Lux junior 2024

17. Internationales Forum für den lichttechnischen Nachwuchs 6. bis 8.9.2024 Dörnfeld/Ilm

100 years of $V(\lambda)$ – What's next?

100 Jahre $V(\lambda)$ – Wie geht es weiter?

Christoph Schierz

Technische Universität Ilmenau
Fakultät für Maschinenbau
Fachgebiet Lichttechnik

Overview

- History: Visual Photometry
- Measuring spectral luminous sensitivity functions
- Spectral luminous efficiency functions since $V(\lambda)$ from 1924
- Cone fundamental based spectral sensitivities
- Impact of introducing cone fundamental based new $V_F(\lambda)$
- Influences still not considered
- Summary

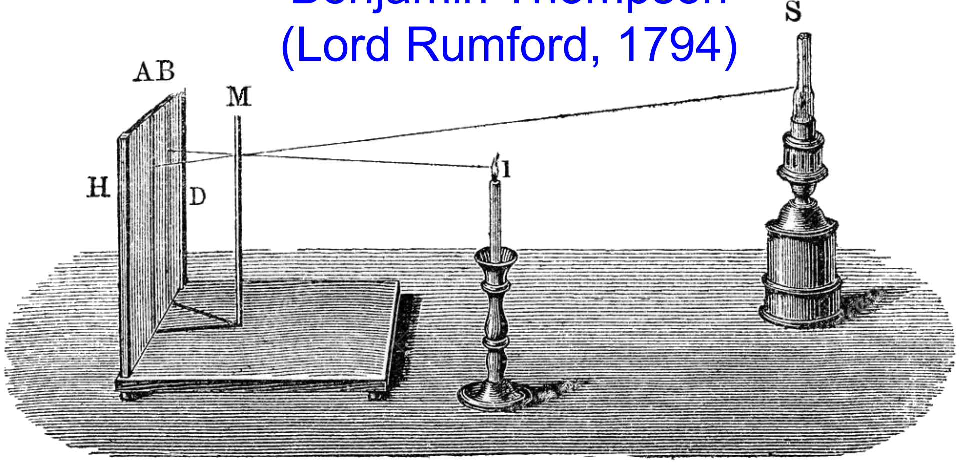
Overview

- **History: Visual Photometry**
- Measuring spectral luminous sensitivity functions
- Spectral luminous efficiency functions since $V(\lambda)$ from 1924
- Cone fundamental based spectral sensitivities
- Impact of introducing cone fundamental based new $V_F(\lambda)$
- Influences still not considered
- Summary

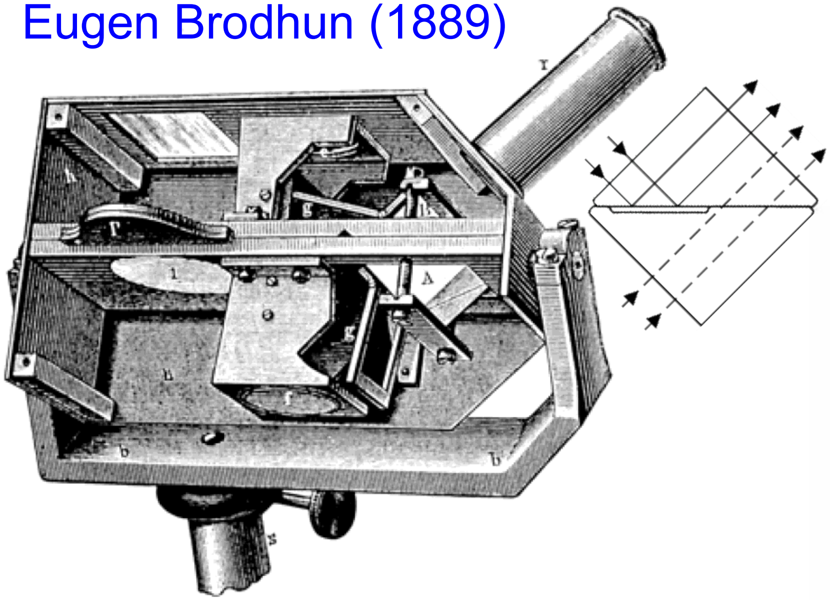
Measurement of brightness

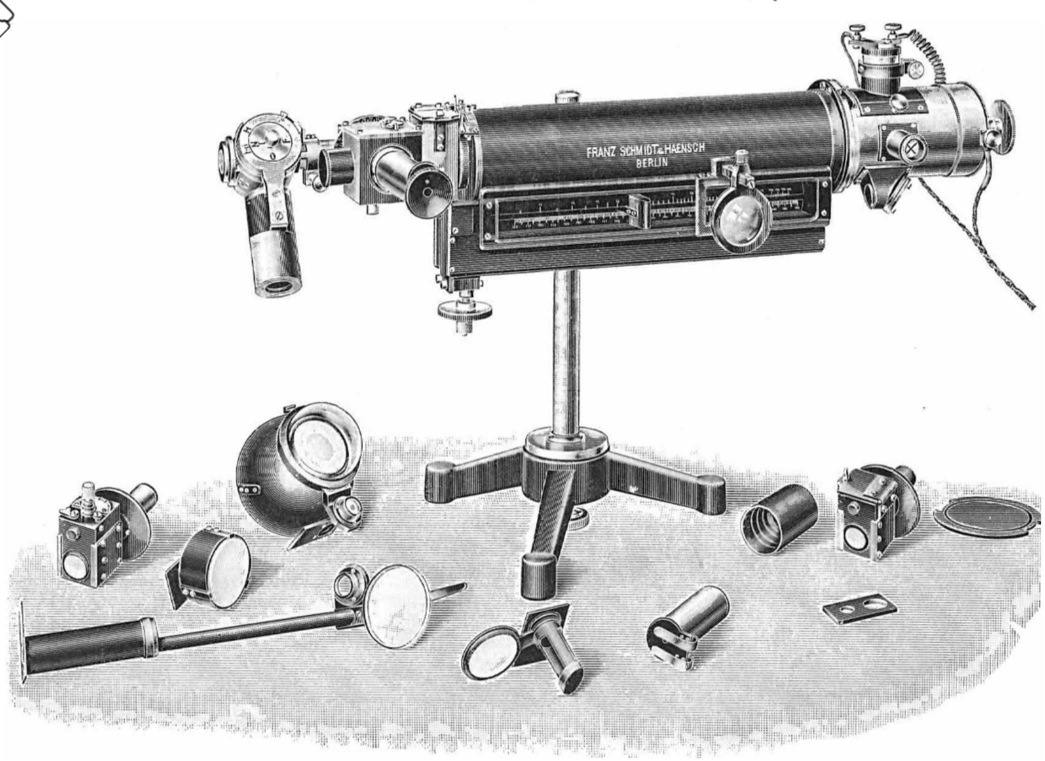
Visual photometry

Photometer according to
Benjamin Thompson
(Lord Rumford, 1794)



Photometer according to
Otto Lummer and
Eugen Brodhun (1889)





Universalphotometer Mod. 1
of Schmid & Haensch
with accessories (after 1930)

Visual measuring device

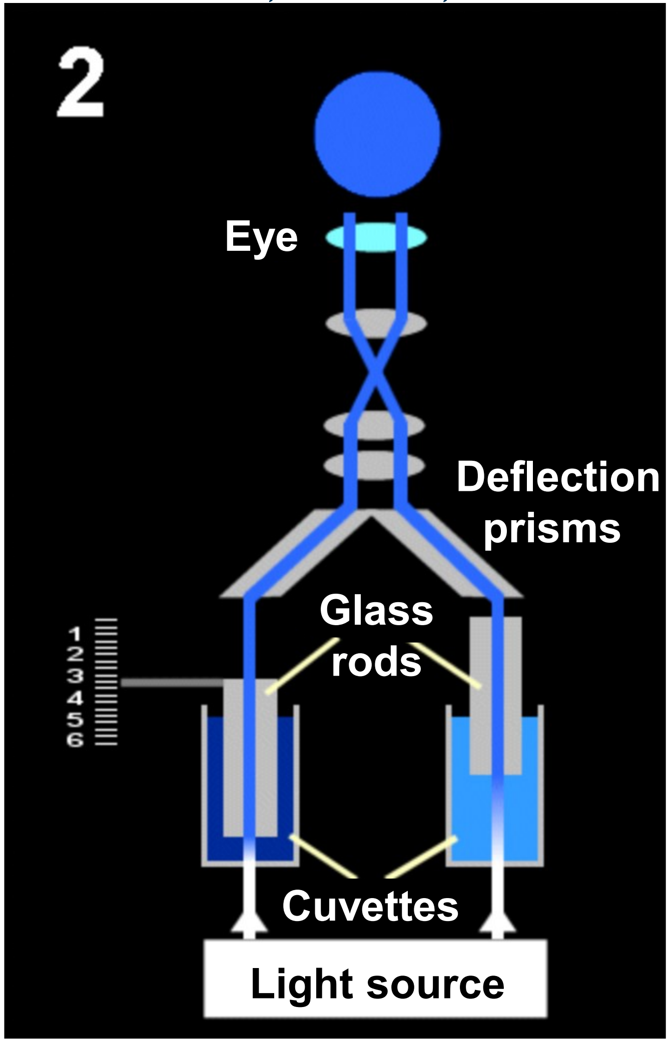
Monochromatic Colorimeter

Determination of the concentration of coloured compounds (1854)

Jules Duboscq
(1817-1886)

Science Museum Group

K. Bauer, W. Hübl, 2002

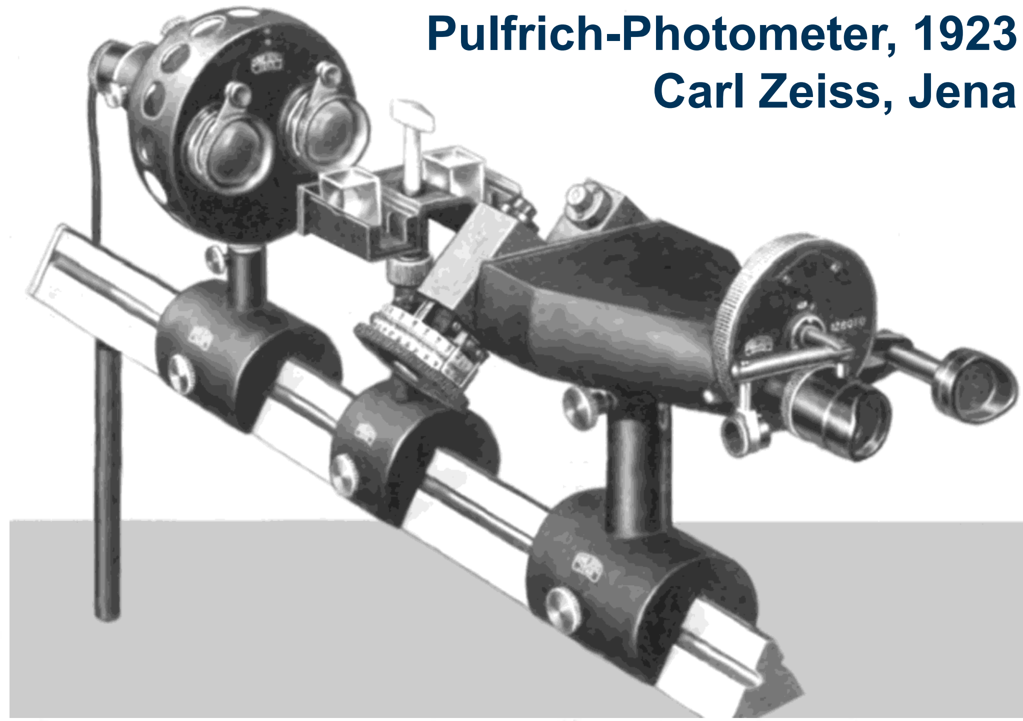


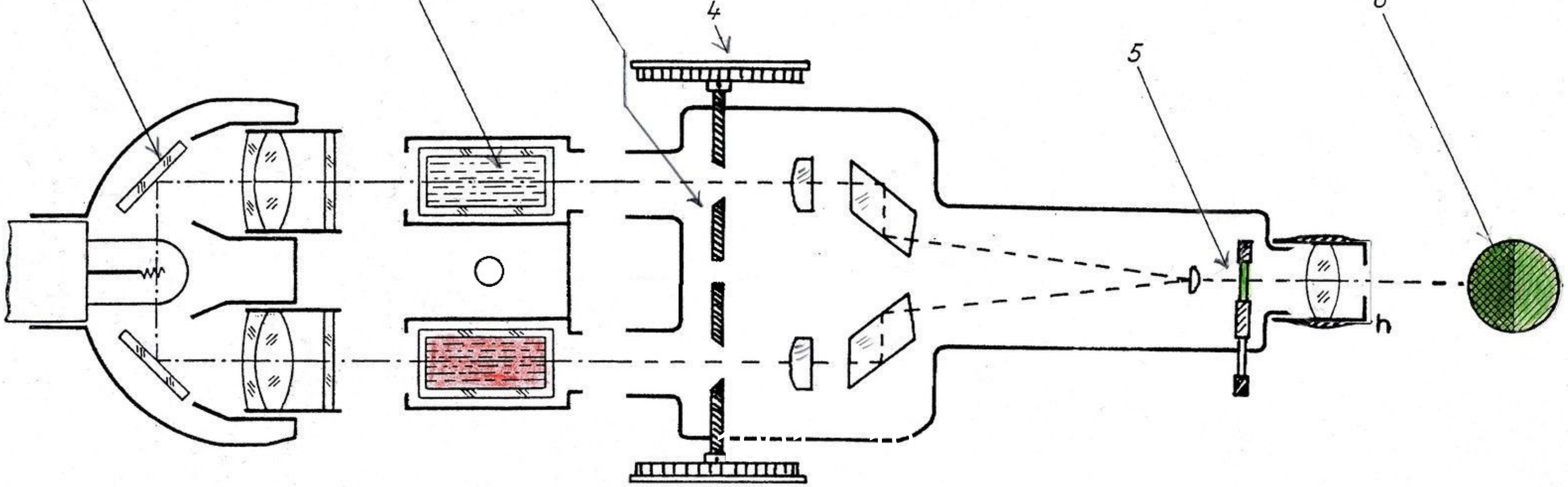
Visual measuring device

Clinical Colorimeter

Carl Pulfrich
(1858-1927)

Pulfrich-Photometer, 1923
Carl Zeiss, Jena



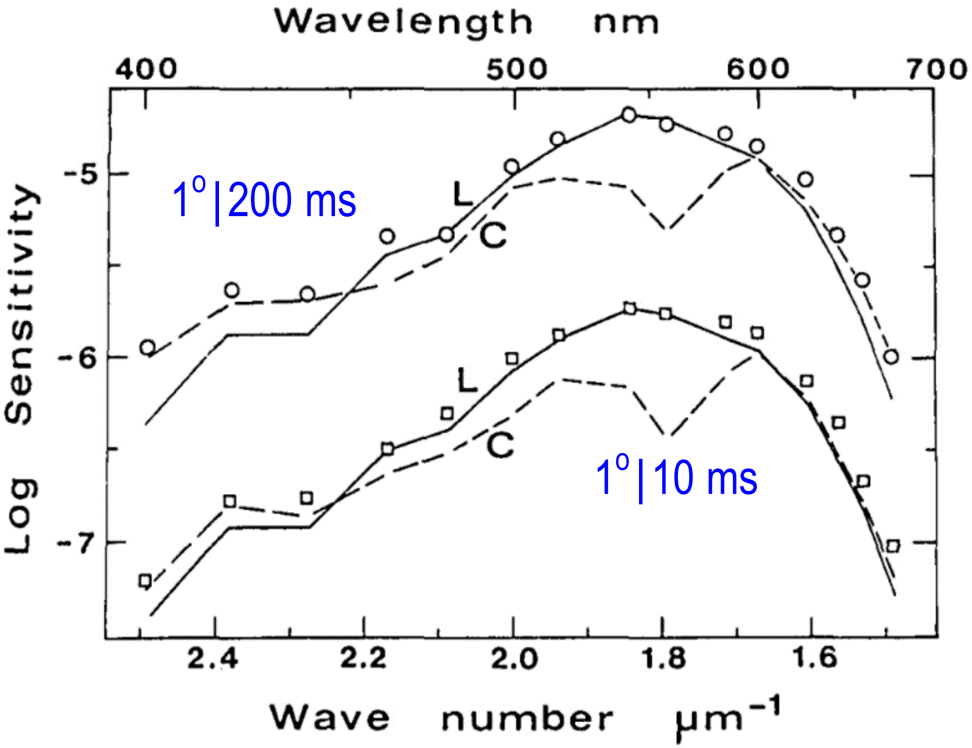


Overview

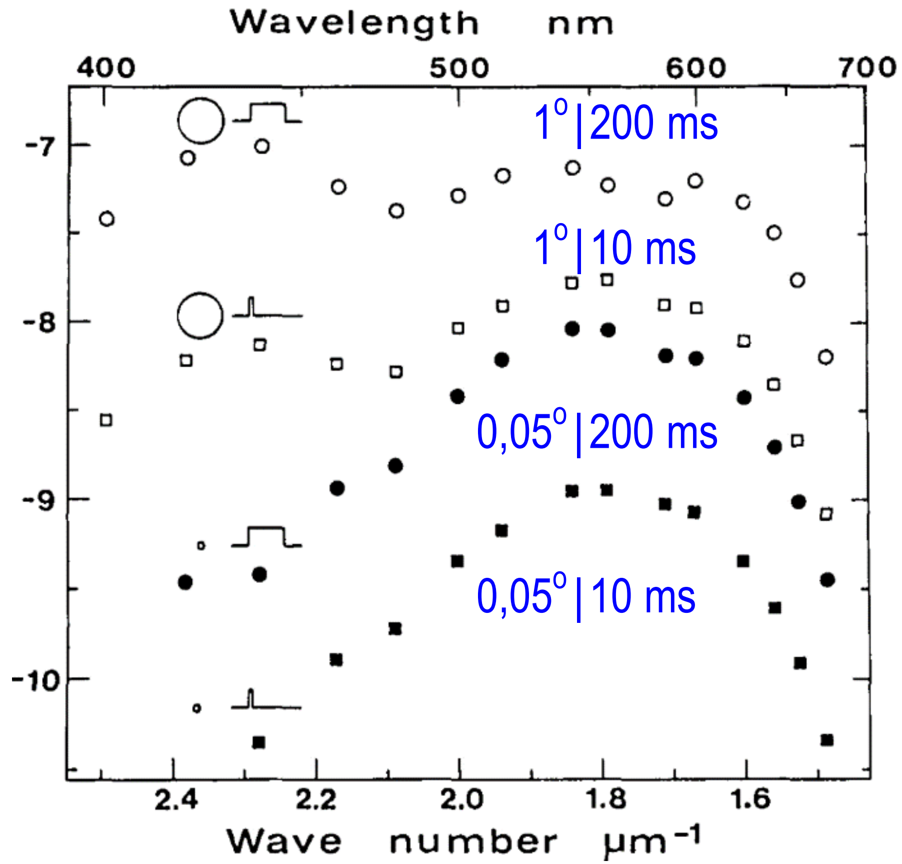
- History: Visual Photometry
- **Measuring spectral luminous sensitivity functions**
- Spectral luminous efficiency functions since $V(\lambda)$ from 1924
- Cone fundamental based spectral sensitivities
- Impact of introducing cone fundamental based new $V_F(\lambda)$
- Influences still not considered
- Summary

Threshold methods

Absolute threshold on black | *Incremental threshold on white*



Black background



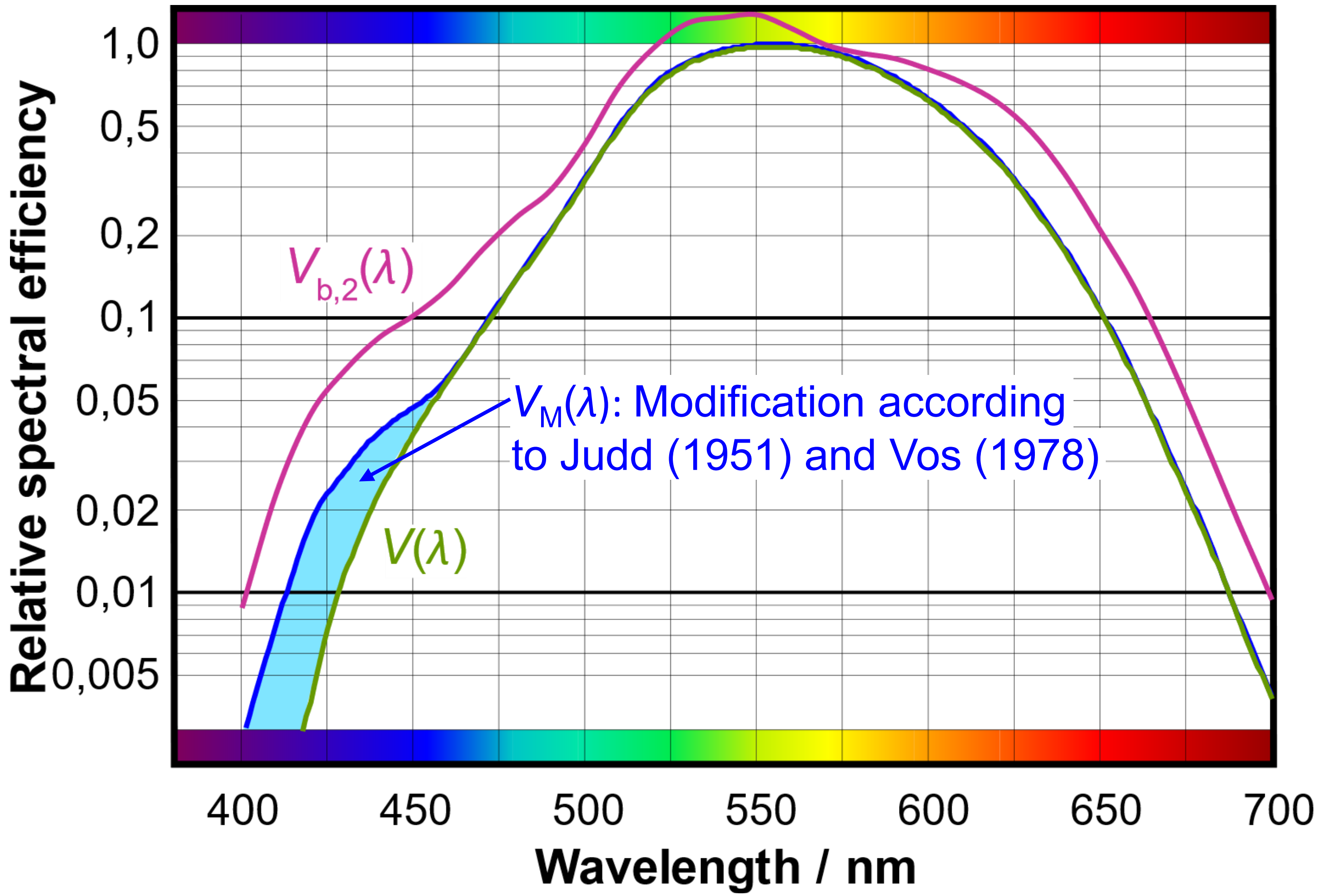
White background
(1000 Troland, size 4°, 3200 K)

P.E. King-Smith, D. Carden, 1976

Direct heterochromatic photometry

$V_{b,2}(\lambda)$: Monochromatic 2° colour stimuli (non-additive)

$V_M(\lambda)$: ≈ Monochromatic point source (additive)

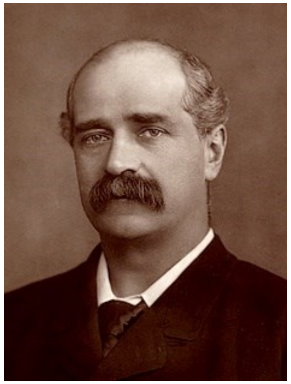


CIE Report 75:1988

CIE Report 86:1990

Linear additivity

Abney's law



Sir William Abney
(1843 – 1920)

The total luminance of light composed of several wavelengths is equal to the sum of the luminances of its monochromatic components

Subadditivity: $L_\mathrm{v}(\lambda_1 + \lambda_2) < L_\mathrm{v}(\lambda_1) + L_\mathrm{v}(\lambda_2)$

Additivity: $L_\mathrm{v}(\lambda_1 + \lambda_2) = L_\mathrm{v}(\lambda_1) + L_\mathrm{v}(\lambda_2)$

Superadditivity: $L_\mathrm{v}(\lambda_1 + \lambda_2) > L_\mathrm{v}(\lambda_1) + L_\mathrm{v}(\lambda_2)$

Additivity is imperative for a workable system of photometry: $V(\lambda)$ must be additive, regardless of the composition of the spectral radiance $L_{\mathrm{e},\lambda}(\lambda)$. This enables spectral integration with $V(\lambda)$ as a weighting function:

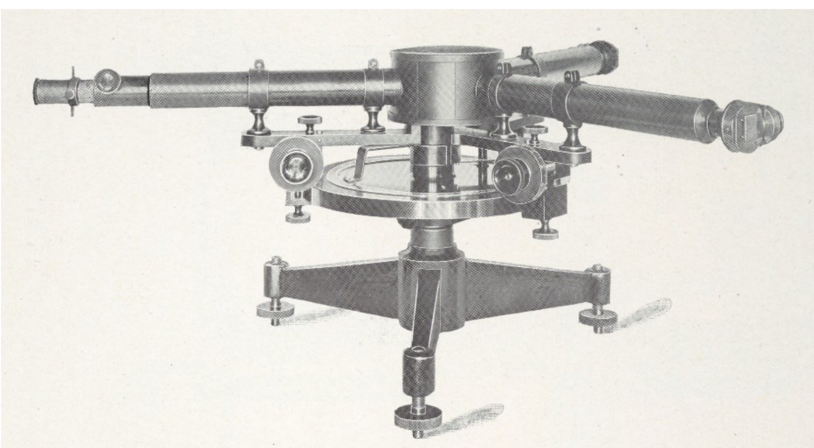
$$L_\mathrm{v} = K_\mathrm{m} \int_\lambda L_{\mathrm{e},\lambda}(\lambda) \cdot V(\lambda) \cdot \mathrm{d}\lambda$$

W. Abney et al., 1886
W. Abney, 1913

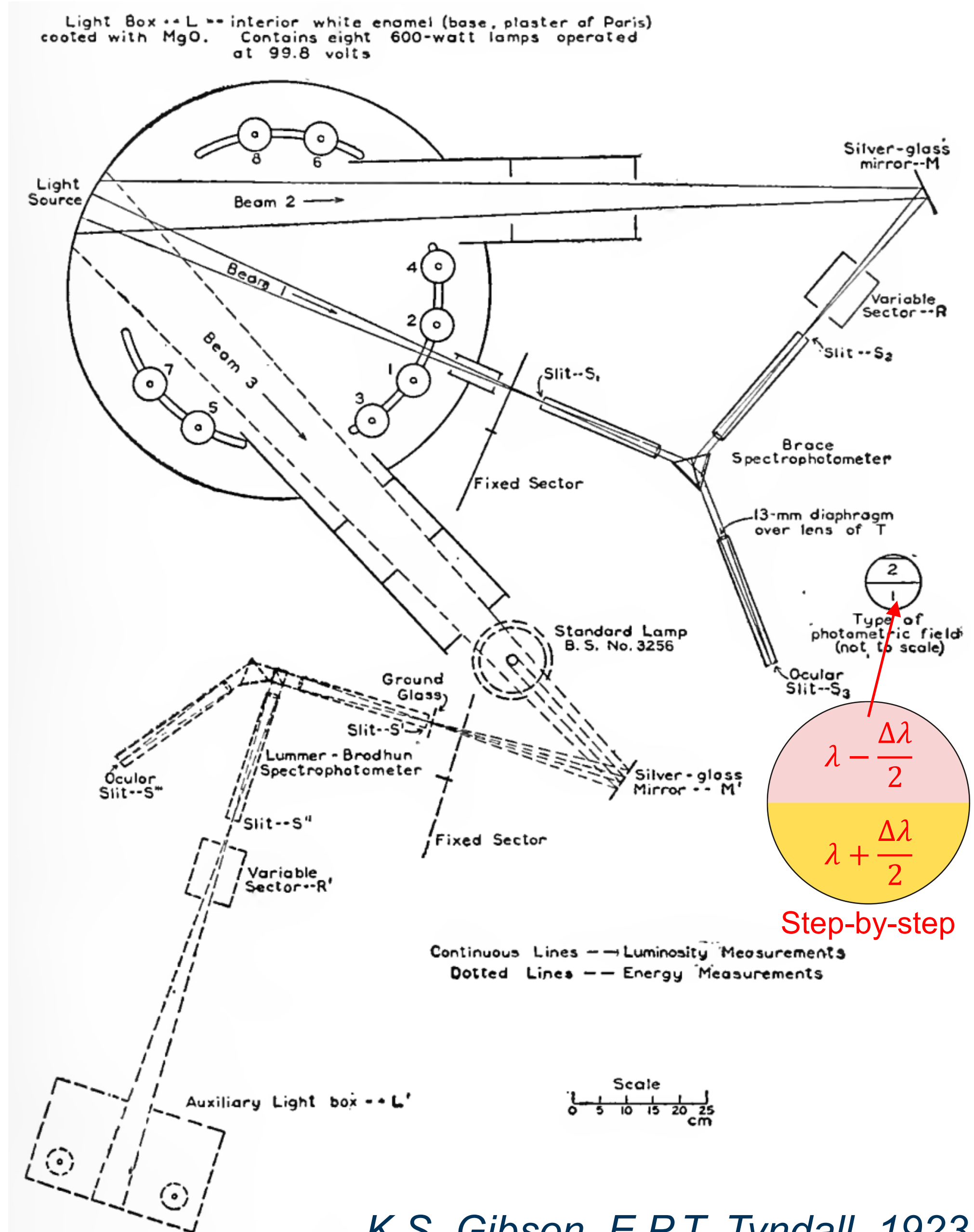
Direct heterochromatic photometry

Kasson S. Gibson
(1890 – 1979)

Edward P. T. Tyndall
(1893 - 1979)

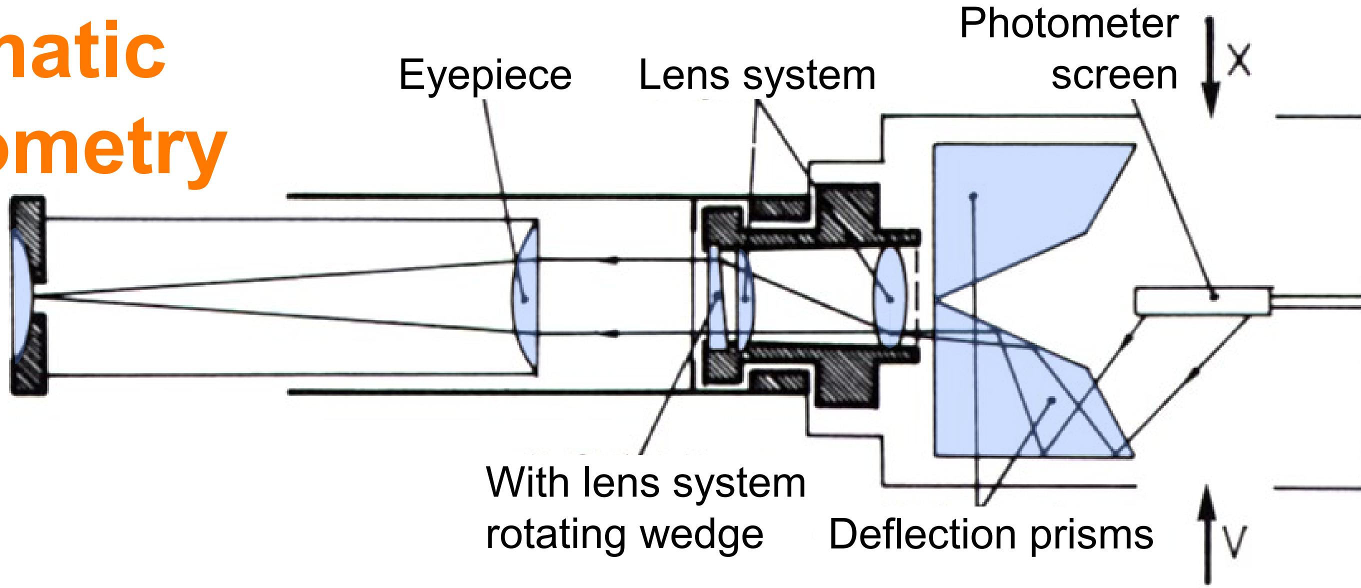


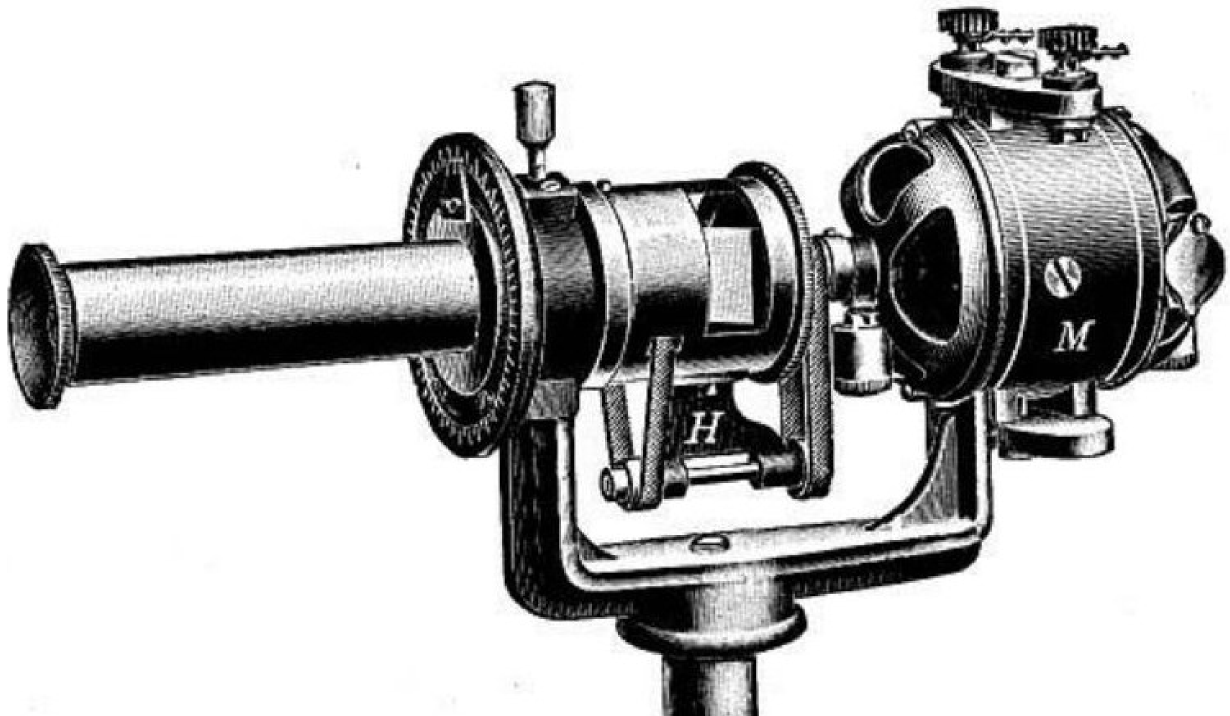
Brace Spectrophotometer



K.S. Gibson, E.P.T. Tyndall, 1923

Heterochromatic flicker photometry





Measuring spectral-sensitivity functions

Overview

P. Lennie et al., 1993

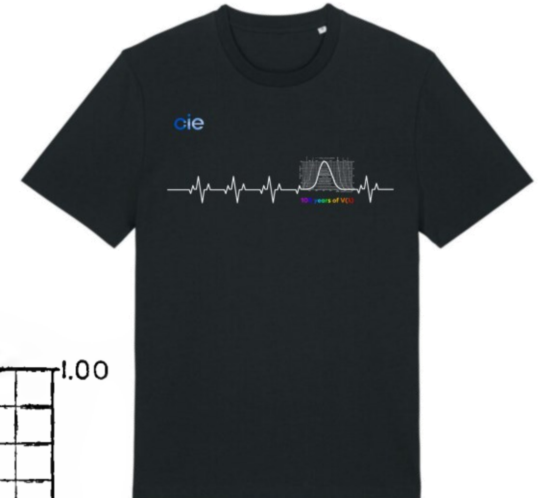
Method	Stimulus	Function form	Additivity
Using temporal or spatial alternation			
Heterochromatic flicker photometry (HFP)	low luminance	$V(\lambda)$-like	Yes
	high luminance	$V(\lambda)$-like	No
Grating visual acuity		$V(\lambda)$-like	Yes
Motion minimisation		$V(\lambda)$-like	Yes
Direct heterochromatic photometry			
Brightness matching	small	$V(\lambda)$-like	Yes
	large	Broader	No
Step by step equality of brightness		$V(\lambda)$-like	Yes
Minimally distinct border (MDB)		$V(\lambda)$-like	Yes
Checkerboard patterns	3′ juxtaposed elements	$V(\lambda)$-like	Yes
	3′ separated elements	$V(\lambda)$-like	No
Threshold methods			
Absolute threshold	small, brief	$V(\lambda)$-like	Yes
	large, long	Notch @ 570 nm	No
Increment threshold on white background	small, brief	$V(\lambda)$-like	≈ Yes
	large, long	3 broad peaks	No
Radiance for critical flicker fusion (CFF)	low photopic luminance	$V(\lambda)$-like	
Landolt C visual acuity		$V(\lambda)$-like	Yes
Increment grating detection	1 Troland	$V(\lambda)$-like	Yes
	1000 Troland	Broader	No @ low c/°
Speeded response			
Criterion reaction time		$V(\lambda)$-like	

Overview

- History: Visual Photometry
- Measuring spectral luminous sensitivity functions
- **Spectral luminous efficiency functions since $V(\lambda)$ from 1924**
- Cone fundamental based spectral sensitivities
- Impact of introducing cone fundamental based new $V_F(\lambda)$
- Influences still not considered
- Summary

$V(\lambda)$ data compilation

https://vlambda.machtgluecklich.shop/



Step-by-step method
Flicker method

K.S. Gibson, E.P.T. Tyndall, 1923

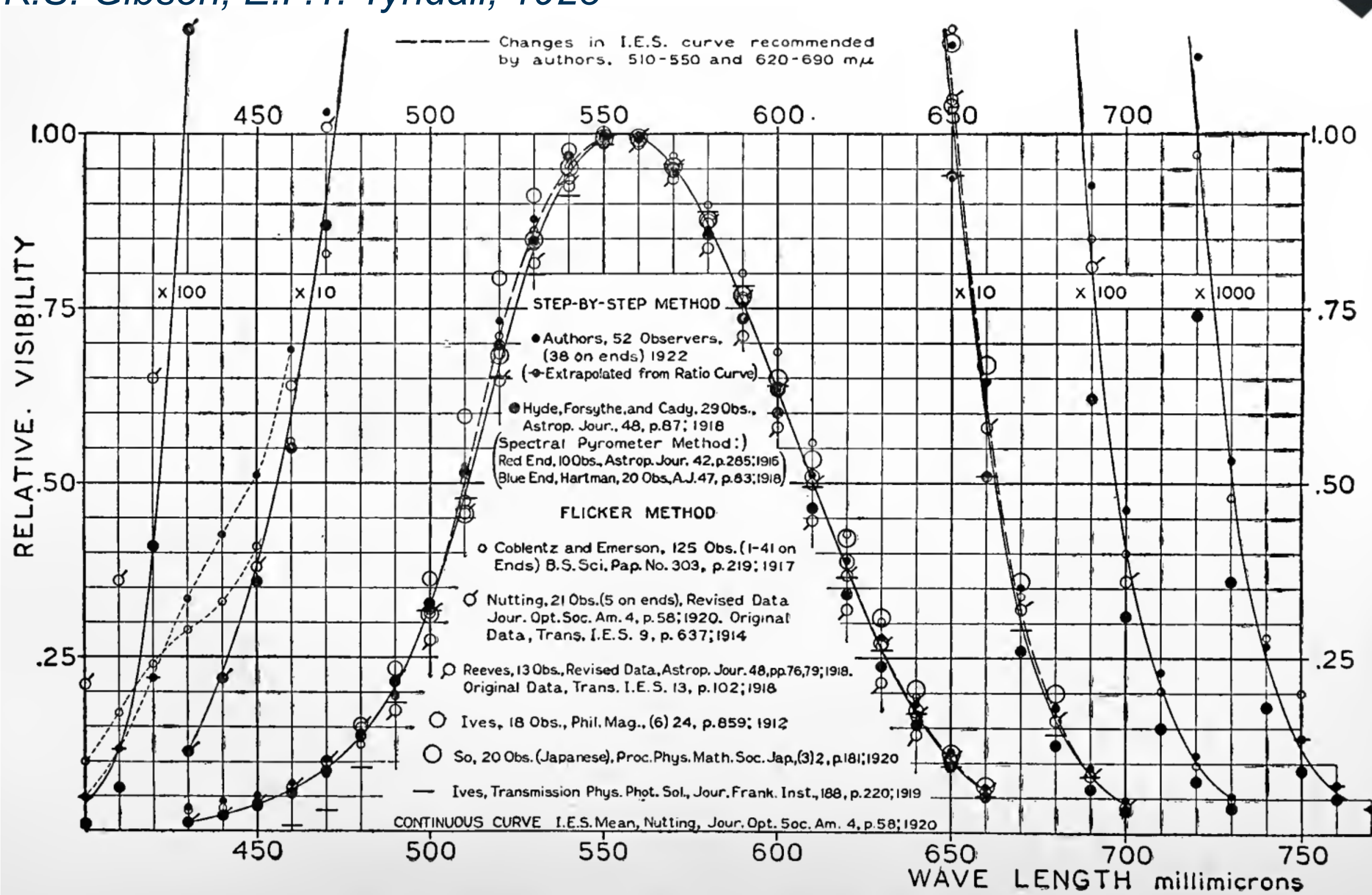
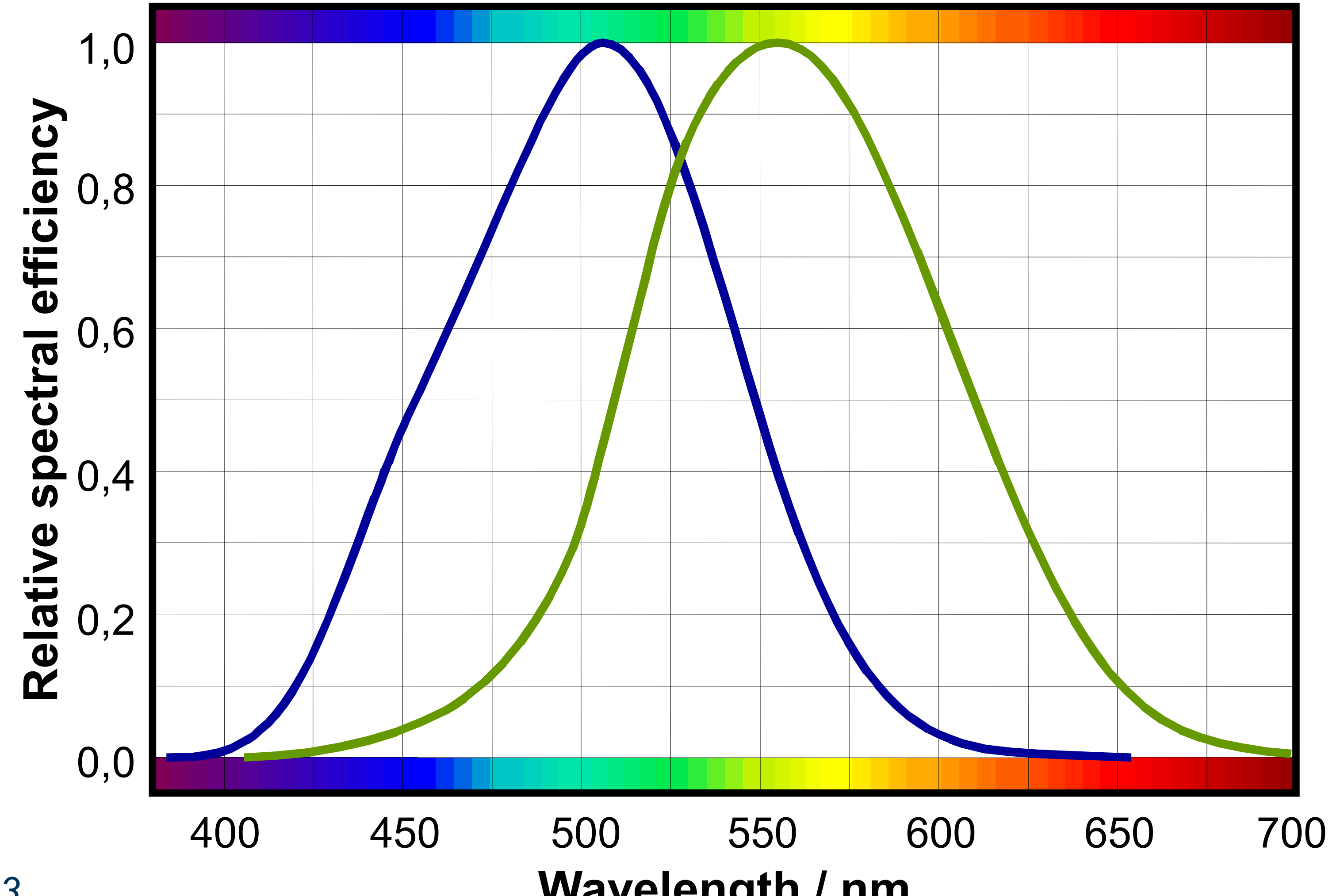


FIG. 19.—*Compilation of visibility data. See Table 3 and Figure 21.*

Spectral luminous efficiency functions

V'(λ) scotopic (night vision)
from 1951, field outside macula

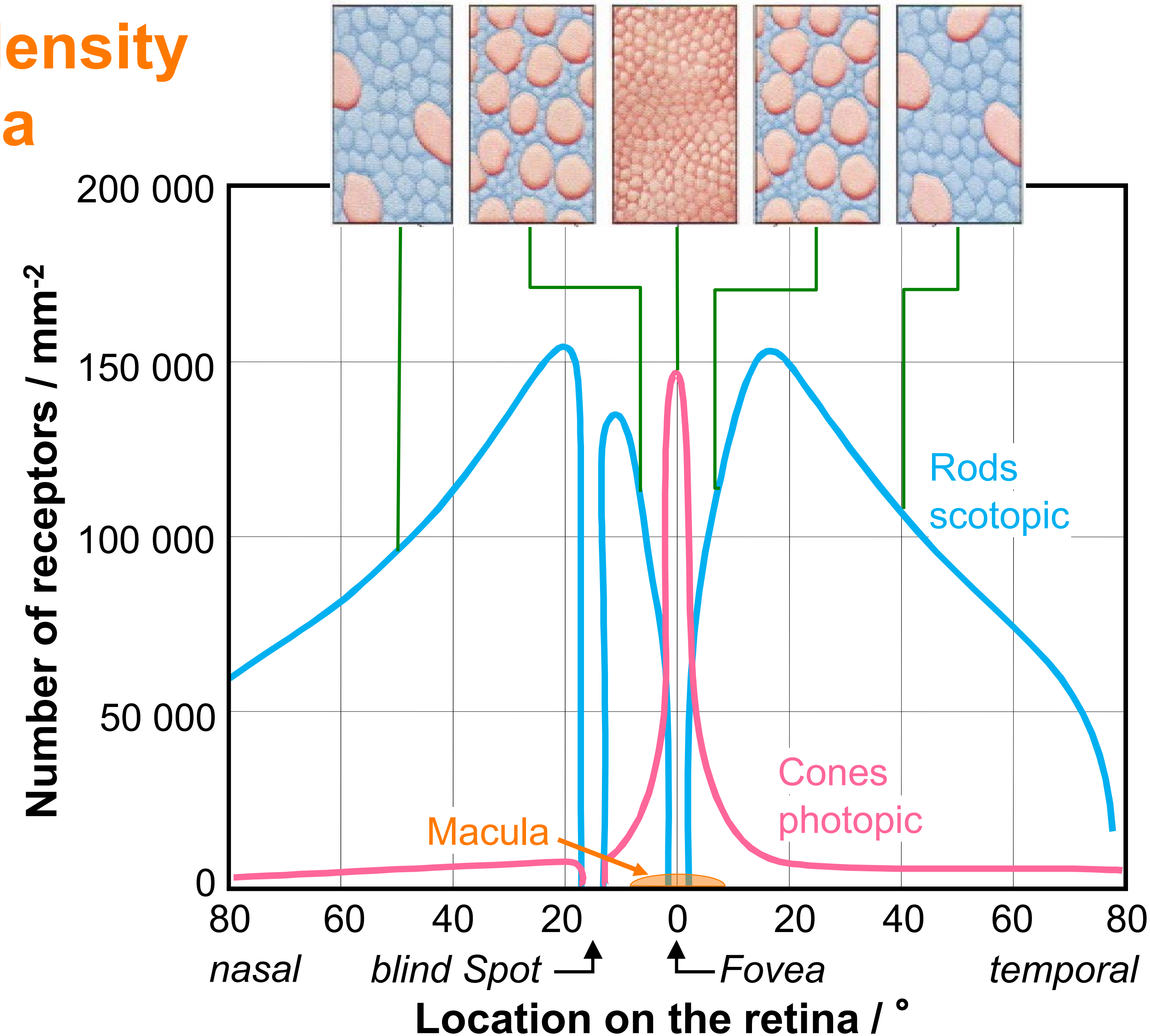
V(λ) photopic (day vision)
from 1924, field size of 2°



ISO/CIE 23539:2023

The SPIRIT of science
TECHNISCHE UNIVERSITÄT ILMENAU

Receptor density of the retina



G. Osterberg, 1935

Spectral luminosities introduced by the CIE

Overview

Symbol	**Intro-ductory year**	**Application context** Luminance region, field size (remark)	**Current reference**
$V(\lambda)$ $= \bar{y}(\lambda)$	1924 1931	photopic, 2°	ISO/CIE 23539:2023 ISO/CIE 11664-1:2019
$V'(\lambda)$	1951	scotopic, 20° + 1° [8° above fovea]	ISO/CIE 23539:2023
$\bar{y}_{10}(\lambda)$ $= V_{10}(\lambda)$	1964 2005	photopic, 10°	ISO/CIE 11664-1:2019 ISO/CIE 23539:2023
$V_{b,2}(\lambda)$	1988	photopic, 2° (monochromatic source)	CIE 075-1988
$V_{b,10}(\lambda)$	1988	photopic, 10° (monochromatic source)	CIE 075-1988
$V_{M}(\lambda)$	1990	photopic, 2° (Judd-Vos correction)	CIE 086-1990
$V_{a}(\lambda)$	2011	photopic, 2° (age dependent)	CIE 196:2011
$V_{F}(\lambda)$	2015	photopic, 2° (cone-fundamental)	CIE 170-2:2015
$V_{F,10}(\lambda)$	2015	photopic, 10° (cone-fundamental)	CIE 170-2:2015
$V_{mes;m}(\lambda)$	2023	mesopic, ??° (luminance dependent)	ISO/CIE 23539:2023

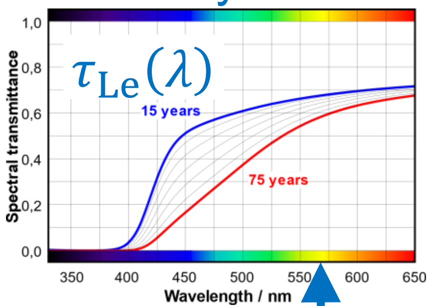
Overview

- History: Visual Photometry
- Measuring spectral luminous sensitivity functions
- Spectral luminous efficiency functions since $V(\lambda)$ from 1924
- **Cone fundamental based spectral sensitivities**
- Impact of introducing cone fundamental based new $V_F(\lambda)$
- Influences still not considered
- Summary

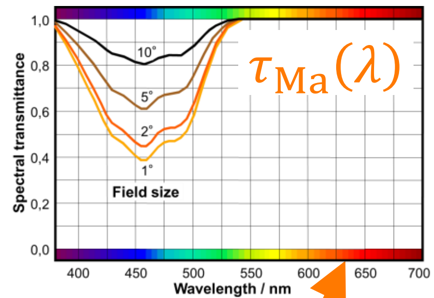
Stages from spectrum to cone responses

Spectral transmissions and absorptions

Spectral transmittance of the eye lens



Spectral transmittance of the macula



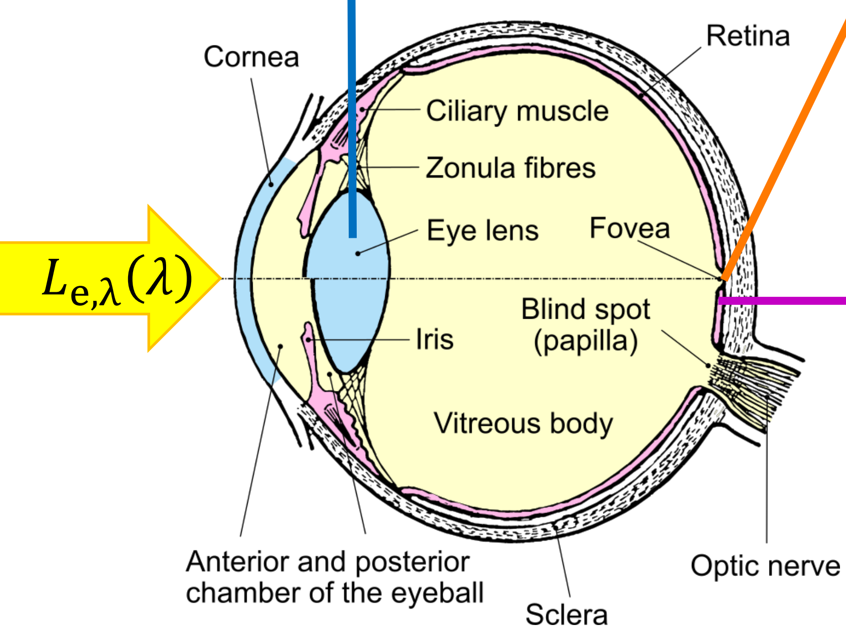
Cone fundamentals

"Sehzapfen-Grundfunktionen"

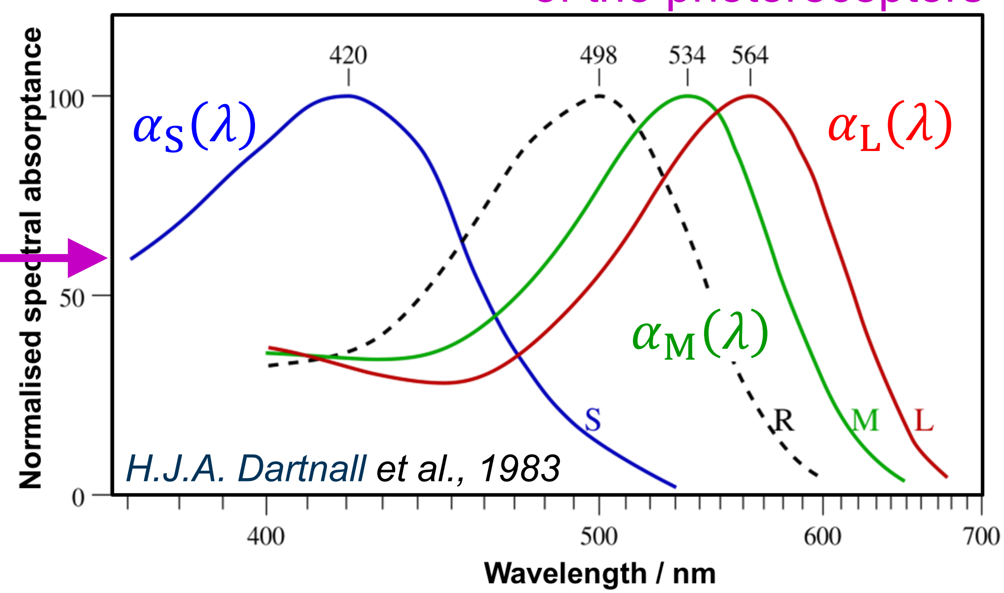
$$\bar{l}(\lambda) = \tau_{Le}(\lambda) \cdot \tau_{Ma}(\lambda) \cdot \alpha_L(\lambda)$$

$$\bar{m}(\lambda) = \tau_{Le}(\lambda) \cdot \tau_{Ma}(\lambda) \cdot \alpha_M(\lambda)$$

$$\bar{s}(\lambda) = \tau_{Le}(\lambda) \cdot \tau_{Ma}(\lambda) \cdot \alpha_S(\lambda)$$



Spectral absorptance of the photoreceptors

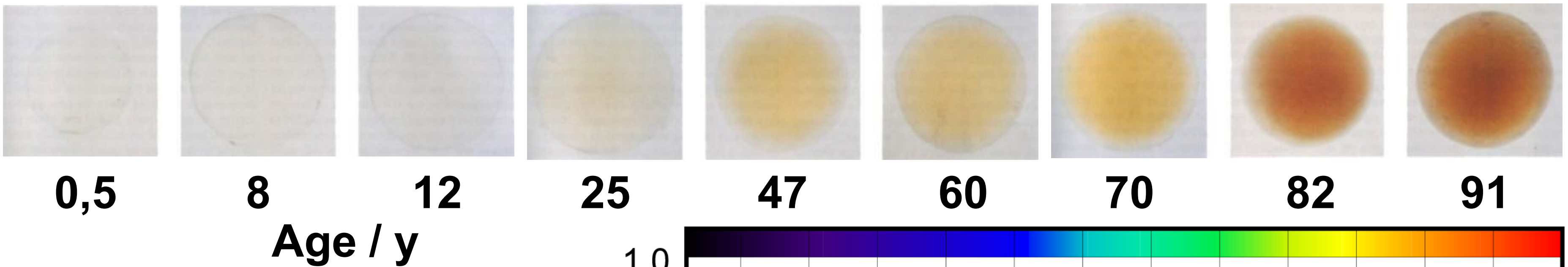


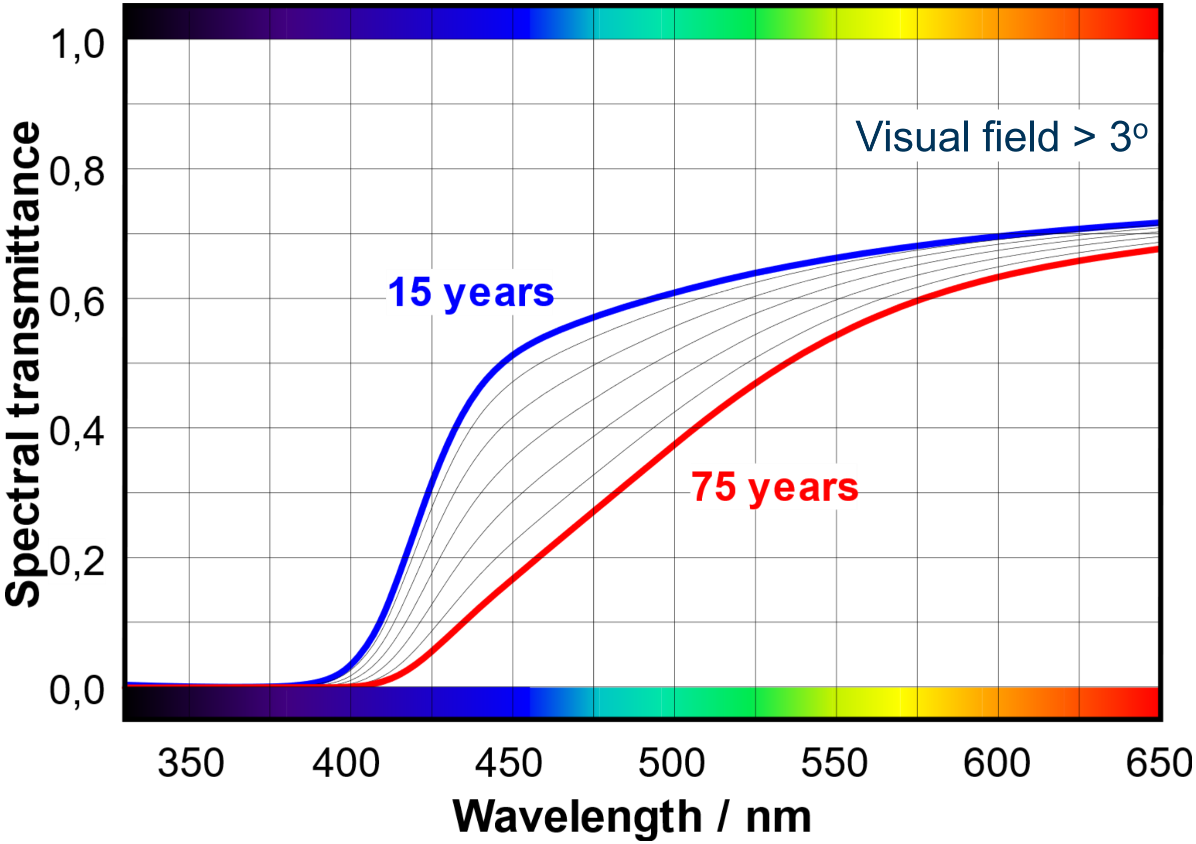
H.J.A. Dartnall et al., 1983

Eye lens transmittance

Age dependency

S. Lerman, 1980

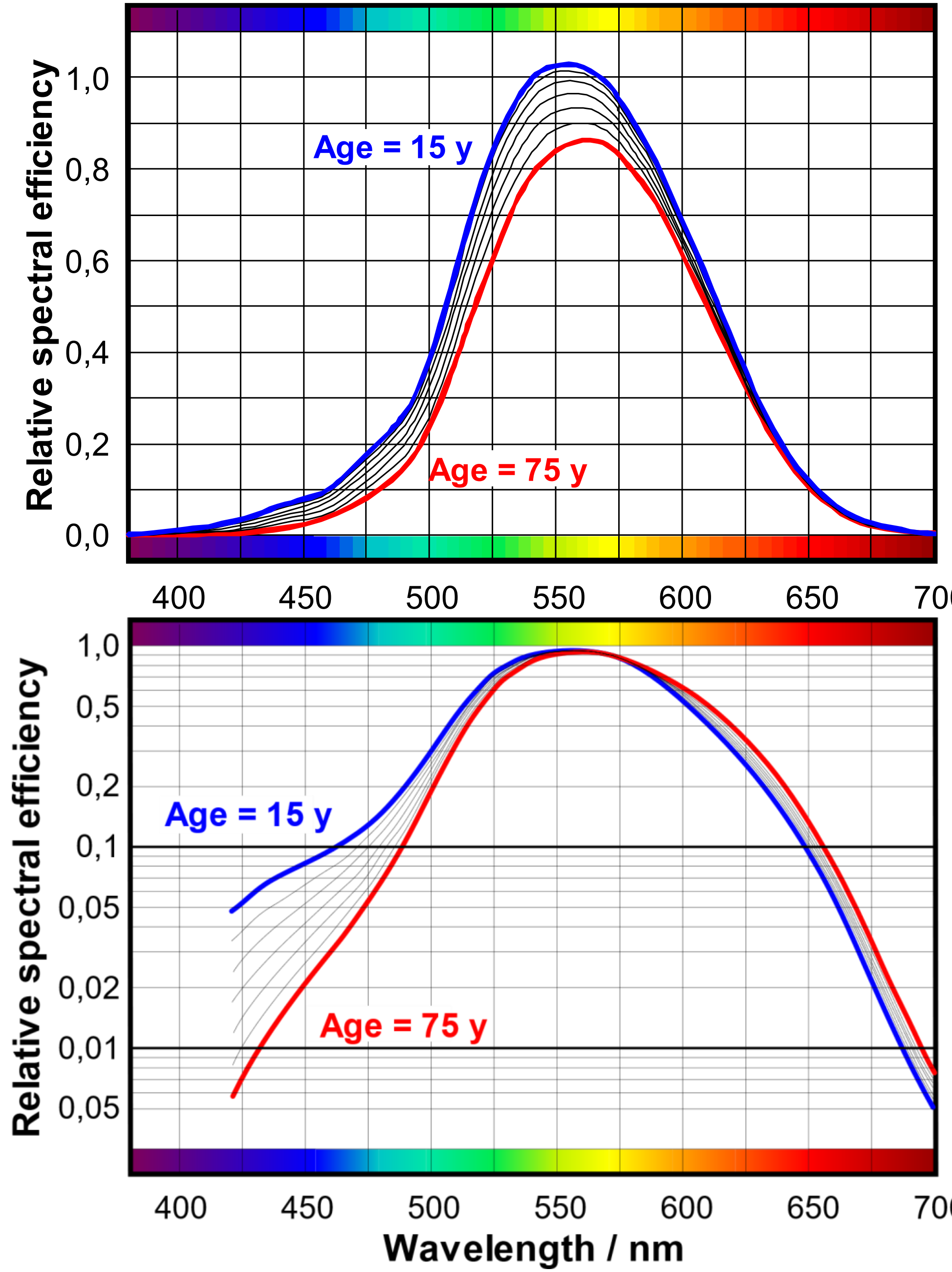




van de Kraats et al., 2007

Spectral luminous efficiency $V_a(\lambda)$

Age-dependent, photopic, visual field 2°



CIE 196:2011
K. Sagawa, Y. Takahashi, 2001

Macula (yellow spot)

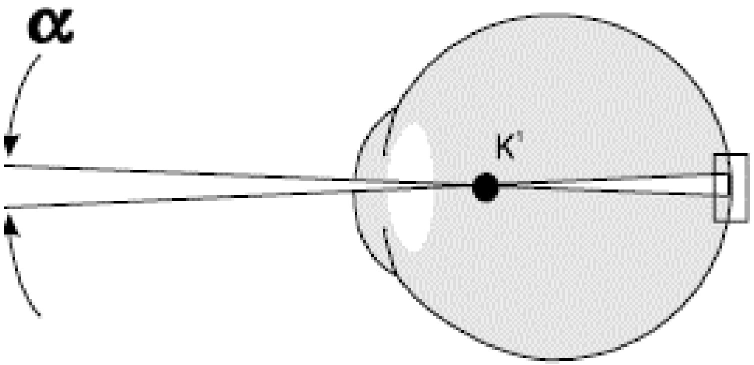
Foveal anatomy of the retina

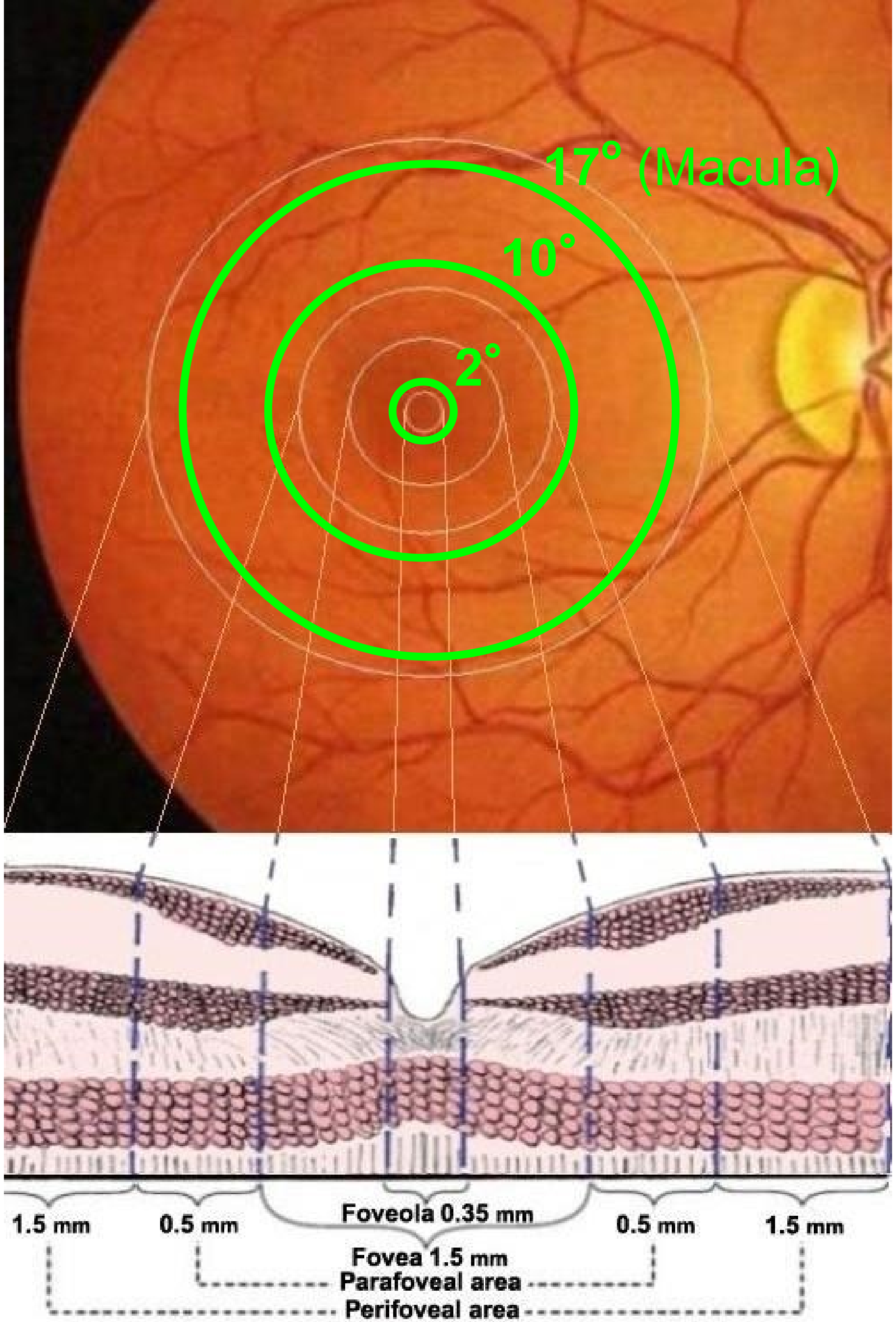
Visual angle α

e.g. 2° (with 0,6 mm diameter)

10° (with 3,0 mm diameter)

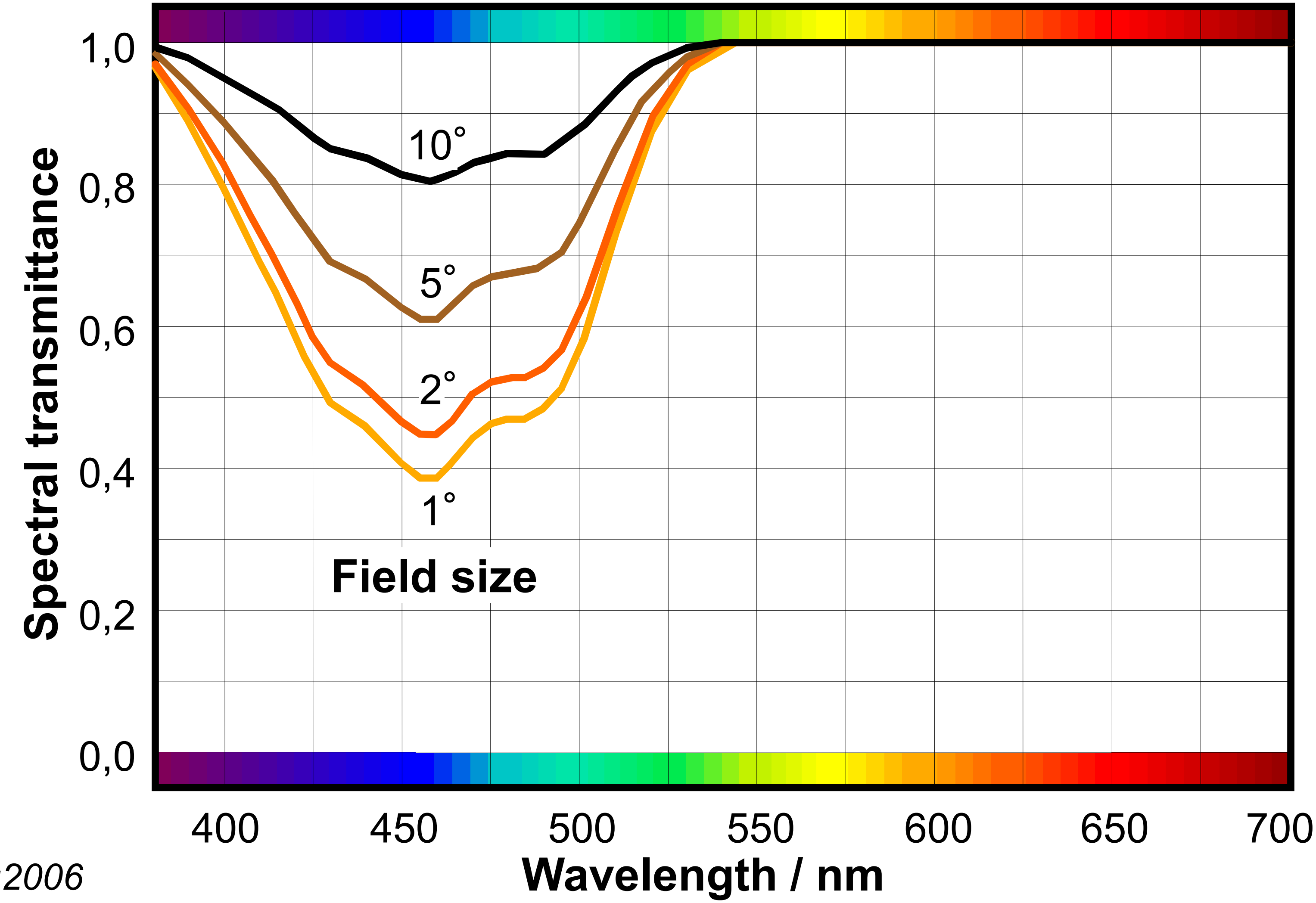
17° (with 5,0 mm diameter)





Macula (yellow spot)

Transmittance and influence of the field size

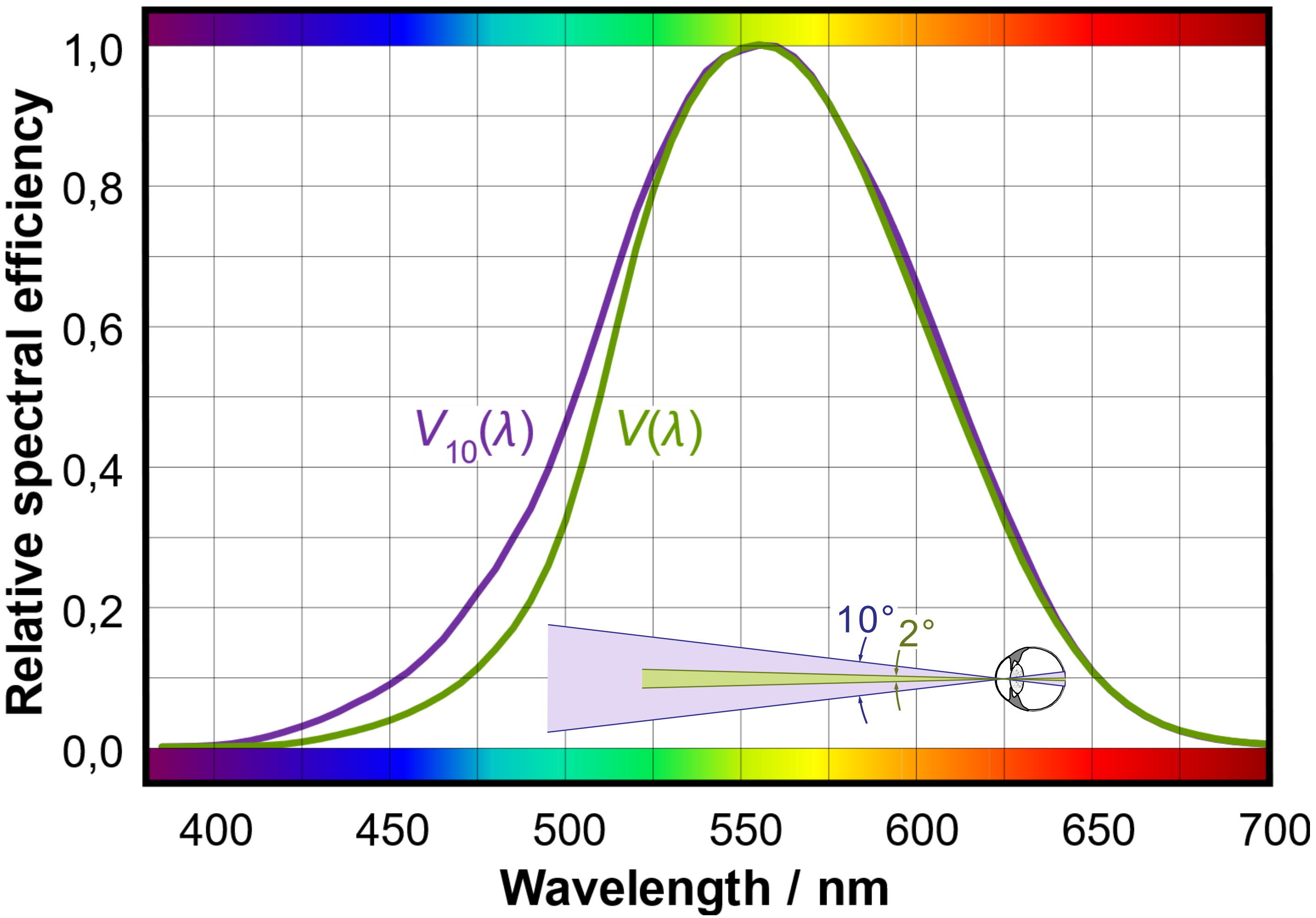


CIE Report 170-1:2006

Spectral luminous efficiency function

$V_{10}(\lambda)$ photopic vision
from 2005, for a field size of 10°

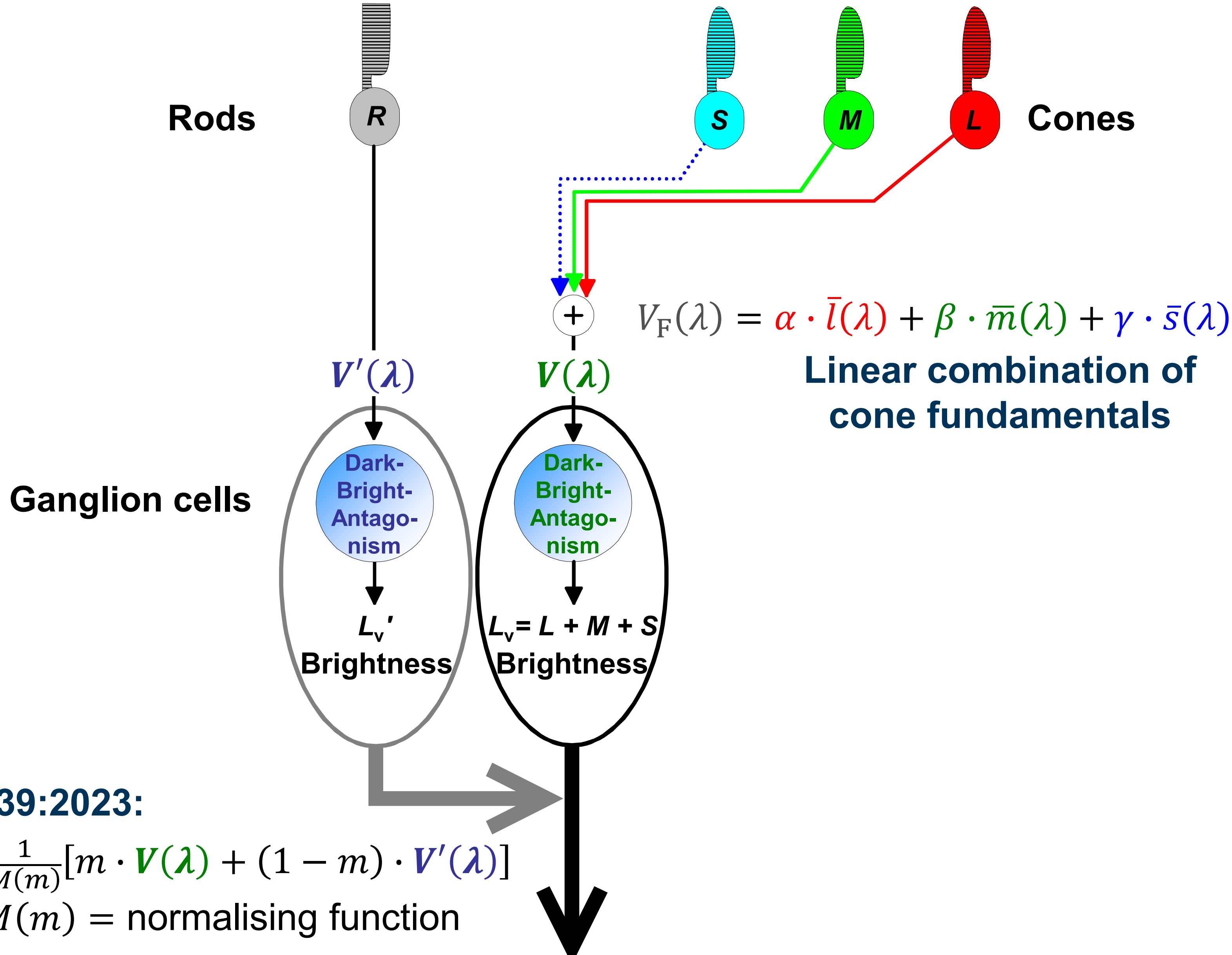
$V(\lambda)$ photopic vision
from 1924, for a field size of 2°



ISO/CIE 23539:2023

Physiological basics of photometry

Photopic
Mesopic
Scotopic



ISO/CIE 23539:2023:

$$V_{mes;m}(\lambda) = \frac{1}{M(m)}[m \cdot V(\lambda) + (1-m) \cdot V'(\lambda)]$$

$0 \leq m \leq 1;\ M(m) =$ normalising function

M- and L-Cone fundamentals

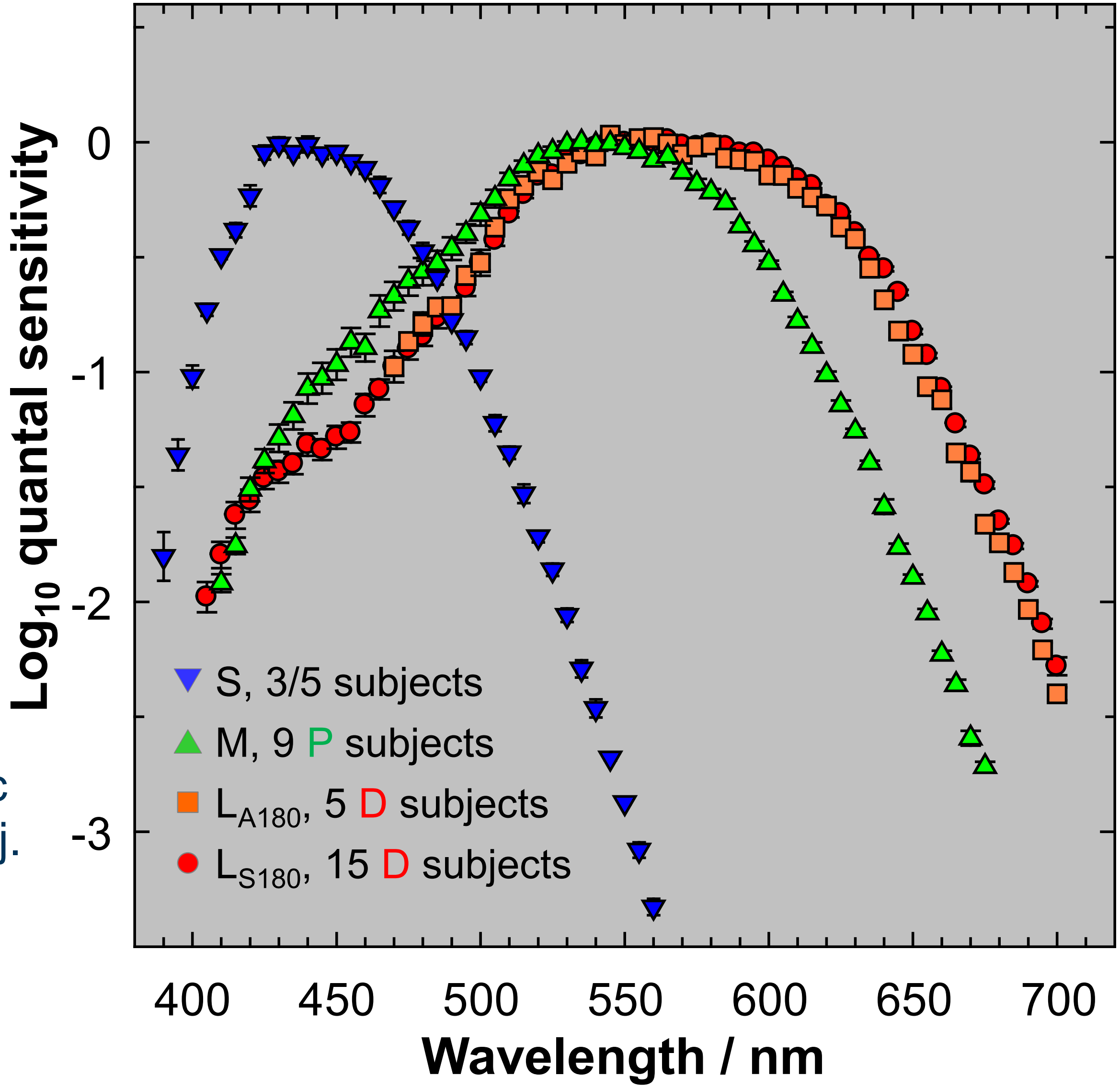
Measurements in observers

Andrew Stockman

- 29 genetically controlled dichromats (D, P; 18…45 y)
- Flicker photometry 2° and 10°: 560 nm vs. λ | 25 Hz & 16 Hz
- Monochromatic background 430 nm | 680 cd/m² | 18°
- Cross-check with colourimetric data of 9 (2°) and 39 (10°) subj. *(Stiles, Burch, 1955 and 1959).*
- *Cross-check with* receptor absorptance spectra *(Dartnall et al., 1983).*

A. Stockman, L.T. Sharpe, 2000

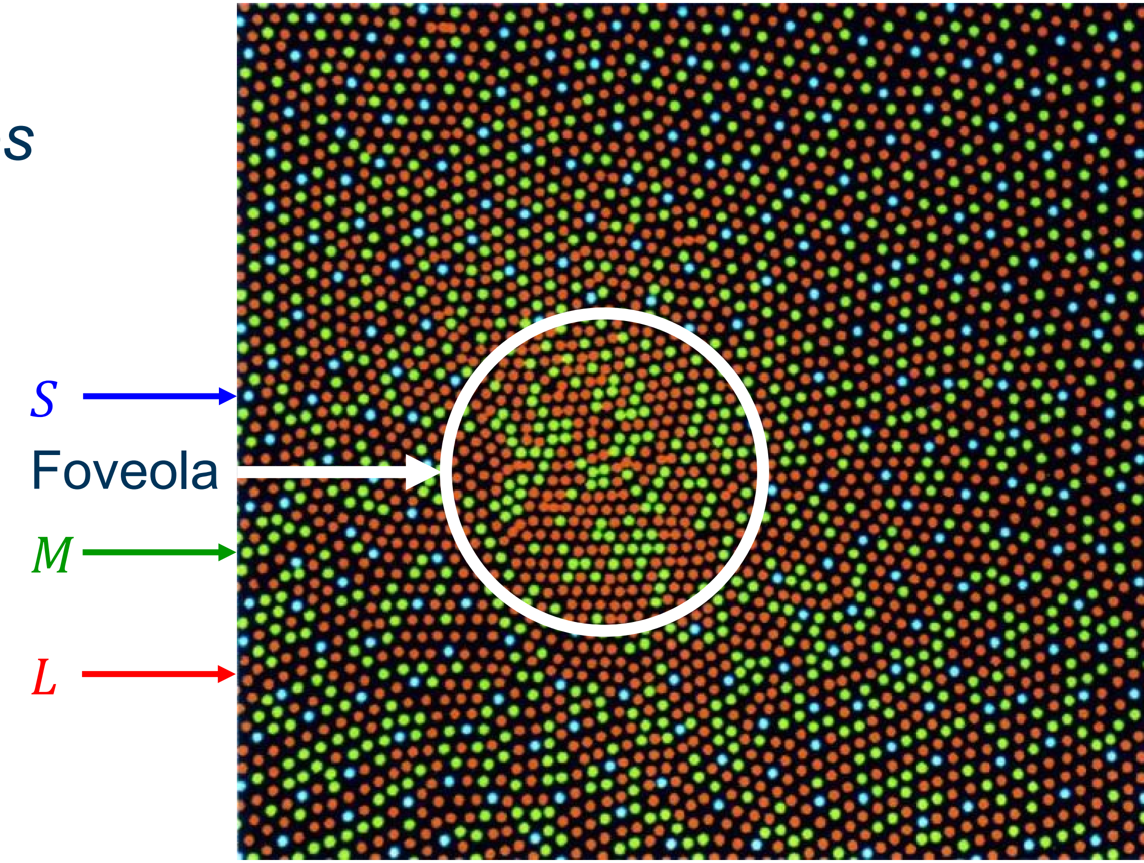
▼ → *A. Stockman, Sharpe L.T., Fach C., 1999*



Receptor mosaic

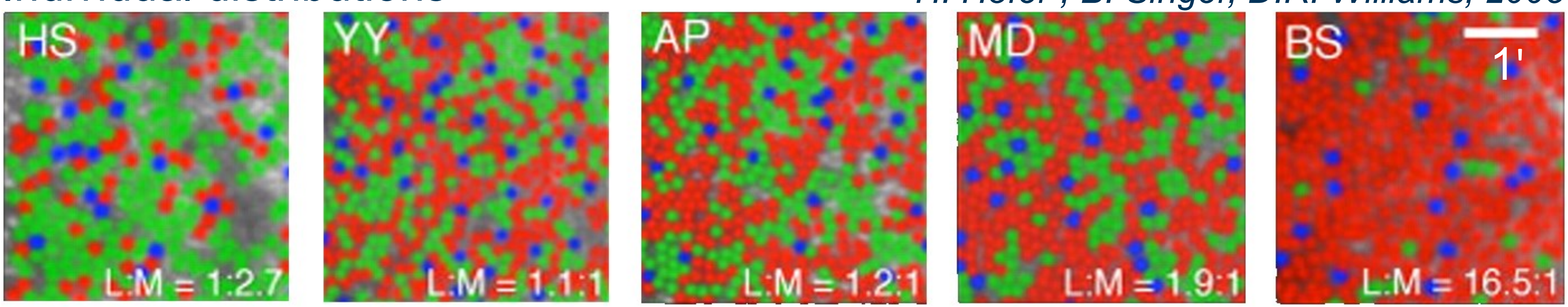
Distribution of cone types

- Psychophysical data suggest that the relative number of receptor types in the 2° field is 1:17:34 *(Vos, 1990)*.
- Does the number of receptor types determine the spectral luminous sensitivity?
- Apparently not: the individual absolute sensitivities of the receptor types are decisive.



Individual distributions

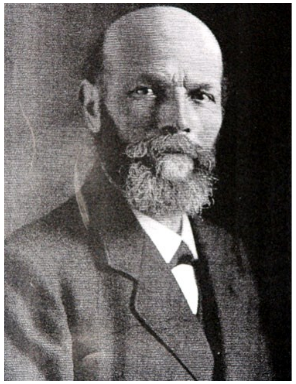
H. Hofer , B. Singer, D.R. Williams, 2005



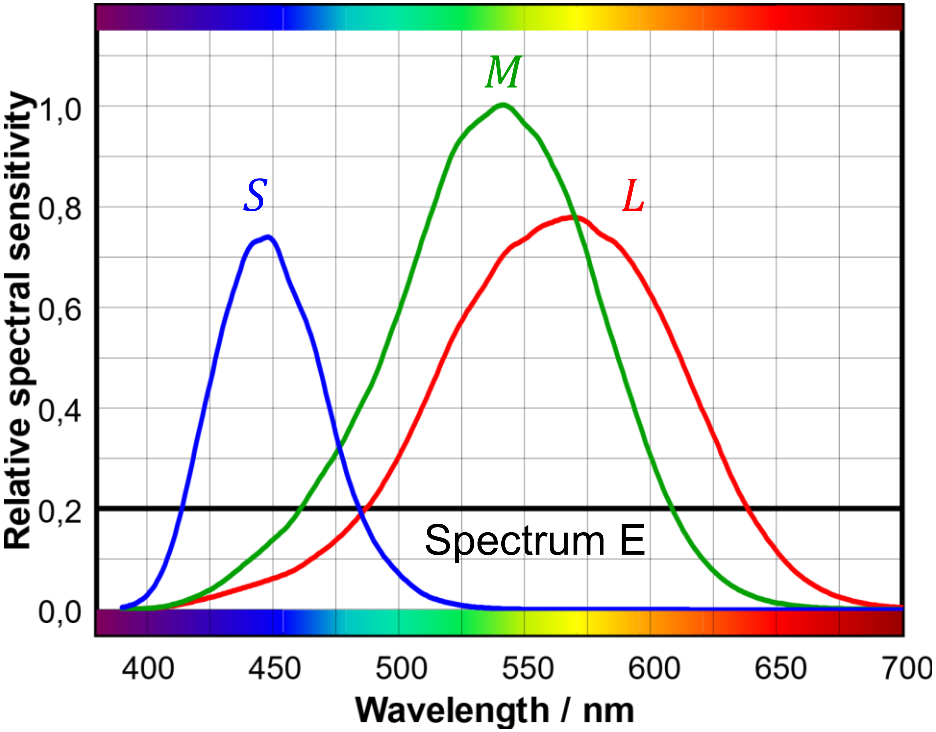
Von Kries chromatic adaptation transform

von Kries coefficients $k_\mathrm{S}, k_\mathrm{M}, k_\mathrm{L}$

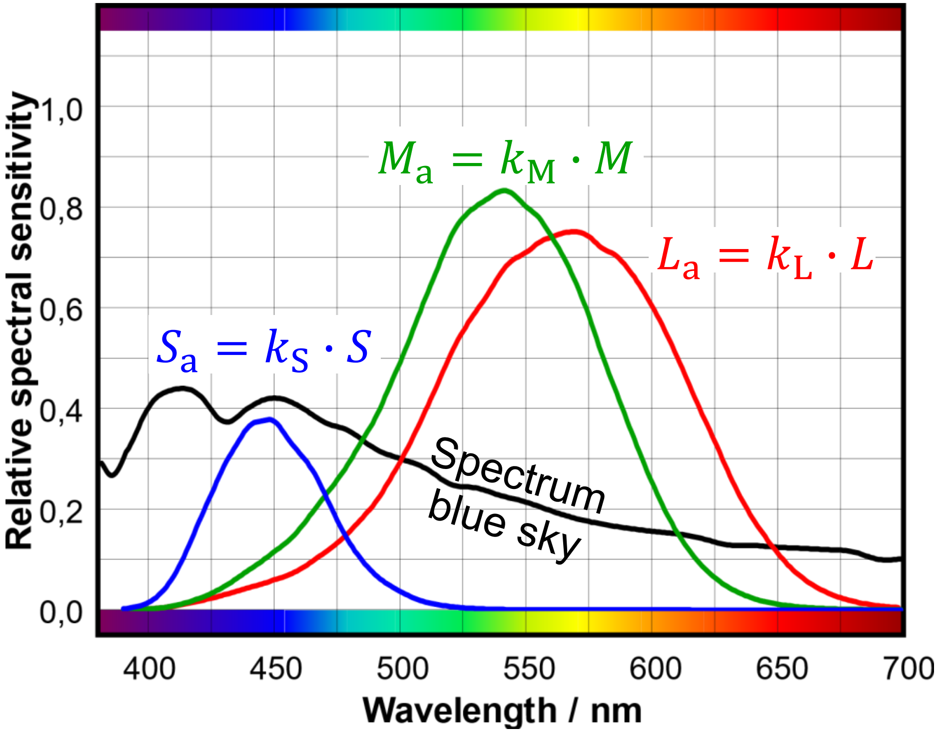
Johannes von Kries
(1853-1928)



Receptors equally strongly adapted to the equal energy spectrum E



Colour adaptation to the spectrum of the blue sky



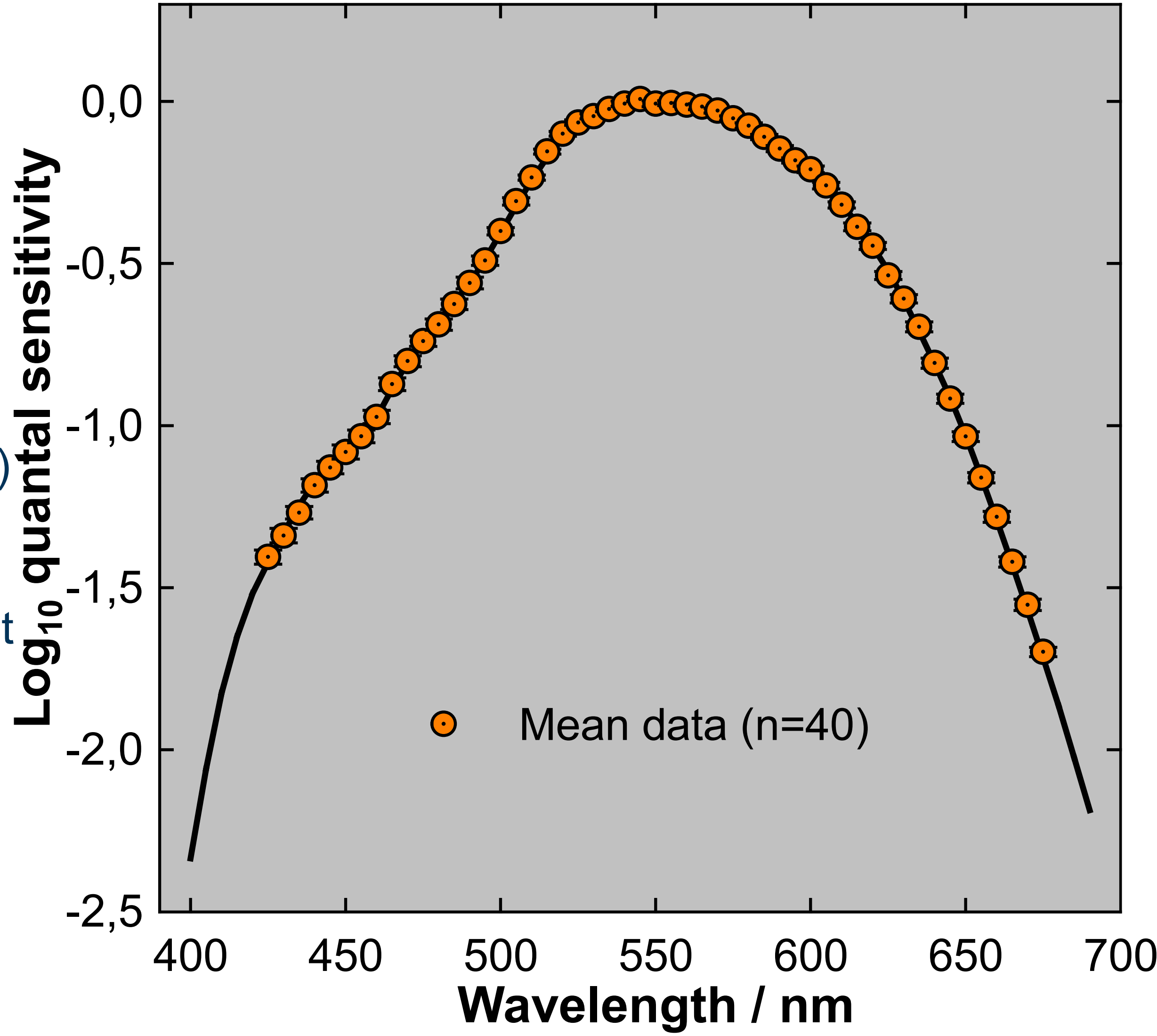
Luminous efficiency function *V*(λ)*

Measurements in observers

Lindsay Theodore Sharpe

- 40 genetically controlled tri-chromats (5 f, 25 m; 18…48 y)
- Flicker photometry: 560 nm vs. *λ* | 25 Hz | 2°
- White background, equivalent to D65 | 566 cd/m² | 16°
- Correction of the influence of the visual targets on colour adaptation
- Consistent with a linear combination of the M- and L-cone fundamentals

L.T. Sharpe; A. Stockman; W. Jagla; H. Jägle, 2005
L.T. Sharpe; A. Stockman; W. Jagla; H. Jägle, 2011



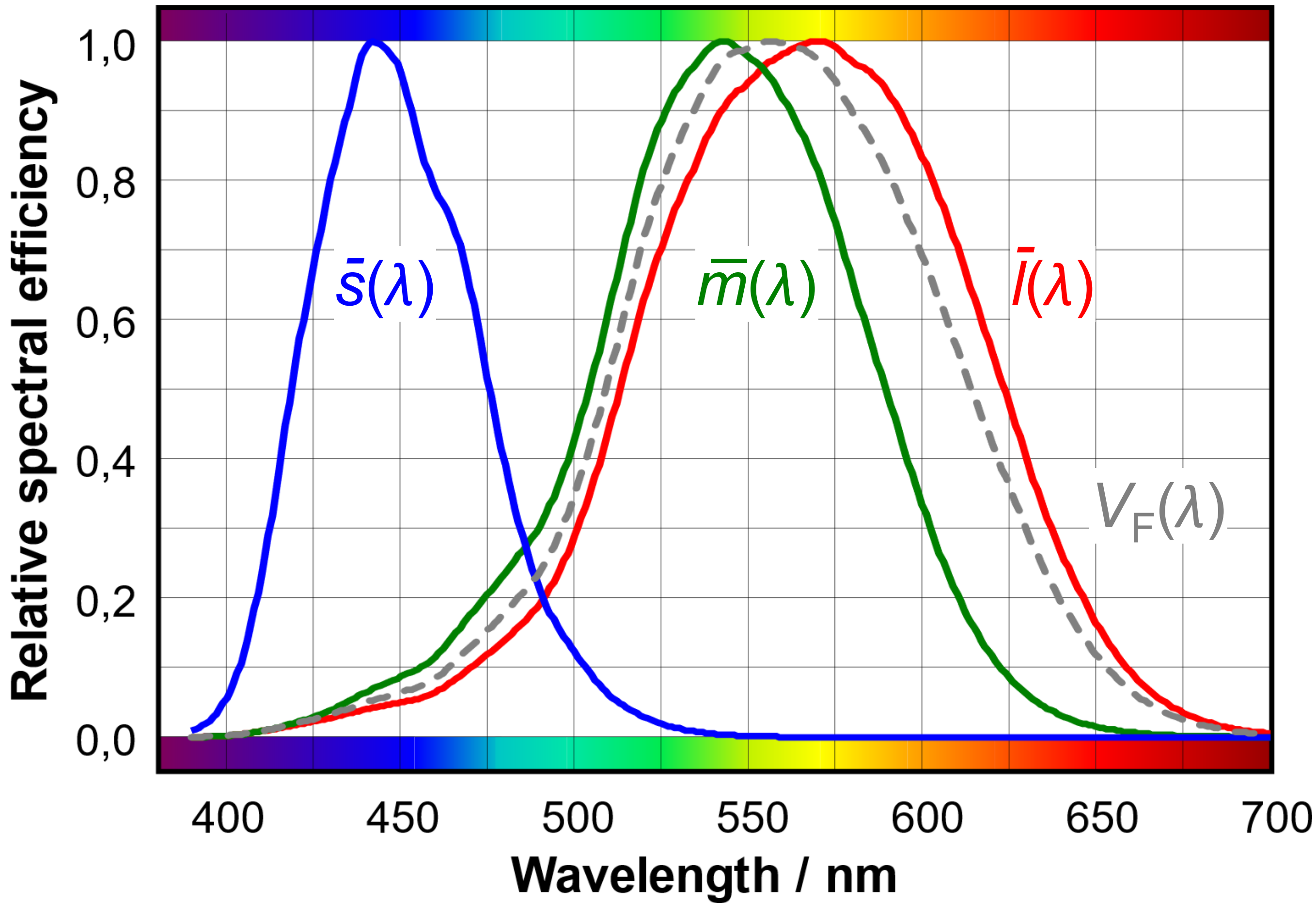
Newly proposed 2° spectral sensitivities

Cone fundamentals $\bar{l}(\lambda)$, $\bar{m}(\lambda)$, $\bar{s}(\lambda)$

Spectral luminous efficiency function $V_F(\lambda)$ for D65-adaptation

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

„ Grundfunktionen basierte spektrale Hellempfindlichkeit "



L.T. Sharpe et al., 2005
CIE 170-1, 2006
L.T. Sharpe et al., 2011
CIE 170-2, 2015

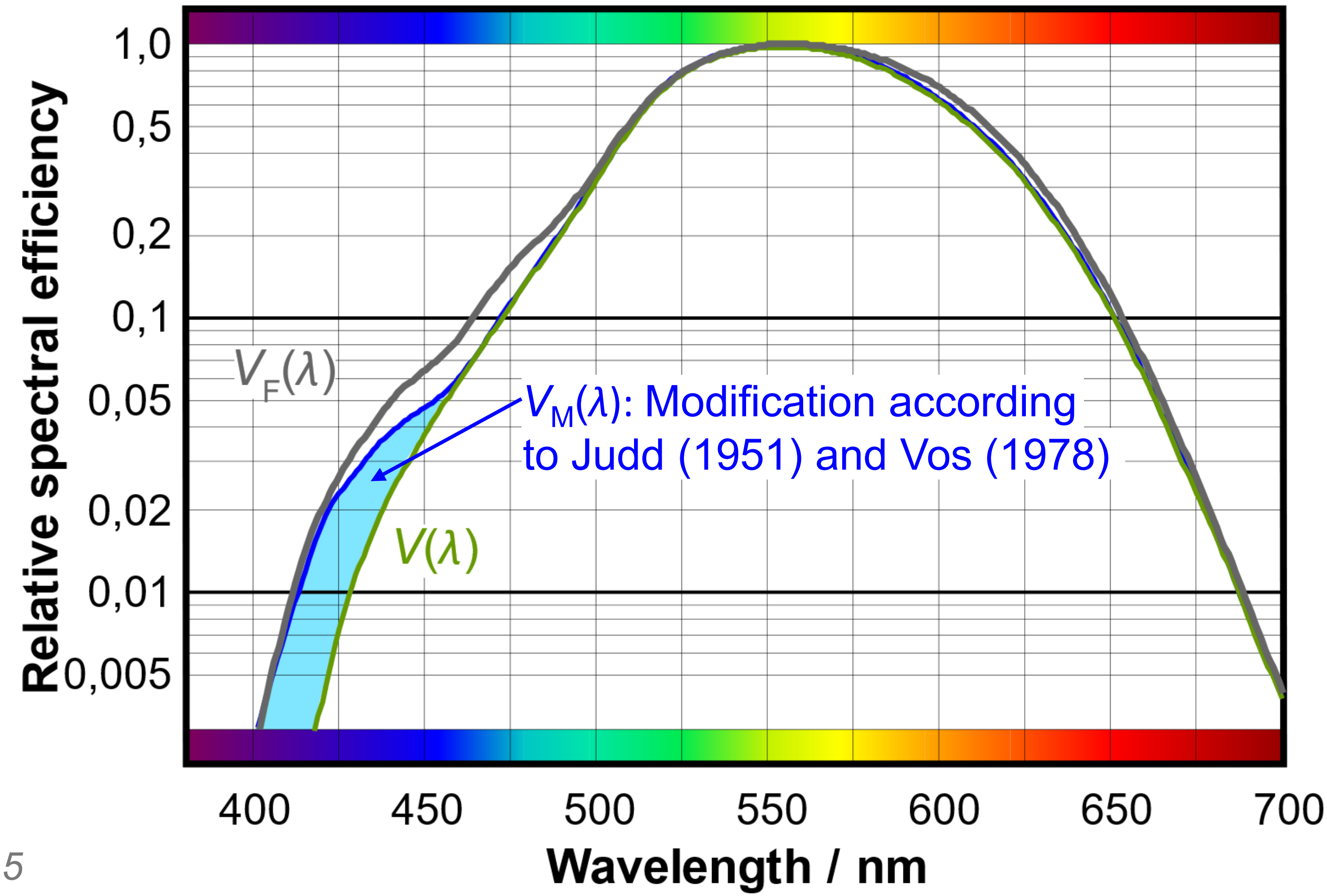
Overview

- History: Visual Photometry
- Measuring spectral luminous sensitivity functions
- Spectral luminous efficiency functions since $V(\lambda)$ from 1924
- Cone fundamental based spectral sensitivities
- **Impact of introducing cone fundamental based new $V_F(\lambda)$**
- Influences still not considered
- Summary

Impact of introducing $V_F(\lambda)$

$V_M(\lambda)$: CIE 1988 Modified

$V_F(\lambda)$: Cone-Fundamental-Based

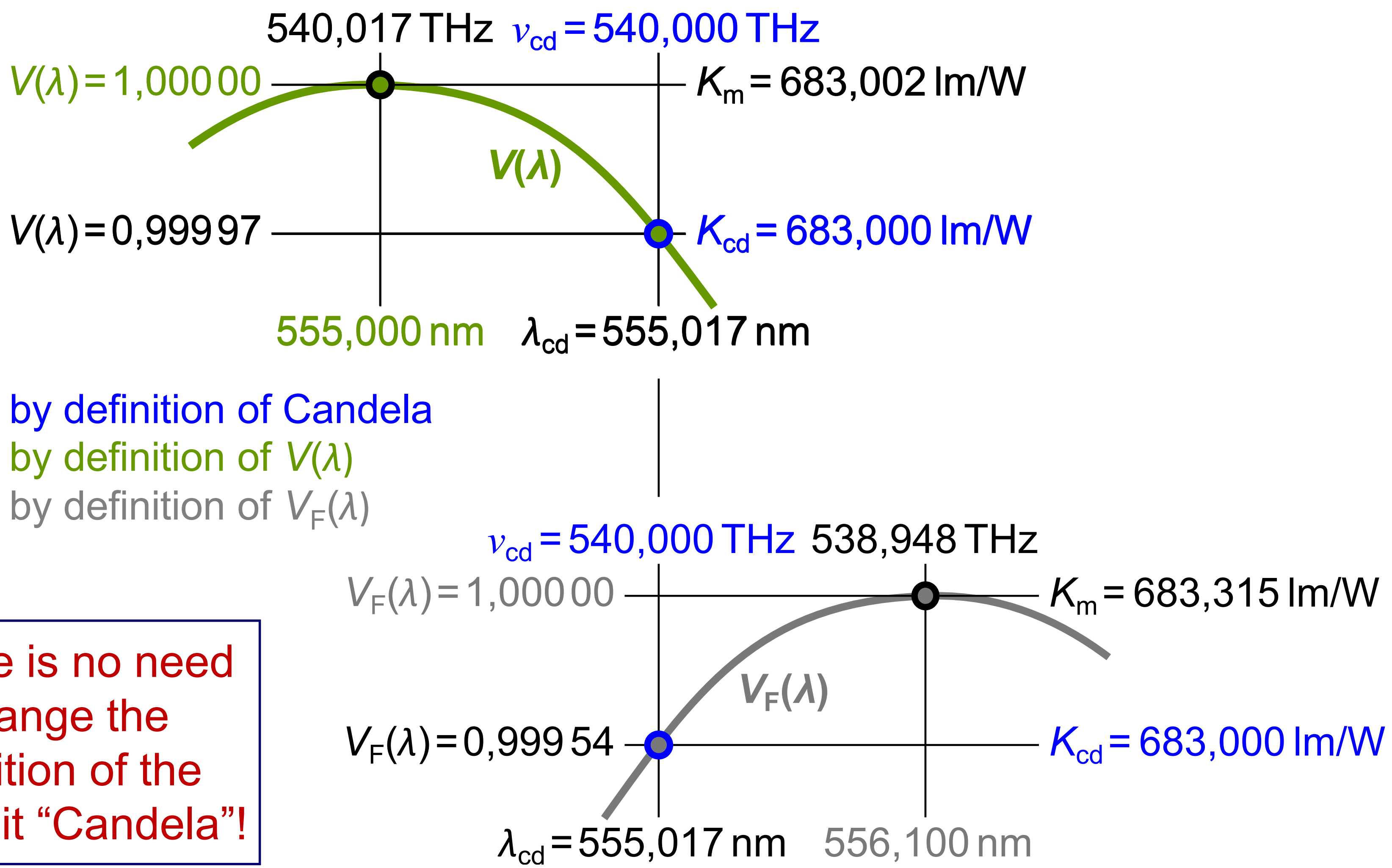


CIE Report 86:1990

CIE Report 170-2:2015

Impact of introducing $V_F(\lambda)$

Definition of SI unit "Candela"



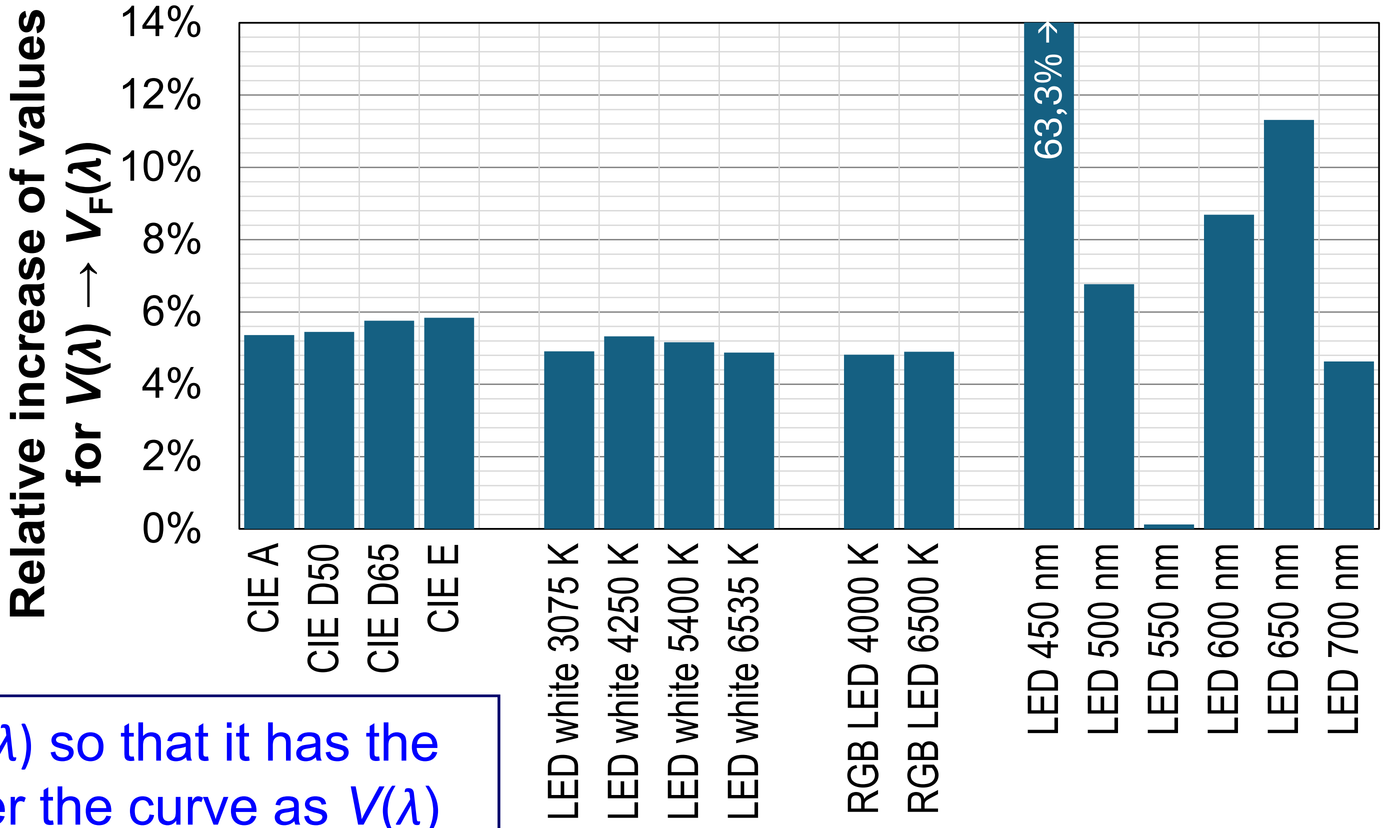
Anchored by definition of Candela
Anchored by definition of $V(\lambda)$
Anchored by definition of $V_F(\lambda)$

→ There is no need to change the definition of the SI unit "Candela"!

Impact of introducing $V_F(\lambda)$

Change of photometric values for typical light sources

→ Is there nevertheless a need to change the definition of the SI unit "Candela"?



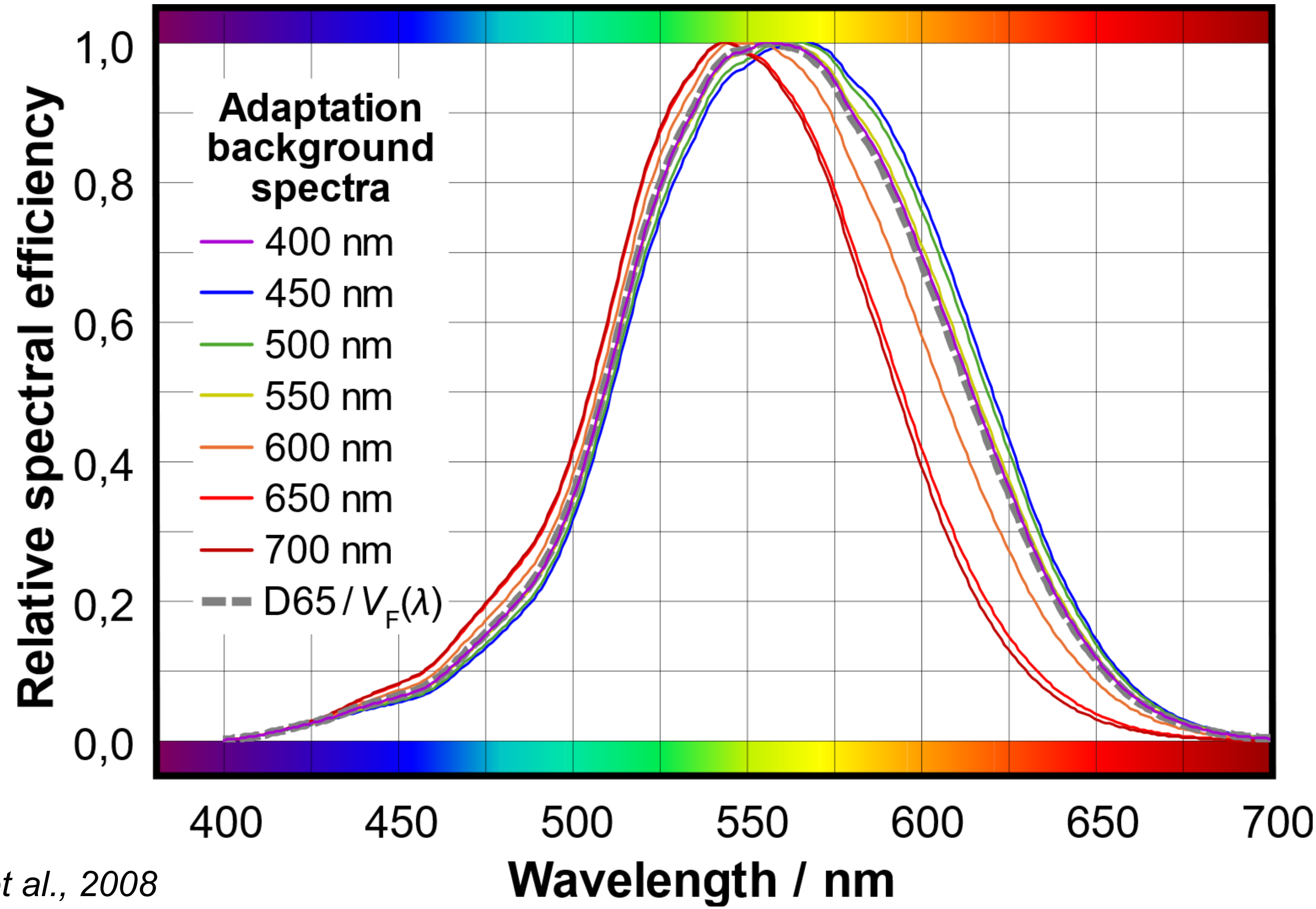
→ No! Reduce $V_F(\lambda)$ so that it has the same area under the curve as $V(\lambda)$ or use equivalent photometric quantities using correction factors.

Overview

- History: Visual Photometry
- Measuring spectral luminous sensitivity functions
- Spectral luminous efficiency functions since $V(\lambda)$ from 1924
- Cone fundamental based spectral sensitivities
- Impact of introducing cone fundamental based new $V_F(\lambda)$
- **Influences still not considered**
- Summary

Luminous efficiency function $V^*_\mu(\lambda)$

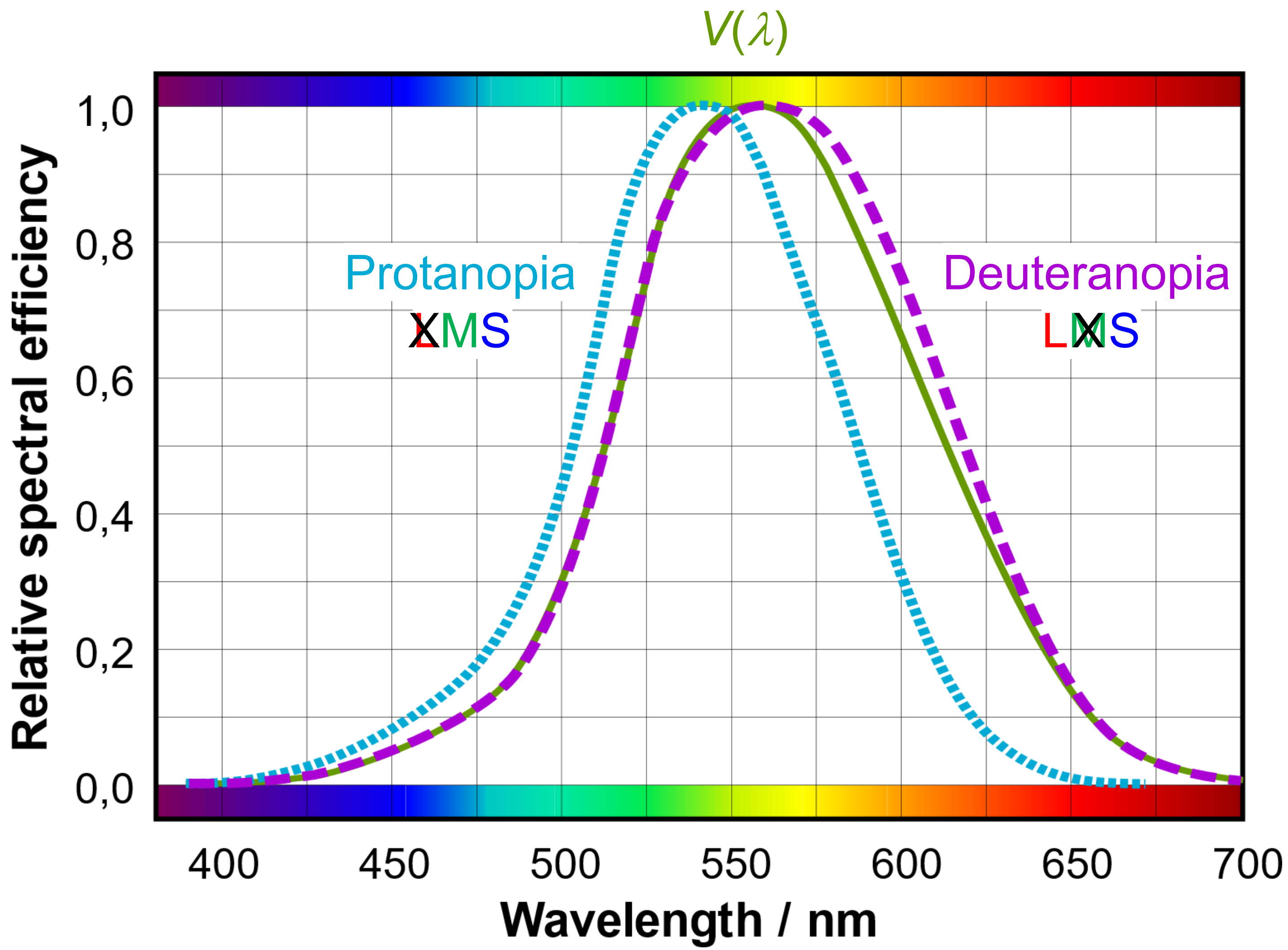
Dependence on chromatic adaptation



A. Stockman et al., 2008

Spectral luminous efficiency

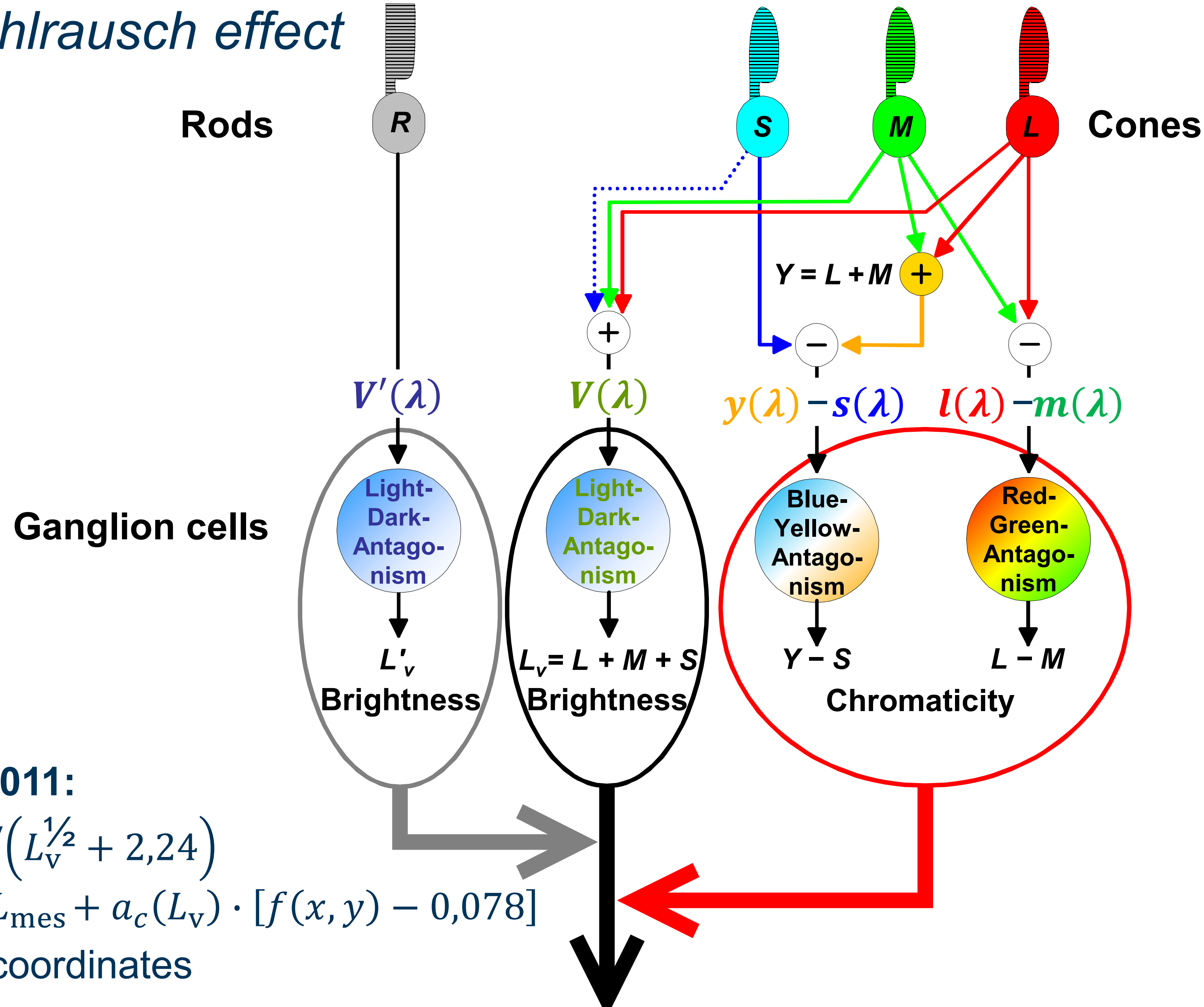
Red-green colour blindness



D.B. Judd, 1979

Influences not considered

Helmholtz-Kohlrausch effect



CIE-Report 200:2011:

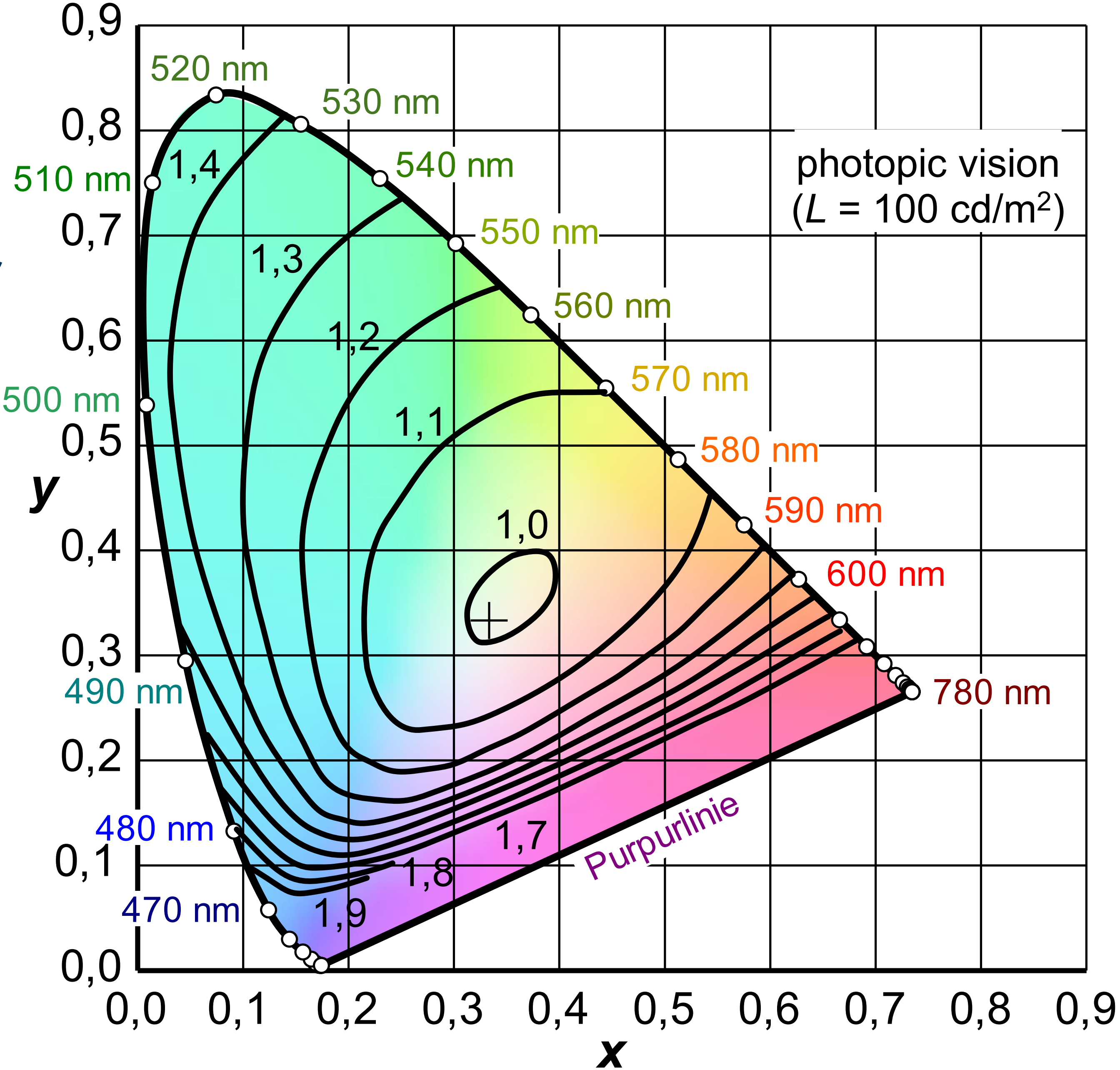
$$a_c(L_v) = 1{,}3 \cdot L_v^{1/2} / \left(L_v^{1/2} + 2{,}24\right)$$

$$\log_{10} L_{eq} = \log_{10} L_{mes} + a_c(L_v) \cdot [f(x,y) - 0{,}078]$$

x, y: chromaticity coordinates

Helmholtz-Kohlrausch effect

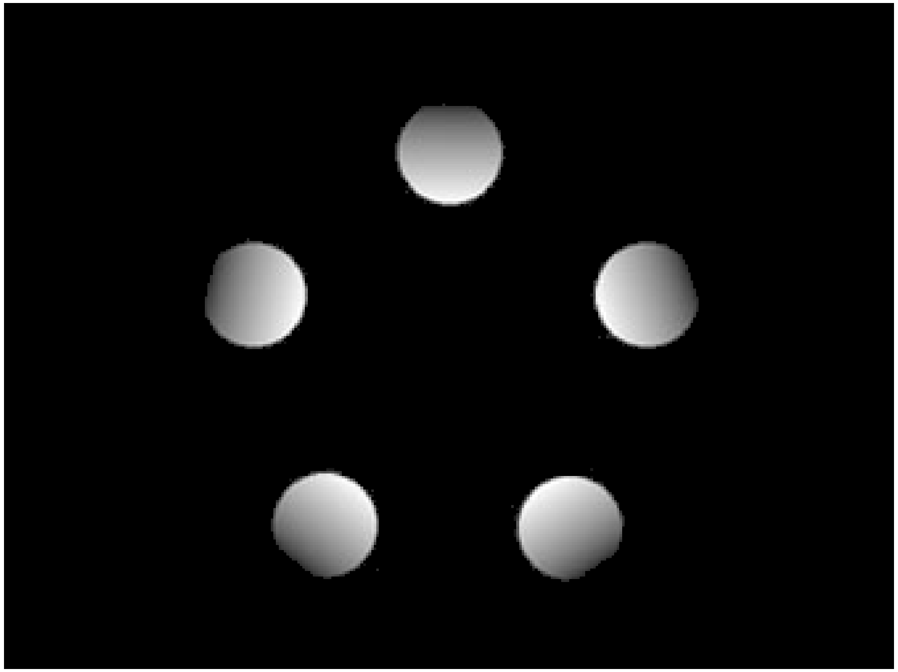
Factor $10^{f(x,y)}$ *for the luminance* L_{eq} *equivalent to white light*

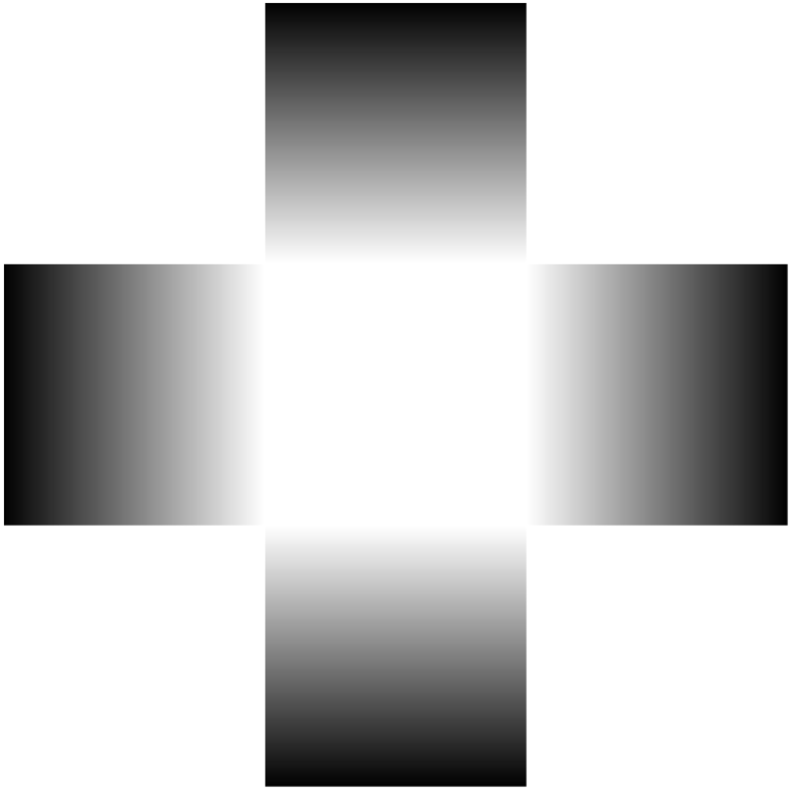


K. Sagawa, 2006

Influence of context

Phantom illumination illusion

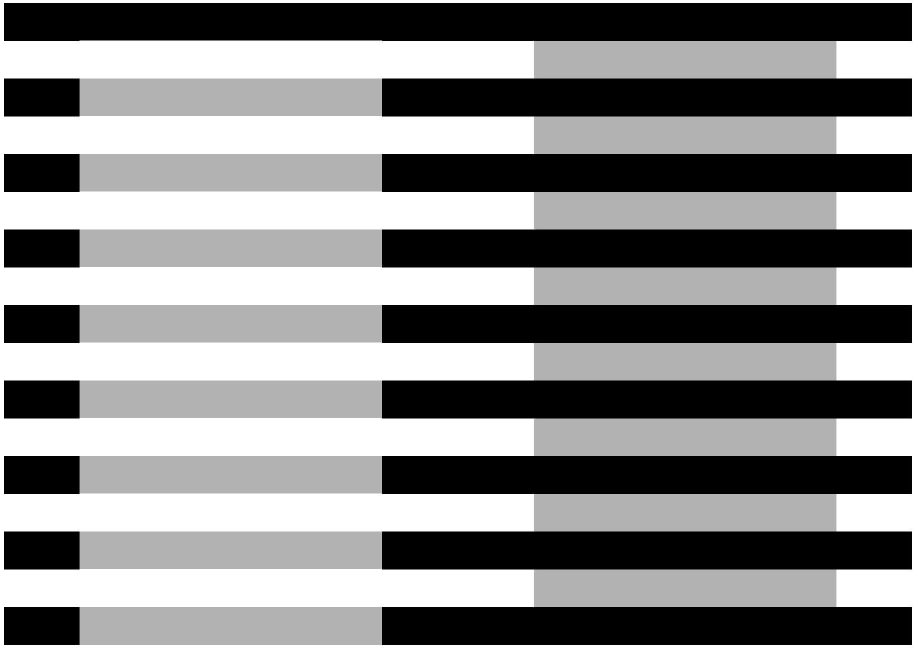




Daniele Zavagno, 2005

Influence of context

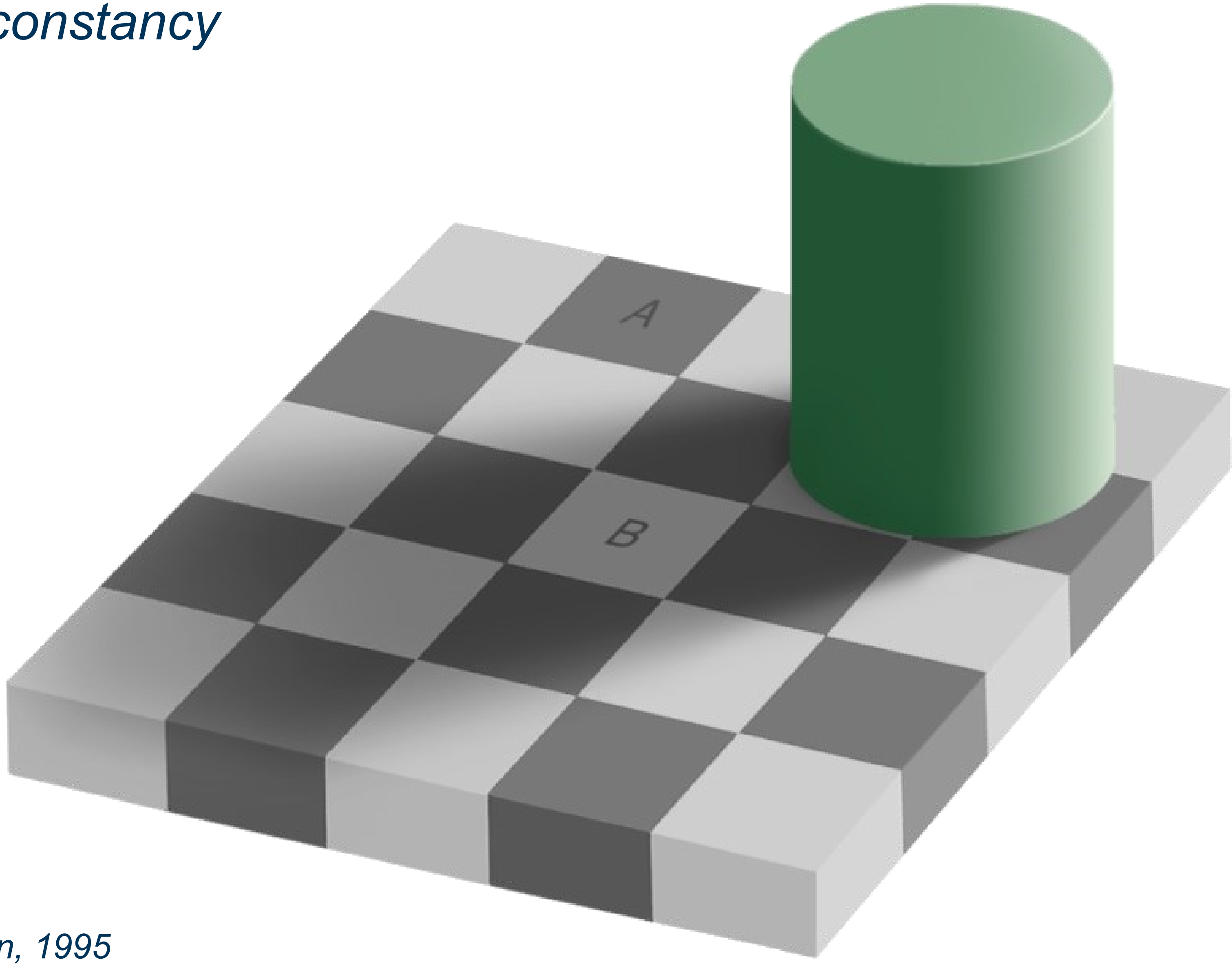
White's illusion



M. White, 1979

Influence of context

Brightness constancy



Edward H. Adelson, 1995

Summary

- Until the beginning of the 20th century, photometry was carried out visually by comparing brightness with a known reference light source.
- Visual photometry becomes inaccurate with different coloured light sources. In addition, the development of photocells at the end of the 19th century required knowledge of the spectral light sensitivity of humans.
- Studies with test subjects showed that flicker photometry and direct heterochromatic photometry using the step-by-step method provided reliable brightness sensitivity functions that also fulfil linear additivity (Abney's law).
- Based on such investigations, the CIE introduced the photopic spectral luminous efficiency function $V(\lambda)$ in 1924, which is still in use today.
- Later, the CIE introduced further $V(\lambda)$-functions that corrected errors in the short-wave spectral range, or are suitable for scotopic and mesopic vision, for other field sizes, for different ages of persons or for monochromatic light sources.
- The latest development is a photometric (and colourimetric) system based on cone fundamentals $\bar{l}(\lambda)$, $\bar{m}(\lambda)$ and $\bar{s}(\lambda)$. A new spectral luminous efficiency function $V_F(\lambda)$, which is compatible with this for illuminant D65, has been published.
- Whether $V_F(\lambda)$ should replace or supplement the existing $V(\lambda)$ and thus jeopardise the SI-unit Candela is currently the subject of controversial debate.
- Colour adaptation to other illuminants, other field sizes and other ages are not considered. However, models for this could be developed.
- Cognitive processes of brightness perception remain unconsidered.

Thank you for your attention!

Univ.-Prof. Dr. Christoph Schierz
TU Ilmenau
Fakultät für Maschinenbau
Fachgebiet Lichttechnik
Prof.-Schmidt-Straße 26
98683 Ilmenau
christoph.schierz@tu-ilmenau.de
http://www.tu-ilmenau.de/lichttechnik/

List of references

- Abney, W.; Festing, E.R. (1886): „Colour photometry". Philos. Trans. R. Soc. London V177 P423-456.
- Abney, W. (1913): Researches in Colour Vision (Longmans, Green, London).
- Adelson E. A. (1995): Checker Shadow Illusion
- CIE 75 (1988): Spectral luminous efficiency functions based upon brightness matching for monochromatic point sources, 2° and 10° fields. CIE Central Bureau, Vienna.
- CIE 86 (1990): 2° spectral luminous efficiency function for photopic vision. CIE Central Bureau, Vienna.
- CIE 170-1 (2006): Fundamental chromaticity diagram with physiological axes - Part 1. CIE, Vienna.
- CIE 170-2 (2015): Fundamental Chromaticity Diagram with Physiological Axes – Part 2: Spectral Luminous Efficiency Functions and Chromaticity Diagrams. CIE Central Bureau, Vienna.
- CIE 196 (2011): CIE Guide to Increasing Accessibility in Light and Lighting. CIE Central Bureau, Vienna.
- CIE 200 (2011): CIE Supplementary System of Photometry. CIE Central Bureau, Vienna.
- Dartnall, H.J.A.; Bowmaker, J.K.; Mollon, J.D. (1983): Human Visual Pigments. Microspectrophotometric Results from the Eyes of Seven Persons. Proc. R. Soc. Lond., B, Biol. Sci. V220 N1218 P115-130.
- Gibson, K.S.; Tyndall, E.P.T. (1923): Visibility of radiant energy. Sci. Pa. Natl. Bur. Stand. V19 P131.
- Hofer, H.; Singer, B.; Williams, D.R. (2005): Different sensations from cones with the same photopigment. J. Vis. V5 N5 P444-454.
- ISO/CIE 23539 (2023): Photometry - The CIE system of physical photometry. CIE Central Bureau, Vienna.
- Judd, D.B. (1951): Secr. Rep. "Colorimetry and artificial daylight," in Proc. 12th Session C.I.E.,Stockholm, Vol. I , Techn. Committee No. 7, Bureau Central de la CIE, Paris, P11.
- Judd, D.B. (1979): Contributions to Color Science. Washington D.C. 20234: NBS P316.
- King-Smith, P.E.; Carden, D. (1976): Luminance and opponent-color contributions to visual detection and adaptation and to temporal and spatial integration. J. Opt. Soc. Am. V66 N7 P709-717.
- Lennie, P.; Pokorny, J.; Smith, V.C. (1993): Luminance. J. Opt. Soc. Am. A V10 N6 P1283.
- Lerman, S. (1980): Radiant energy and the eye. London, Balliere Tindall.
- Osterberg G. (1934): Topography of the layer of rods and cones in the human retina. Acta Ophthal. Suppl. V6 P1-103.

List of references (continued)

- Sagawa, K.; Takahashi, Y. (2001): Spectral luminous efficiency as a function of age. J. Opt. Soc. Am. A V18 N11 P2659.
- Sagawa, K. (2006): Toward a CIE supplementary system of photometry: brightness at any level including mesopic vision. Ophthal. Physiol. Opt. V26 N3 P240-245.
- Sharpe, L.T.; Stockman, A.; Jagla, W.; Jägle, H. (2005): A luminous efficiency function, V*(λ), for daylight adaptation. J. Vis. V5 N11 P948-968.
- Sharpe, L.T.; Stockman, A.; Jagla, W.; Jägle, H. (2011): A luminous efficiency function, V_{D65}*(λ), for daylight adaptation. A correction. Color Res. Appl. V36 N1 P42-46.
- Stiles, W.S.; Burch, J.M. (1955): Interim report to the CIE, Zurich, 1955, on the National Physical Laboratory's investigation of colour-matching (1955). Opt. Acta (Lond) V2 N4 P168-181.
- Stiles, W.S.; Burch, J.M. (1959): N. P. L. colour-matching investigation: Final report (1958). Opt. Acta (Lond) V6 N1 P1-26.
- Stockman, A.; Sharpe, L.T.; Fach, C. (1999): The spectral sensitivity of the human short-wavelength sensitive cones derived from thresholds and color matches. Vision Res. V39 N17 P2901-2927.
- Stockman, A.; Sharpe, L.T. (2000): The spectral sensitivities of the middle- and long-wavelength-sensitive cones derived from measurements in observers of known genotype. Vision Res. V40 N13 P1711-1737.
- Stockman, A.; Jägle, H.; Pirzer, M.; Sharpe, L.T. (2008): The dependence of luminous efficiency on chromatic adaptation. J. Vis. V8 N16 P1-26.
- Van de Kraats, J.; van Norren, D. (2007): Optical density of the aging human ocular media in the visible and the UV. J. Opt. Soc. Am. A V24 N7 P1842-1857.
- Vos, J.J. (1978): Colorimetric and photometric properties of a 2° fundamental observer. Color Res. Appl. V3 N3 P125-128.
- Vos, J.J.; Estévez, O.; Walraven, P.L. (1990): Improved color fundamentals offer a new view on photometric additivity. Vision Res. V30 N6 P937-943.
- White, M. (1979): A new effect on perceived lightness. Perception V8 P413-416.
- Zavagno, D. (2005): The phantom illumination illusion. Percept. Psychophys. V67 N2 P209-218.