>
<td>2780</td>
<td>74.6</td>
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</table>

RGB LED cluster

<table>
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<tr>
<th>Temperature (K)</th>
<th>CRI</th>
</tr>
</thead>
<tbody>
<tr>
<td>2795</td>
<td>39.7</td>
</tr>
</tbody>
</table>
Contrast Sensitivity Functions

Log(Relative Sensitivity) vs. Log(Cycles per Degree)

- younger (20–29 years old)
- older (70–79 years old)
- low vision (average)

Visible ranges at 10% contrast for:
- younger people
- older people
- low vision

Spatial frequency (cycles/degree)
Whiteness

- Whiteness:
  \[ W = Y + 800(x_p - x) + 1700(y_p - y) \]

- Tint:
  \[ T = 1000(x_p - x) - 650(y_p - y) \]
  
  \( T \uparrow \) Greenish, \( T \downarrow \) Reddish

- \( x_p, y_p = D65/10^\circ \)
Effect of Size
Effect of Light Level

- Practical mesopic model
  \[ V_m(\lambda) = x \, V(\lambda) + (1 - x) \, V'(\lambda) \]

- Chromatic mesopic model
  \[ V_m(\lambda) = a_1 \, V(\lambda) + a_2 \, V'(\lambda) + a_3 [L(\lambda) - a_4 M(\lambda)] + a_5 S(\lambda) \]
Effect of Age
Colour Gamut - sRGB
Colour Gamuts

- CIELAB Chroma, C*
- CIELAB Lightness L*

hue = 200
\[ X, Y, Z = k \int S(\lambda) R(\lambda) \bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda) d\lambda \]

CIELAB

CIELUV

CIEDE2000

\[ \Delta E^* = \sqrt{\left( \frac{\Delta L^*}{k_L S_L} \right)^2 + \left( \frac{\Delta C_{ab}^*}{k_C S_C} \right)^2 + \left( \frac{\Delta H_{ab}^*}{k_H S_H} \right)^2 + \left( \frac{\Delta C_{ab}^* \Delta H_{ab}^*}{k_{CH} S_{CH}} \right)^2} \]
CIE/ISO Standards

- ISO 11664-1: 2008(E)/CIE S 014-1/E: 2006: *Colorimetry – Part 1, CIE Standard colorimetric observers*
- *Colorimetry – Part 3, Calculation of tristimulus values*
- *Colorimetry – Part 5, Calculation of colour difference*
In Addition …

- Improved colour matching functions
- Tristimulus integration
- Redefining the D illuminants
- Range of the CIEDE2000 colour difference formula
- Terminology
Division 8: Image Technology

Original scene
Division 8: Image Technology

Original scene
CIECAM02

Sample $X,Y,Z$

Chromatic adaptation

Cone response

Surround induction

White $X_w,Y_w,Z_w$

Surround $Y_b$

Source $L_A$

Correlates of:
- redness/greenness, $a$
- yellowness/blueness, $b$
- brightness, $Q$
- lightness, $J$
- colourfulness, $M$
- chroma, $C$
- saturation, $s$
- hue angle, $h$
- hue composition, $H$
Colour Difference for Imaging

1. Different examples of the same technology
2. Cross media
Gamut Mapping

L = 100

L = 0

-a
+b
+a
-b

www.drycreekphoto.com
Gamut Mapping

[Diagram showing color gamuts and mapping techniques]
Mixed Illumination

Soft copy

Hard copy
Multispectral Imaging

Original

Image
Spatial Appearance Models

Spatial effects:
- Sharpness
- Contrast
- Graininess

Colour effects:
- Hue
- Chroma
- Lightness

Image
In Addition …

- Improvements to CIECAM02
- High dynamic-range imaging
- Image archiving
- Video compression assessment
- Office illumination for imaging
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References

• CIE Publication 82, CIE History 1913-1988, 1989


Colour Appearance

- TC 1-74 Measurement of Appearance Network - MaPNet
- Committee Report – January 2009
- Summary of Lecture: www.npl.co.uk
- Contact me: mrpointer@btinternet.com
Thank you very much!
Methods for re-defining CIE D illuminants

TC1-74
Real colour gamuts

TC1-73
Measurement of appearance network: MApNet

TC1-72
Tristimulus integration

TC1-71
Metameric samples for indoor daylight evaluation

TC1-70
Colour rendition by white light sources

TC1-69
Effect of stimulus size on colour appearance

TC1-68
Indoor daylight illuminant

TC1-66
Terminology for vision, colour and appearance

TC1-64
Validity of the range of CIEDE2000

TC1-63
Categorical colour identification

TC1-61
Standards in colorimetry

TC1-57
Improved colour matching functions

TC1-56
Uniform colour space for industrial colour difference evaluation

TC1-55
Practical daylight simulators for colorimetry

TC1-44
Colour appearance for reflection/VDU comparison

TC1-27
The effect of dynamic and stereo visual images on human health

TC1-36  Fundamental chromaticity diagram
TC1-37  Supplementary system of photometry
TC1-41  Extension of V(\lambda) beyond 830nm
TC1-42  Colour appearance in peripheral vision
TC1-54  Age-related change of visual response
TC1-58  Visual performance in the mesopic range
TC1-60  Contrast sensitivity function
TC1-67  The effect of dynamic and stereo visual images on human health
D1 Reporters

R1-19  Specification on individual variation in heterochromatic matching
R1-32  Emotional aspects of colour and light
R1-36  Action spectra for glare
R1-37  Definition of visual field for conspicuity
R1-38  Concept and application of equivalent luminance
R1-39  Alternative forms of the CIEDE2000 colour difference equation
R1-40  Scene dynamic range
R1-42  Extensions of CIECAM02
R1-43  Standard deviate observer
R1-44  Limits of normal colour vision
R1-46  Evaluation of whiteness
R1-47  Hue angles of elementary colours
<table>
<thead>
<tr>
<th>TC8-02</th>
<th>Colour difference evaluation in images</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC8-07</td>
<td>Multi-spectral imaging</td>
</tr>
<tr>
<td>TC8-08</td>
<td>Spatial appearance models</td>
</tr>
<tr>
<td>TC8-09</td>
<td>Image archiving</td>
</tr>
<tr>
<td>TC8-10</td>
<td>Office illumination for imaging</td>
</tr>
<tr>
<td>TC1-58</td>
<td>CIECAM02 mathematics</td>
</tr>
<tr>
<td>R8-08</td>
<td>Image appearance model framework</td>
</tr>
</tbody>
</table>