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# CIE 170-2 Cone-Fundamental-Based Colorimetry and Photometry

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1. Introduction
2. CIE 1931 Colorimetry
3. CIE 2006 Colorimetry (CIE 170 : Cone-Fundamental-Based Colorimetry and Photometry)
4. Current and Future CIE activities

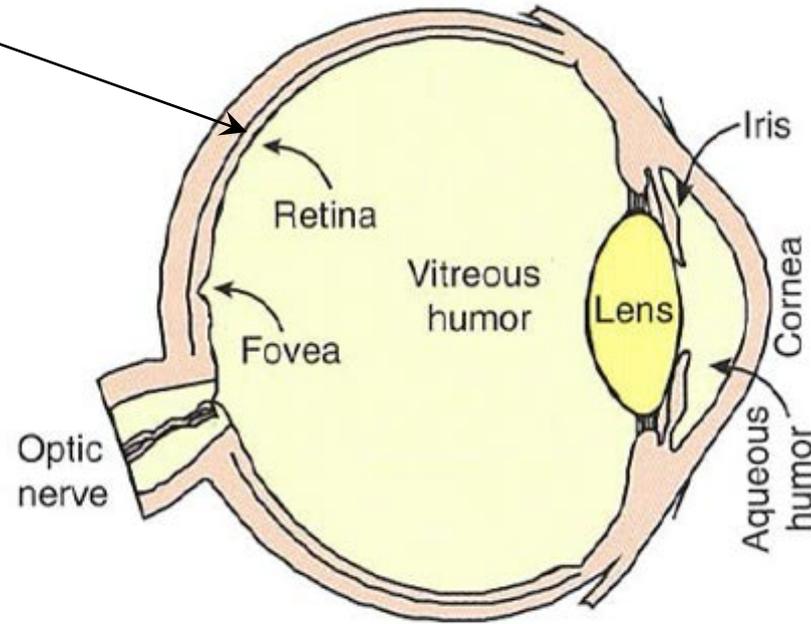
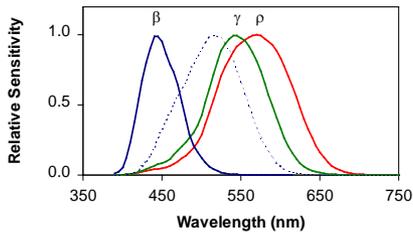
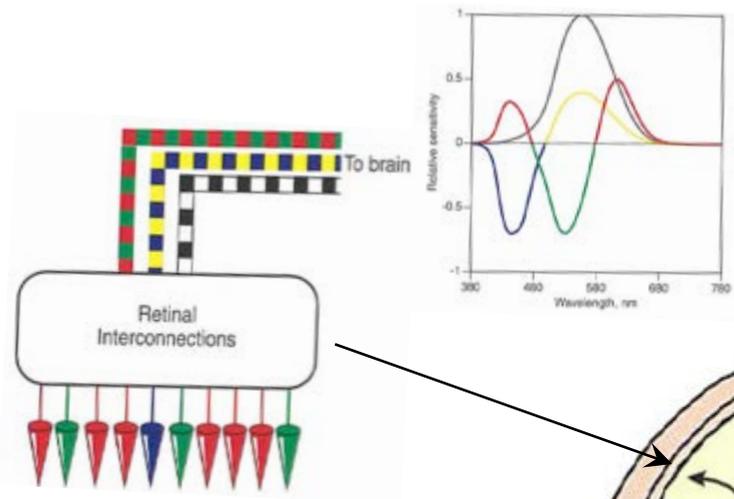


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# Human Visual System

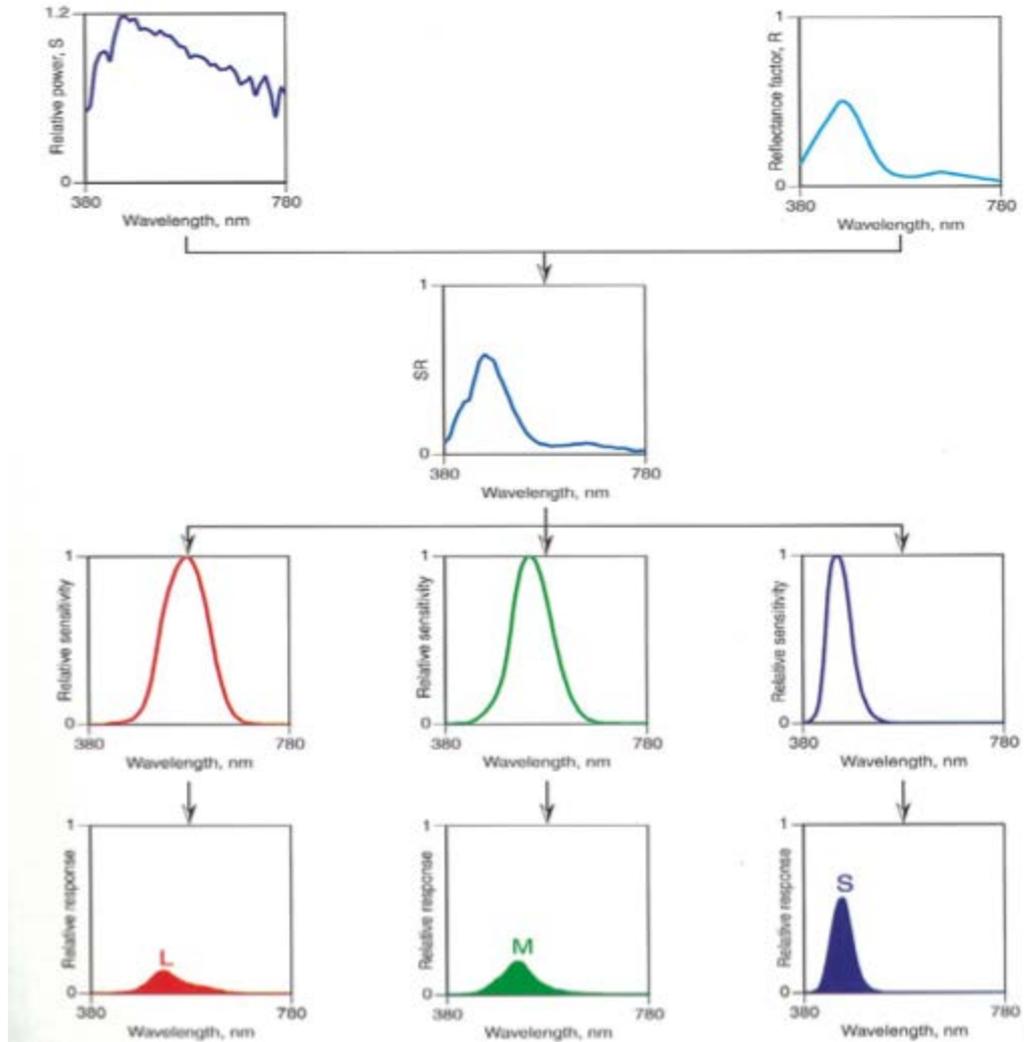
1. Luminance Channel (L+M+S)
  - High spatial resolution
2. Red-Green Channel (L-M)
3. Yellow-Blue Channel (L+M-S)
  - Low spatial resolution



Retinal  
Photoreceptors  
: Cones (L,M,S) & Rods

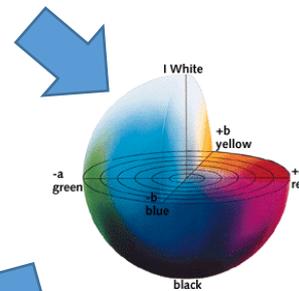
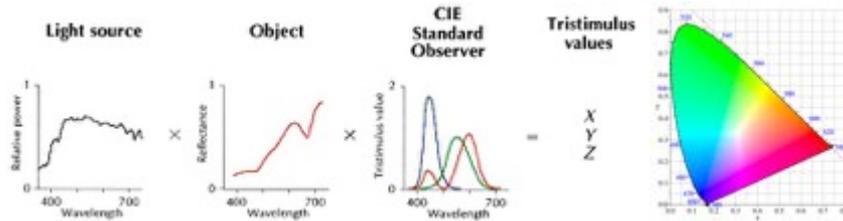
The cross section of the human eye.

# Trichromacy

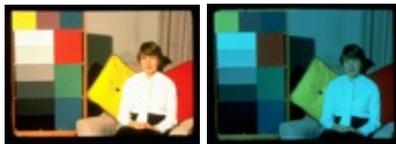


# Brief History of CIE Colorimetry

Color specification **CIE 1931 Chromaticity (XYZ, Yxy)**



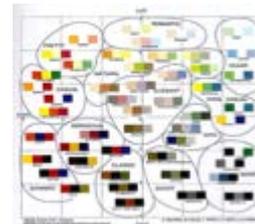
Uniform Color Space  
**CIELAB, CIELUV**  
Color Difference  
Equation  
**CIEDE2000,**



Color Appearance  
Model  
**CIECAM02**

Color/Lighting Quality, Preference, Emotion

Visual  
Appearance  
Model

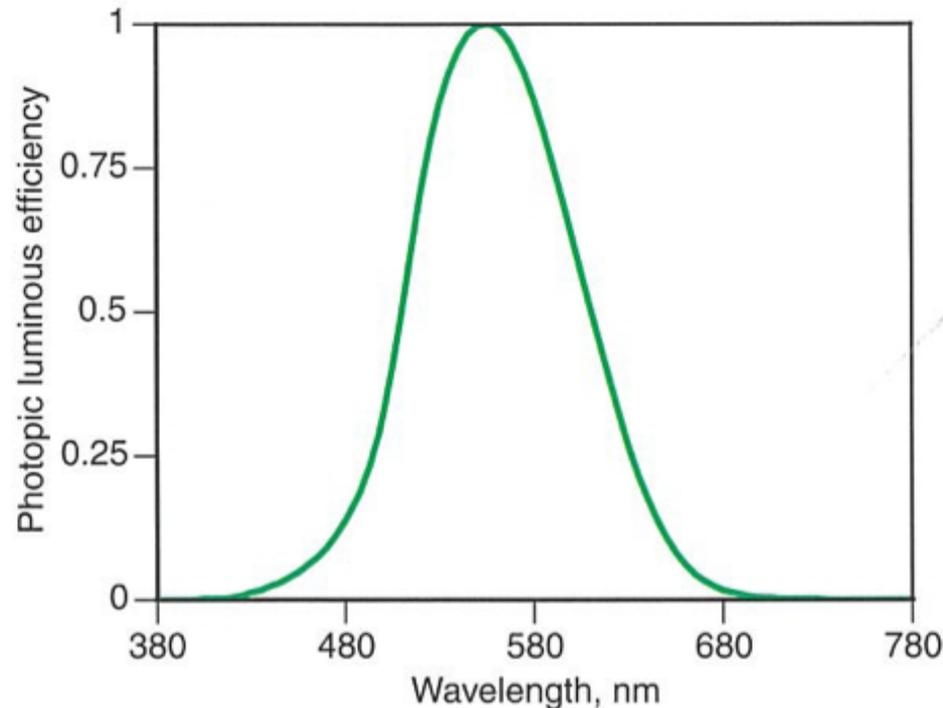




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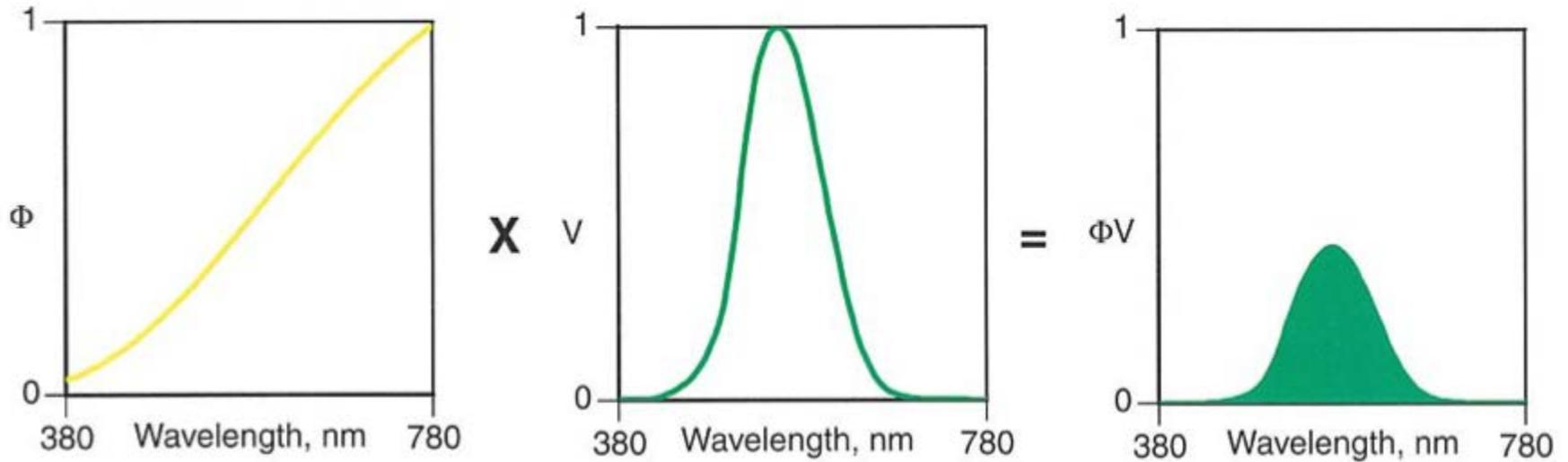
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# 1924 CIE Standard Photometric Observers : $V(\lambda)$



- 1924  $V(\lambda)$  function is too low in the blue part of the spectrum.
- A corrected  $V_M(\lambda)$  function has been officially accepted by the CIE in 1988 (CIE, 1990).

# Calculating Photopic Quantities



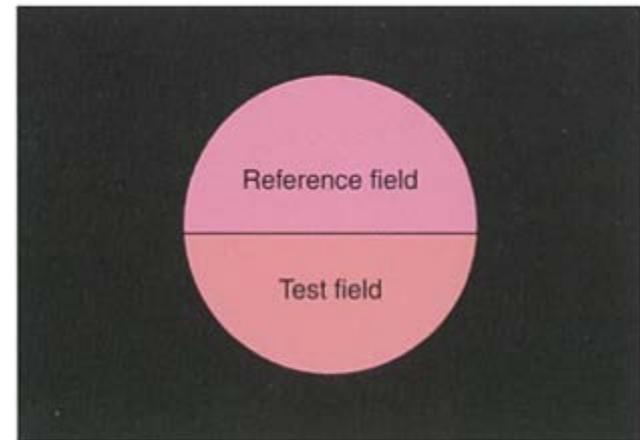
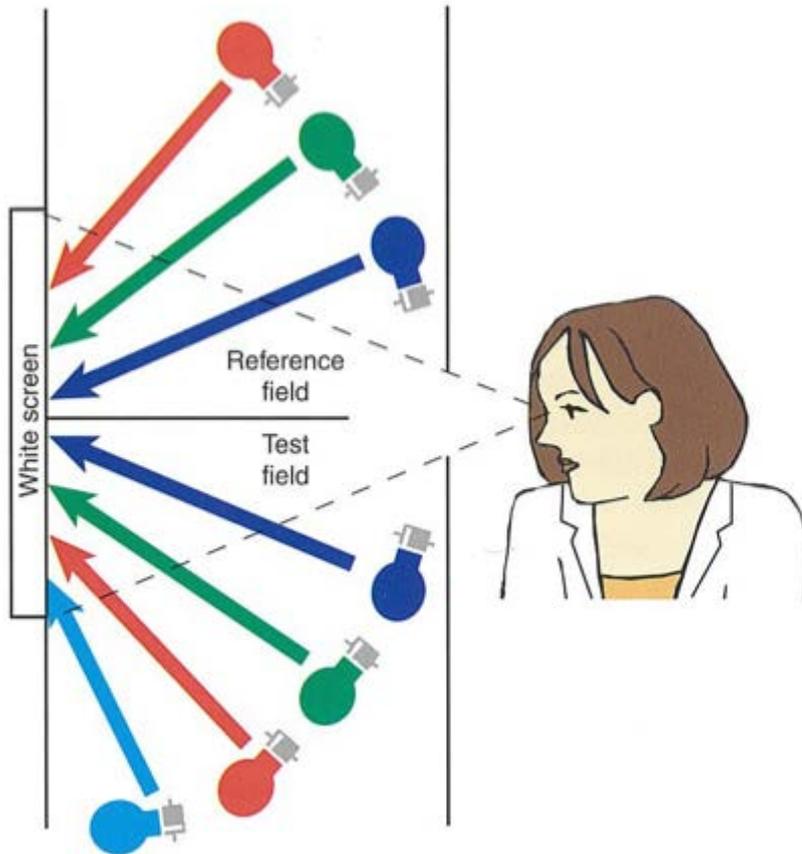
# SI photometry units

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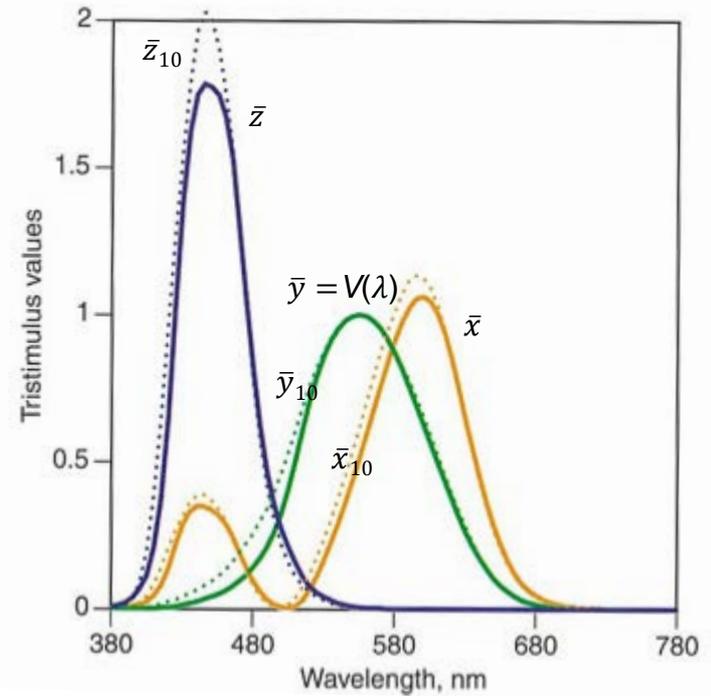
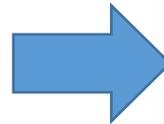
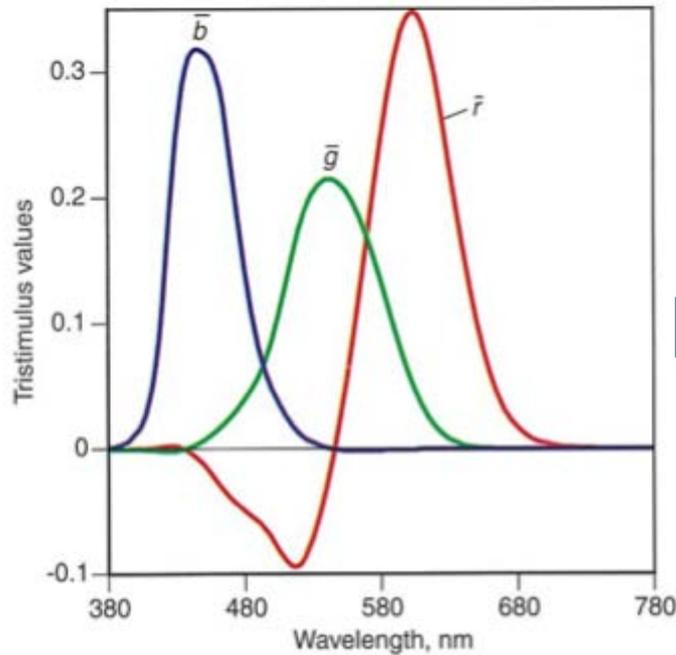
Quantity	Symbol	SI unit	Abbr.	Notes
Luminous energy	$Q_v$	lumen second	lm·s	units are sometimes called talbots
Luminous flux	F	lumen (= cd·sr)	lm	also called luminous power
Luminous intensity	$I_v$	candela (= lm/sr)	cd	an SI base unit
Luminance	$L_v$	candela per square metre	cd/m <sup>2</sup>	units are sometimes called nits
Illuminance	$E_v$	lux (= lm/m <sup>2</sup> )	lx	Used for light incident on a surface
Luminous emittance	$M_v$	lux (= lm/m <sup>2</sup> )	lx	Used for light emitted from a surface
Luminous efficacy		lumen per watt	lm/W	ratio of luminous flux to radiant flux

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# Color-Matching Experiment



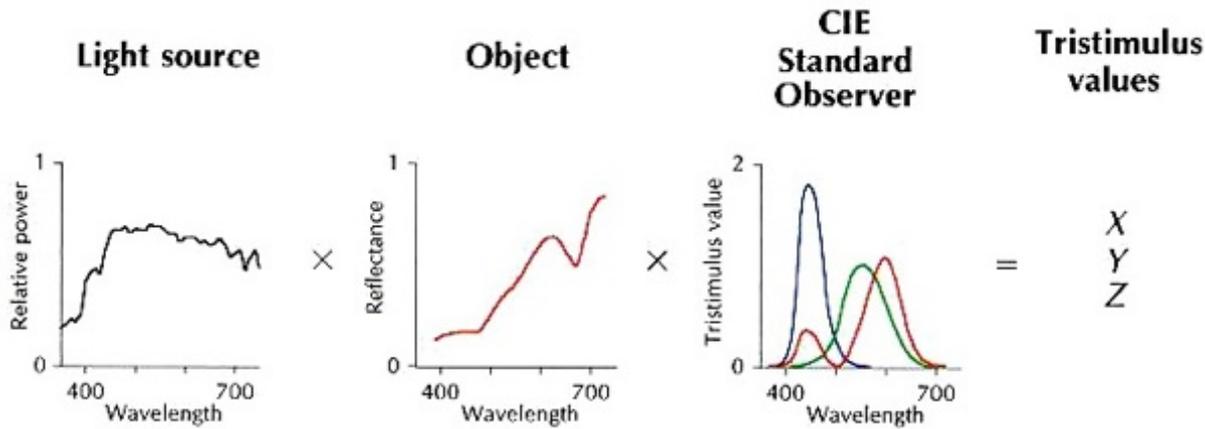
# CIE Standard Observers



- Negative tristimulus
- Colorimetric vs. Photometric values

# CIE 1931 Colorimetry

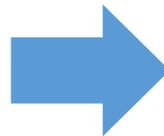
- CIE XYZ system (1931)



$$X = k \sum_{\lambda=380}^{780} S(\lambda) R(\lambda) \bar{x}(\lambda)$$

$$Y = k \sum_{\lambda=380}^{780} S(\lambda) R(\lambda) \bar{y}(\lambda)$$

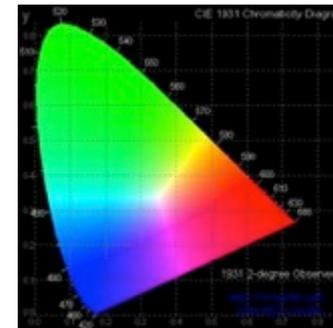
$$Z = k \sum_{\lambda=380}^{780} S(\lambda) R(\lambda) \bar{z}(\lambda)$$



$$x = \frac{X}{X + Y + Z}$$

$$y = \frac{Y}{X + Y + Z}$$

$$z = \frac{Z}{X + Y + Z}$$





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# Technical Reports on CIE 2006 Colorimetry

- CIE 170-1:2006 Fundamental Chromaticity Diagram With Physiological Axes
  - Part I of the report is limited to the choice of a set of colour matching functions and estimates of cone fundamentals for the normal observer, ranging in viewing angle from 1-degree to 10-degree.
- CIE 170-2:2015 Fundamental Chromaticity Diagram With Physiological Axes - Part 2: Spectral Luminous Efficiency Functions and Chromaticity Diagrams

# Cone Fundamentals (CIE 170-1:2006)

- Cone fundamentals for field sizes 1-degree to 10-degree and age between 20 and 80 years

$$\bar{l}(\lambda) = \alpha_{i,l}(\lambda) \cdot 10^{-D_{\tau, \max, \text{macula}} \cdot D_{\text{macula, relative}}(\lambda) - D_{\tau, \text{ocul}}(\lambda)}$$

$$\bar{m}(\lambda) = \alpha_{i,m}(\lambda) \cdot 10^{-D_{\tau, \max, \text{macula}} \cdot D_{\text{macula, relative}}(\lambda) - D_{\tau, \text{ocul}}(\lambda)}$$

$$\bar{s}(\lambda) = \alpha_{i,s}(\lambda) \cdot 10^{-D_{\tau, \max, \text{macula}} \cdot D_{\text{macula, relative}}(\lambda) - D_{\tau, \text{ocul}}(\lambda)}$$

# Photometric Aspects: $V_F(\lambda)$

- Cone-Fundamental-Based Spectral Luminous Efficiency Functions
  - optimal coefficients were found to be close to experimental data as well as being close to a currently used photopic spectral luminous efficiency function.

$$V_F(\lambda) = \alpha \bar{l}(\lambda) + \beta \bar{m}(\lambda) + \gamma \bar{s}(\lambda).$$

# Photometric Aspects: $V_F(\lambda)$

In terms of quanta

$$V_{F,q}(\lambda) = 0,674\ 131\ 88 \bar{l}_q(\lambda) + 0,356\ 683\ 54 \bar{m}_q(\lambda),$$

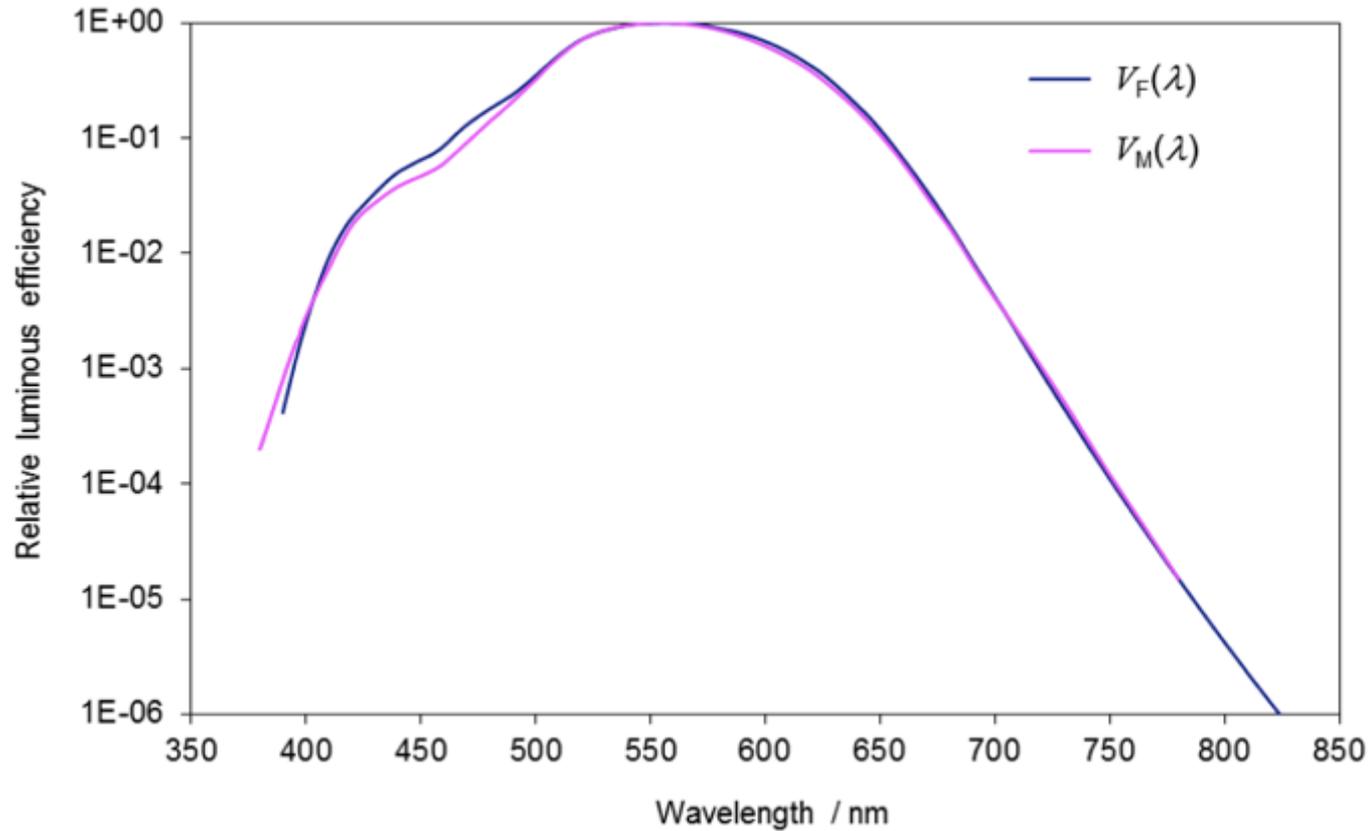
$$V_{F,q,10}(\lambda) = 0,673\ 904\ 86 \bar{l}_{q,10}(\lambda) + 0,356\ 563\ 42 \bar{m}_{q,10}(\lambda),$$

In terms of energy

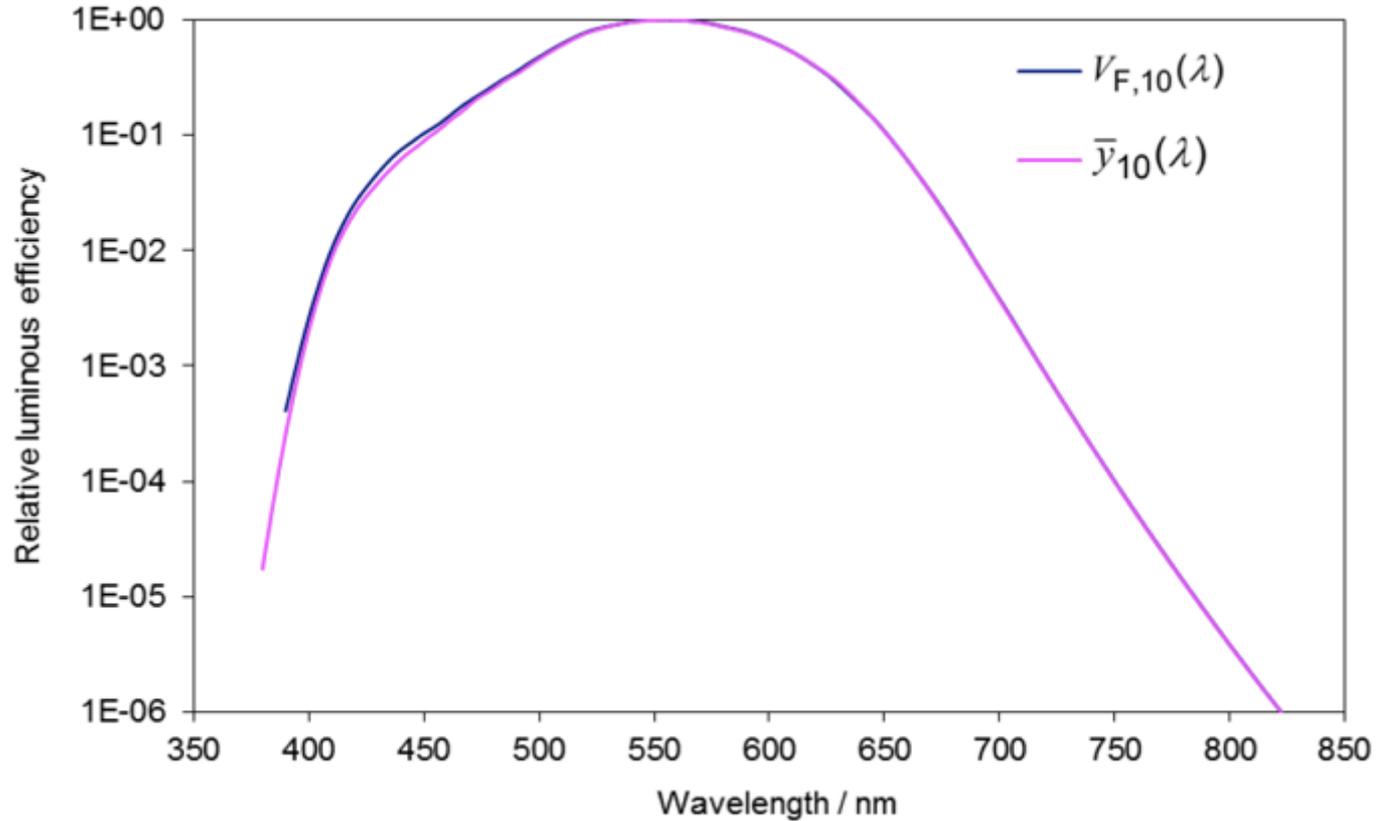
$$V_F(\lambda) = 0,689\ 902\ 72 \bar{l}(\lambda) + 0,348\ 321\ 89 \bar{m}(\lambda),$$

$$V_{F,10}(\lambda) = 0,692\ 839\ 32 \bar{l}_{10}(\lambda) + 0,349\ 675\ 67 \bar{m}_{10}(\lambda),$$

# Photometric Aspects: $V_F(\lambda)$ vs. $V_M(\lambda)$



# Photometric Aspects: $V_{F,10}(\lambda)$ vs. $\bar{y}_{10}(\lambda)$



# Cone-Fundamental-Based Colorimetric Systems

- Compliant with the Principles of the CIE XYZ Concept

$$\bar{x}_F(\lambda) = \alpha_{11} \bar{l}(\lambda) + \alpha_{12} \bar{m}(\lambda) + \alpha_{13} \bar{s}(\lambda)$$

$$\bar{y}_F(\lambda) = \alpha_{21} \bar{l}(\lambda) + \alpha_{22} \bar{m}(\lambda) + \alpha_{23} \bar{s}(\lambda)$$

$$\bar{z}_F(\lambda) = \alpha_{31} \bar{l}(\lambda) + \alpha_{32} \bar{m}(\lambda) + \alpha_{33} \bar{s}(\lambda),$$



$$X_F = k_F \int_{\lambda} \varphi_{\lambda}(\lambda) \bar{x}_F(\lambda) d\lambda \quad x_F = \frac{X_F}{X_F + Y_F + Z_F}$$

$$Y_F = k_F \int_{\lambda} \varphi_{\lambda}(\lambda) \bar{y}_F(\lambda) d\lambda \quad y_F = \frac{Y_F}{X_F + Y_F + Z_F}$$

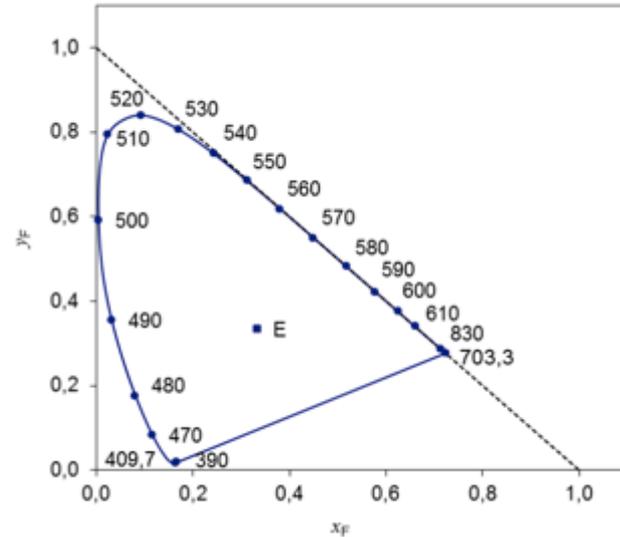
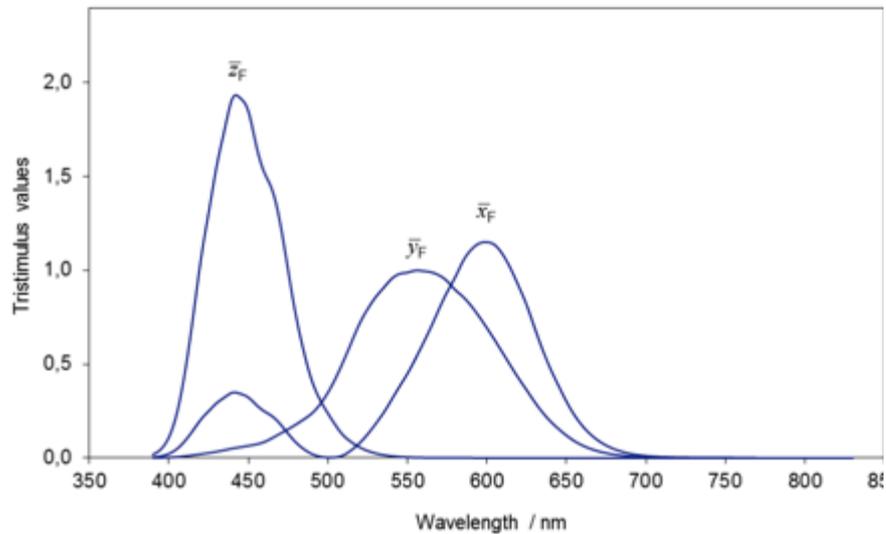
$$Z_F = k_F \int_{\lambda} \varphi_{\lambda}(\lambda) \bar{z}_F(\lambda) d\lambda, \quad z_F = \frac{Z_F}{X_F + Y_F + Z_F},$$

# General CIE XYZ Concept

1. All tristimulus values of any (real) colour stimulus are to be non-negative.
  2. The relative contributions of the X-, the Y- and the Z-primary to luminous flux, as referred to the spectral luminous efficiency function representative of the observer, are to be 0, 1 and 0, respectively.
  3. The tristimulus values of Illuminant E (the equi-energetic spectrum) are to be equal.
- definition of the S-cone fundamental
  - conformity of the cone-fundamental-based chromaticity coordinates with the chromaticity coordinates of the CIE standard colorimetric system for the same field size

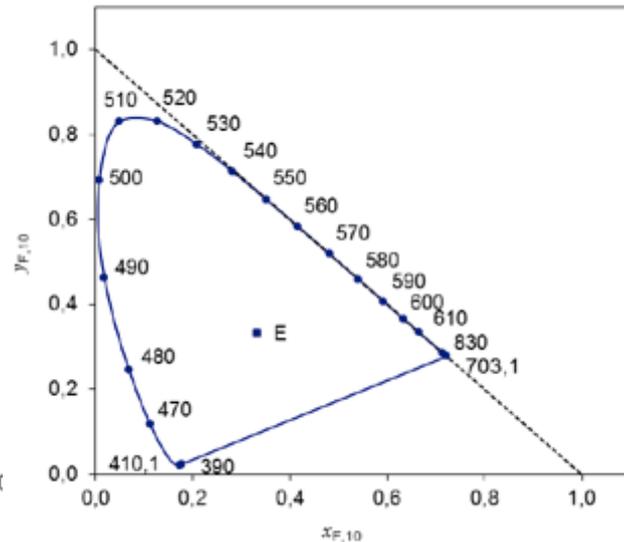
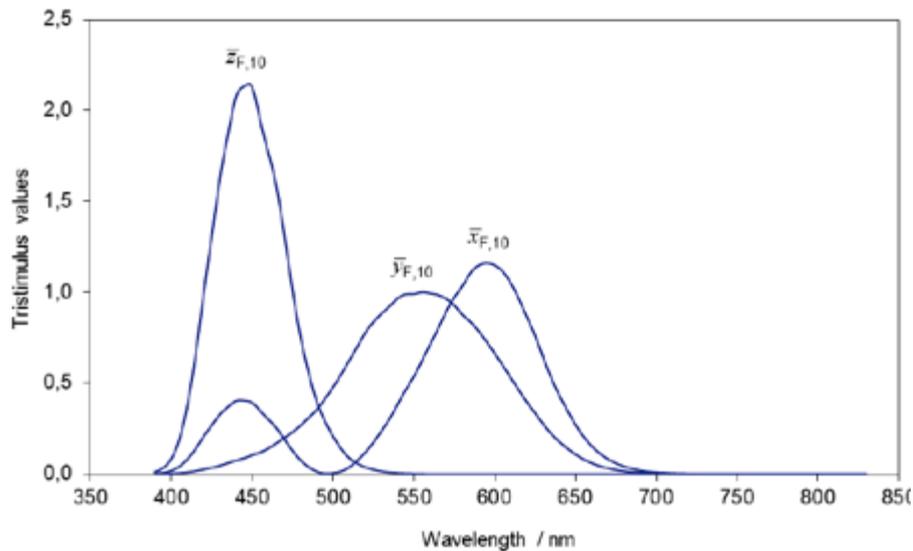
# Cone-Fundamental-Based Spectral Tristimulus Values for 2-degree

$$\begin{pmatrix} \bar{x}_F(\lambda) \\ \bar{y}_F(\lambda) \\ \bar{z}_F(\lambda) \end{pmatrix} = \begin{pmatrix} 1,947\ 354\ 69 & -1,414\ 451\ 23 & 0,364\ 763\ 27 \\ 0,689\ 902\ 72 & 0,348\ 321\ 89 & 0 \\ 0 & 0 & 1,934\ 853\ 43 \end{pmatrix} \begin{pmatrix} \bar{l}(\lambda) \\ \bar{m}(\lambda) \\ \bar{s}(\lambda) \end{pmatrix}$$

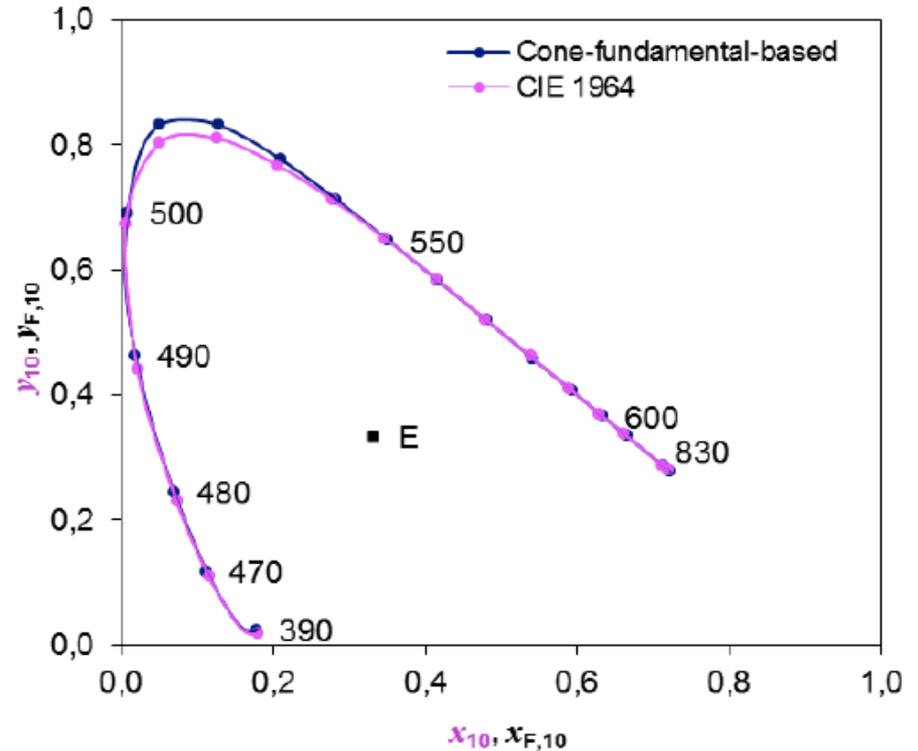
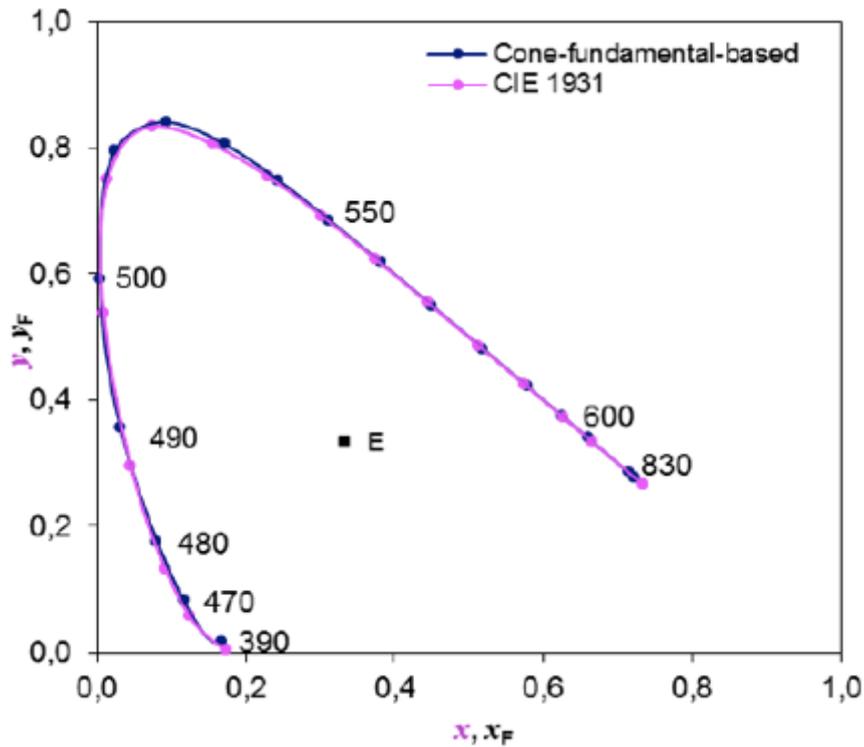


# Cone-Fundamental-Based Spectral Tristimulus Values for 10-degree

$$\begin{pmatrix} \bar{x}_{F,10}(\lambda) \\ \bar{y}_{F,10}(\lambda) \\ \bar{z}_{F,10}(\lambda) \end{pmatrix} = \begin{pmatrix} 1,939\,864\,43 & -1,346\,643\,59 & 0,430\,449\,35 \\ 0,692\,839\,32 & 0,349\,675\,67 & 0 \\ 0 & 0 & 2,146\,879\,45 \end{pmatrix} \begin{pmatrix} \bar{l}_{10}(\lambda) \\ \bar{m}_{10}(\lambda) \\ \bar{s}_{10}(\lambda) \end{pmatrix},$$



# Cone-fundamental vs. CIE 1931





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# Current and Future CIE activities

- TC1-97: Age- and Field-Size-Parameterised Calculation of Cone-Fundamental-Based Spectral Tristimulus Values (TCC: Jan Henrik Wold)
- Consideration should be given to the replacement of the 1931 colorimetric system by the CIE 2006 colorimetric system for the calculation of colorimetric parameters to be used for the computation of lighting quality data.
- Therefore, intensive field trials are required to help the colour, imaging and lighting industries to have confidence that CIE 2006 colorimetry is fit for their use.

# References

- Roy S. Berns, "Billmeyer and Saltzman's Principles of Color Technology", 3rd Ed., Wiley-Interscience (2000)
- CIE170-1:2006: Fundamental Chromaticity Diagram with Physiological Axes - Part 1.
- CIE170-2:2015: Fundamental Chromaticity Diagram with Physiological Axes – Part 2: Spectral Luminous Efficiency Functions and Chromaticity Diagrams.

# Q&A



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