International Commission on Illumination
Commission Internationale de l'Eclairage
Internationale Beleuchtungskommission

Quantifying photobiological and photochemical effects

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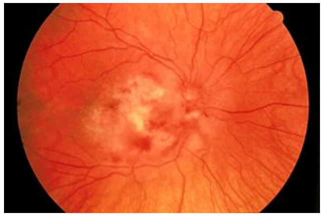
Photobiological and Photochemical Effects

erythema

blue light hazard



production of previtamin D3

photosynthesis

ipRGC-influenced light responses:

"sleep-wake regulation" "(non-)seasonal depression" "pupillary reflex"

"heart rate" "thermoregulation"

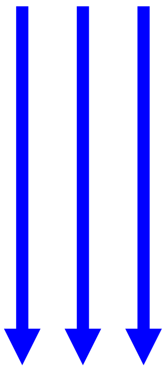
Outline:

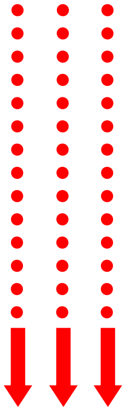
- What ? -> Measurement quantities
- How ? -> Measurement devices

Quantifying Optical Radiation

Radiometric System

Photon System





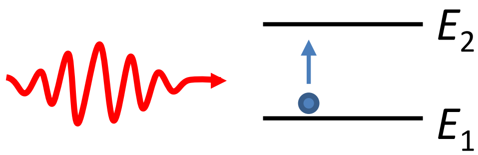
Quantities:
Energy, flux, power, irradiance,...
Units:
J, W, W m^{-2}

Quantities:
Photon flux, photon irradiance,...
Units:
s^{-1} , s^{-1} m^{-2}

c.f. International Lighting Vocabulary (CIE S017, http://eilv.cie.co.at)

Interaction of Photon with Molecules

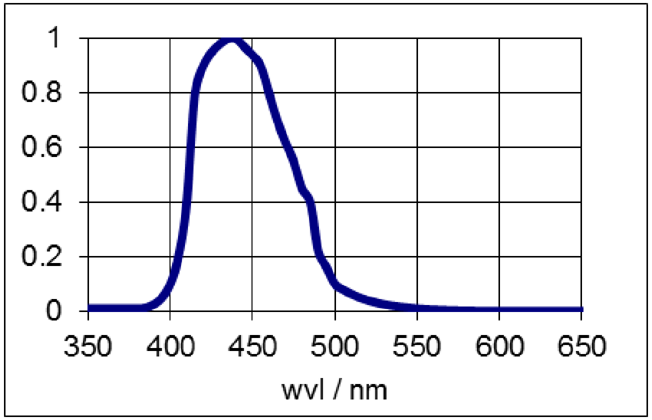
$$E_{\text{photon}} = h\nu = \frac{hnc}{\lambda}$$



$$\Delta E = E_2 - E_1 = \frac{hnc}{\lambda}$$

- Most interactions depend on the energy of the photon, and thus its frequency and wavelength
- The *effectiveness* of the interaction in function of wavelength is expressed by an *action spectrum*

$A_{\text{act}}(\lambda)$

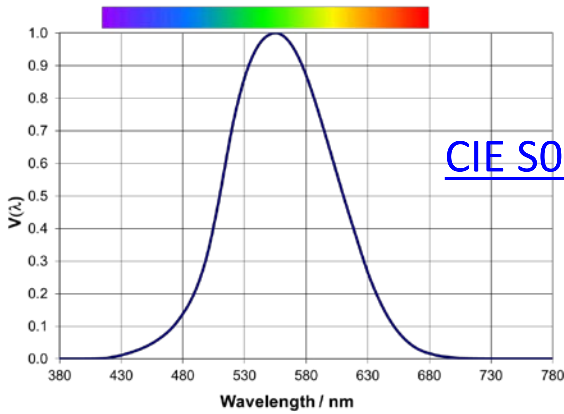


- The action spectrum is a dimensionless function and usually normalized to 1

Examples of Action Spectra

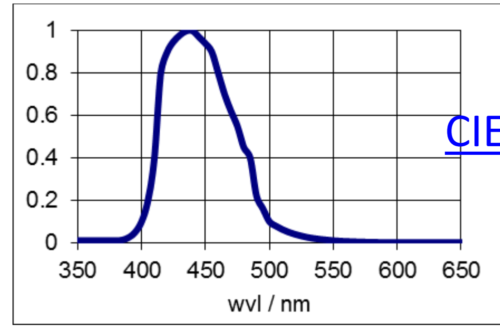
Spectral luminous efficiency

$V(\lambda)$



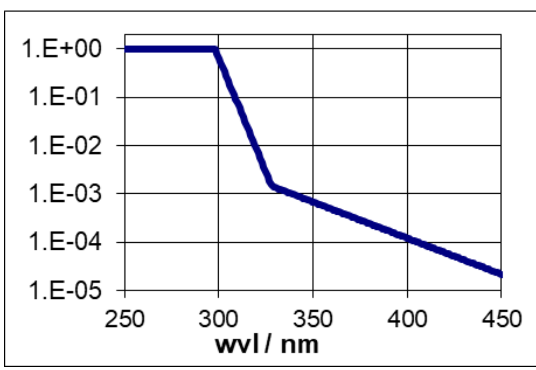
CIE S010

Blue light hazard



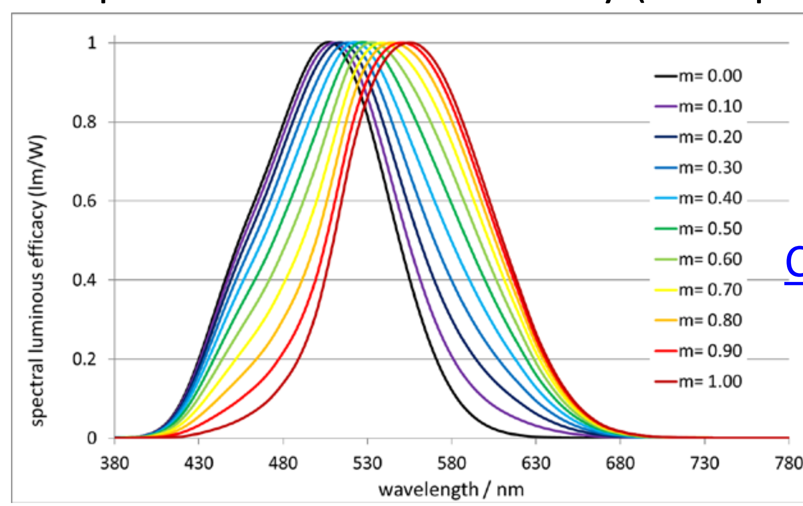
CIE S009

Erythema



CIE S007

Spectral luminous efficiency (mesopic vision)

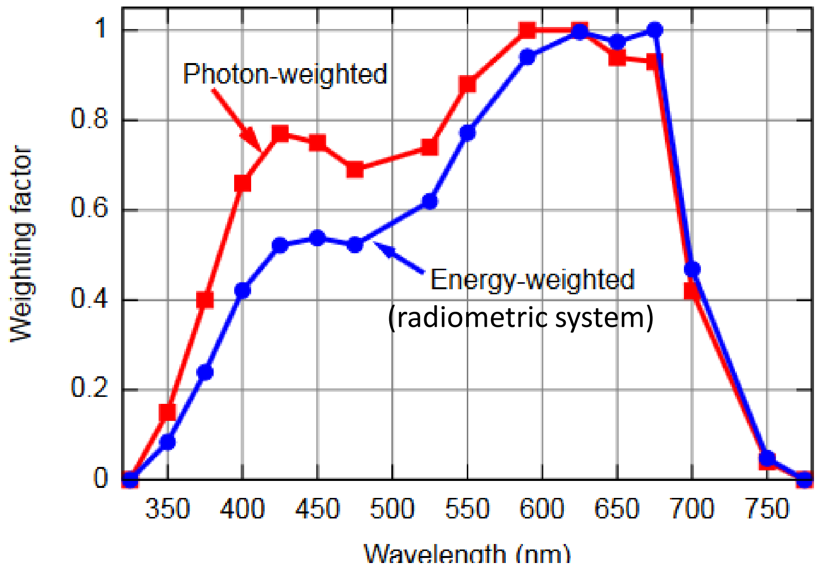


CIE 191

Use internationally agreed action spectra

Action Spectra – Choice of System

- The action spectra depends on the used system of quantities (i.e. photon or radiometric system)
- N.B. the form and peak wavelength are different

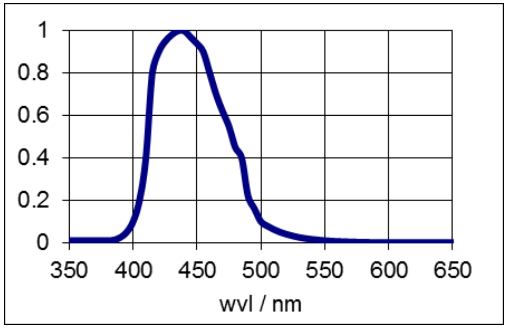


https://en.wikipedia.org/wiki/Photosynthetically_active_radiation#Yield_photon_flux :

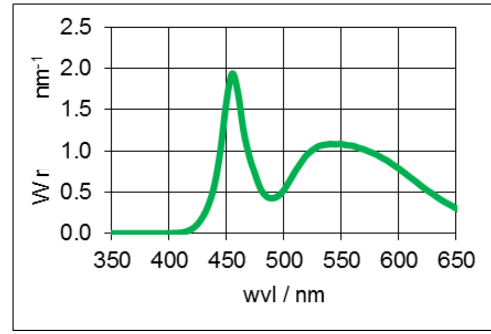
- To avoid confusions, it is essential when using an action spectrum or weighting function to state the system (i.e. radiometric or photon) in which it is defined.

Link of Photobiological/-chemical Response to Incident Polychromatic Radiation:

action spectrum $A_{\mathrm{act}}(\lambda)$



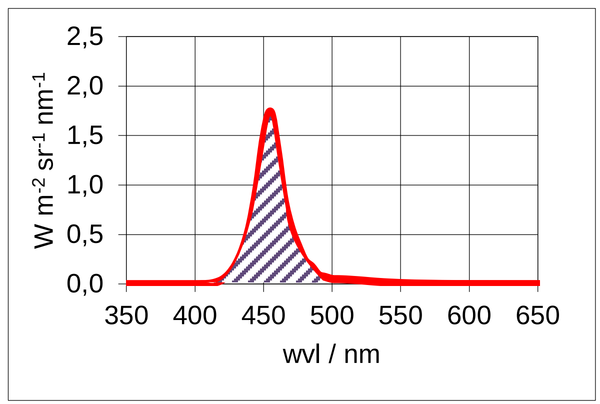
spectral power distribution $\Phi_{\lambda}(\lambda)$



$A_{\mathrm{act}}(\lambda) \cdot \Phi_{\lambda}(\lambda)$

Multiplication

Integration



"Response Quantity": $\Phi_{\mathrm{act}} = \int \Phi_{\lambda}(\lambda) \cdot A_{\mathrm{act}}\,(\lambda)\,\mathrm{d}\lambda$

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Units

Quantities shall be expressed in internationally agreed units (i.e. reference quantities): The SI

http://www.bipm.org

Example: Effective irradiance

$$E_{\mathrm{act}} = \int E_\lambda(\lambda)\, A_{\mathrm{act}}(\lambda)\, \mathrm{d}\lambda$$

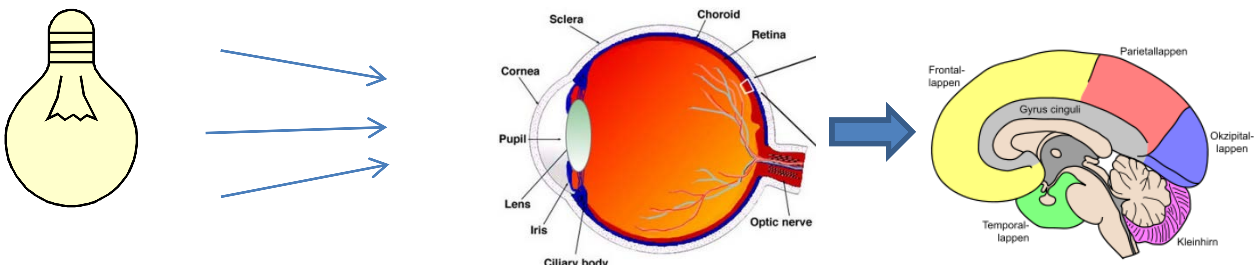
Units: $\mathrm{W{\cdot}m^{-2}}$ **$\mathrm{W{\cdot}m^{-2}{\cdot}nm^{-1}}$** **dimensionless** nm

Different quantities may have the same units.
-> always indicate the quantity

- All effects can be expressed using the SI-units
- Do not define new units!!
- There are no mesopic lumen or melanopic lux…

Further information: CIE TN 002, CIE TN004 and SI-Brochure Appendix 3

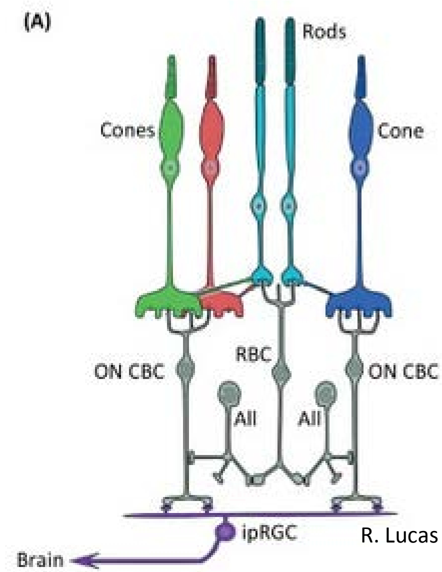
Action Spectra for Non-visual Effects



webvision.me.utah.edu

Common.wikimedia.org

5 photoreceptors



R. Lucas et *al.*

ipRGCs : Intrinsically-Photosensitive Retinal Ganglion Cells

5 action spectra to be defined by CIE JTC 9

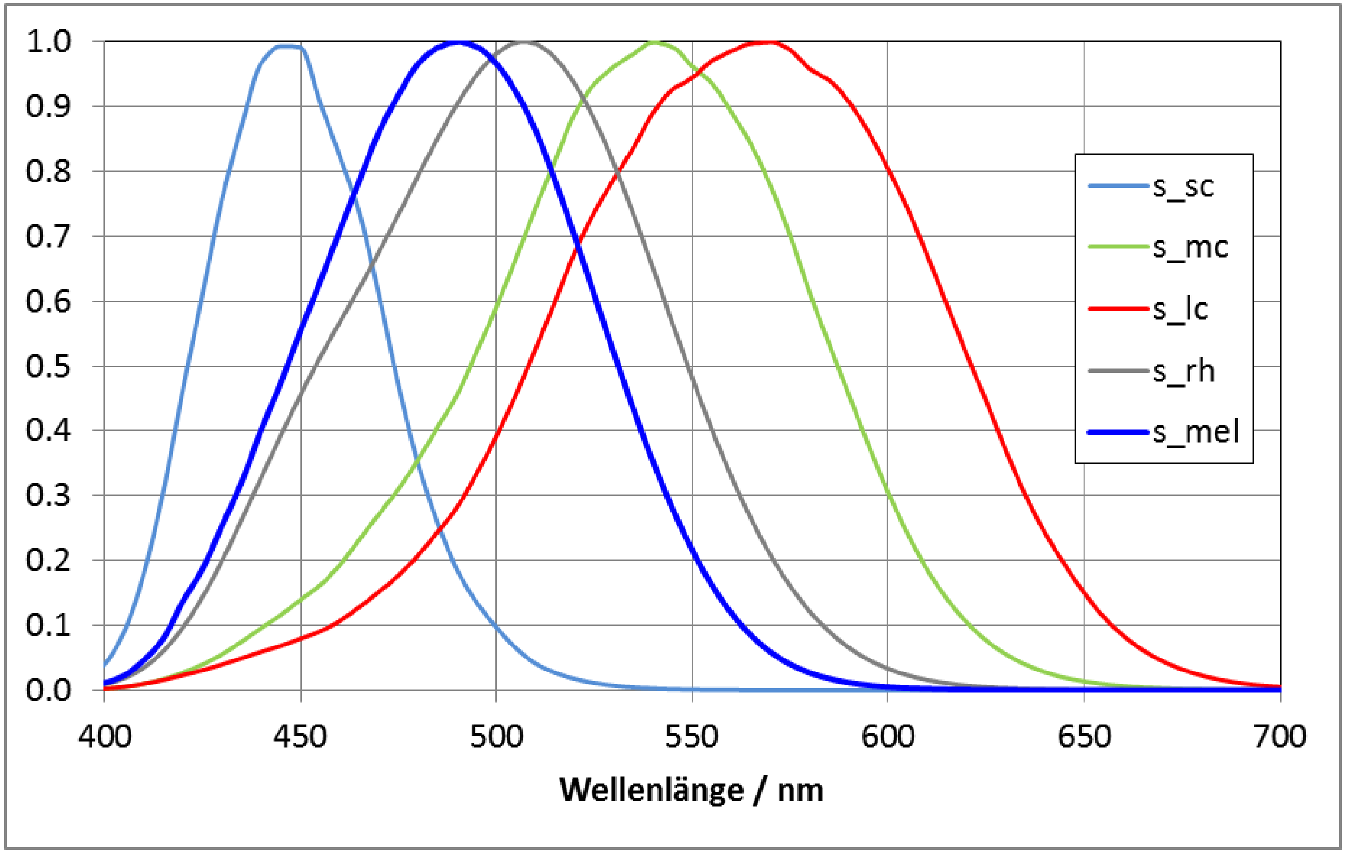
CIE Joint Technical Committee JTC 9: preparing CIE S026

Terminology and notation of the CIE system for metrology of optical radiation for ipRGC-influenced light responses

Response	Index α	Photoreceptor	Photopigment	α-opic action spectrum, $s_{\alpha}(\lambda)$
S-cone-opic	sc	Short-wavelength cones	S-cone photopsin (cyanolabe)	$s_{sc}(\lambda)$
M-cone-opic	mc	Medium-wavelength cones	M-cone photopsin (chlorolabe)	$s_{mc}(\lambda)$
L-cone-opic	lc	Long-wavelength cones	L-cone photopsin (erythrolabe)	$s_{lc}(\lambda)$
Rhodopic	rh	Rods	Rhodopsin	$s_{rh}(\lambda)$
Melanopic	mel	ipRGCs	Melanopsin	$s_{mel}(\lambda)$

Draft (CIE DS026) published on July 18, 2018 for commenting

CIE S026 – Action Spectra



$$\lambda_{mel,max} = 490 \text{ nm}$$

N.B: Peak sensitivity of melopsin is at λ = 480 nm, human pre-receptoral filtering shifts the peak to 490 nm

CIE S026 – Examples of Calculations

- What is the melanopic irradiance for a given spectral distribution and illuminance level?

$$E_{\mathrm{mel}} = \int E_{\lambda}(\lambda) \cdot s_{\mathrm{mel}}(\lambda) \cdot \mathrm{d}\lambda$$

Light Source	Illumi -nance E_{v}	Melanopic Irradiance $E_{\mathrm{e,mel}}$
Standard Illuminant A	100 lx	65.7 mW/m^2
Standard Illuminant D65	100 lx	132.6 mW/m^2
LED (4000 K)	100 lx	83.9 mW/m^2

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CIE S026 – Examples of Calculations

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Light Source	Illumi-nance E_{v}	Melanopic Irradiance $E_{\mathrm{e,mel}}$	Melanopic daylight (D65) efficacy ratio $\gamma_{\mathrm{v,mel}}^{\mathrm{D65}}$	Melanopic equivalent daylight (D65) illuminance $E_{\mathrm{v,mel}}^{\mathrm{D65}}$
Standard Illuminant A	100 lx	65.7 mW/m^2	0.496	49.6 lx
Standard Illuminant D65	100 lx	132.6 mW/m^2	1	100 lx
LED (4000 K)	100 lx	83.9 mW/m^2	0.632	63.2 lx

alternative but equivalent concepts

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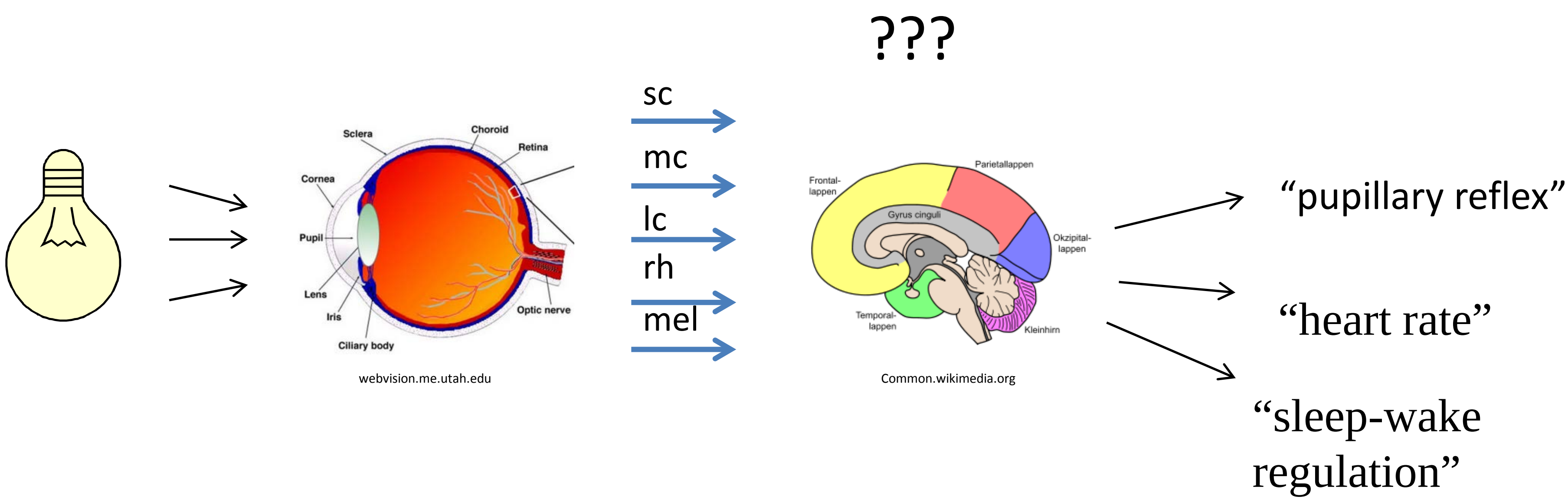
Non-visual effects

- For non visual effects it is not sufficient to state on the photometric values (lx, cd/m2,…) but additional information has to be given (i.e. α-opic quantities)
- There are some clear evidences that the non-visual effects depend not only on one α-opic quantity but on a combination of several quantities
- Report always all 5 quantites (or specify the spectral distribution)
- Use CIE S026 as framework for your experiments on non-visual effects

Non-visual effects: the missing link

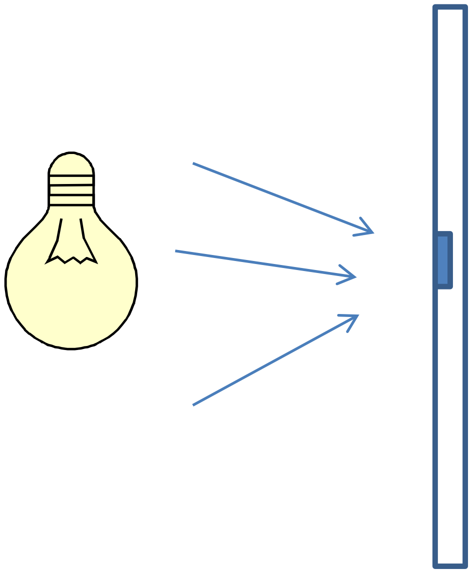


For visual effects the relation are quite well known however for non-visual effect still research is needed!!

-> CIE research strategy (http://www.cie.co.at/research-strategy/)

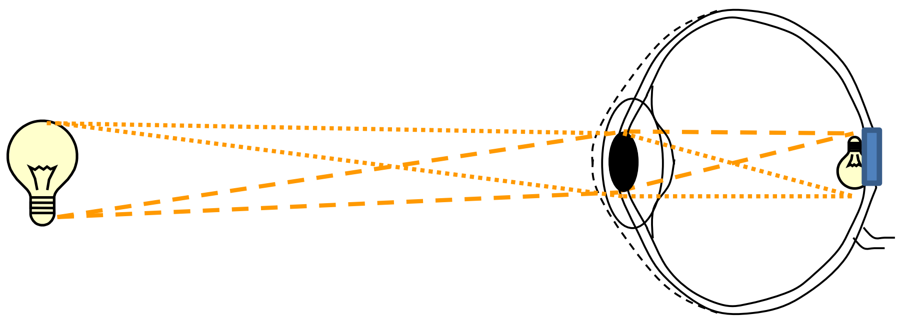
Geometrical considerations: Location of the photo-receiver

Surface (Skin, Cornea)



Irradiance, W/m^2

Optical Imaging System (Eye)



Radiance, $W/(m^2\ sr)$

Considerations on “radiance”

Ideally: the spatial radiance distribution is measured and the spatial distribution of the photoreceptors in the eye is considered

However

- The spatial distribution of the photoreceptors on the retina is not (enough) known
- Eye / head movement will “smear out” this distribution, mainly in horizontal direction

Alternative concepts:

- Averaging the radiance over a given field of view (PBS)
- Use of vertical irradiance with limiting the field of view

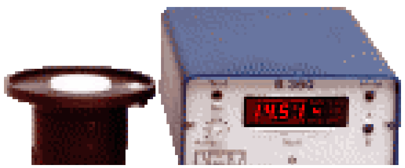
CIE S026 – Limitation of Field-of-View

Recommendation from CIE S026 : In absence of scientific evidences vertical irradiance with limitation of the field-of-view is taken:

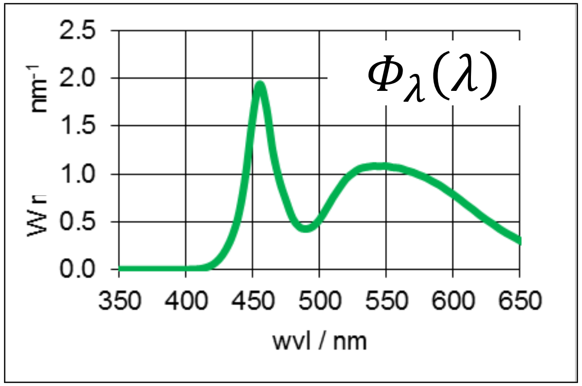
Environmental illumination	Vertical extent	Horizontal extent (left-right)
Indoor	50° above 0° to 70 ° below 0°	180° (with both eyes)
Outdoor	20° above 0° to 70° below 0°	180° (with both eyes)

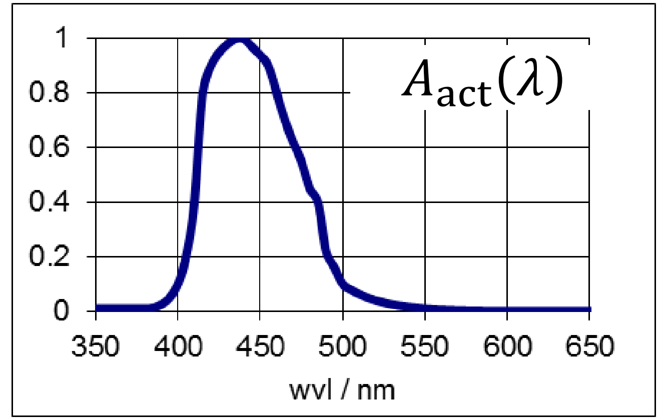
Alternative concept could be vertical (*semi-)cylindrical* α-opic irradiance with limitation of field-of-view

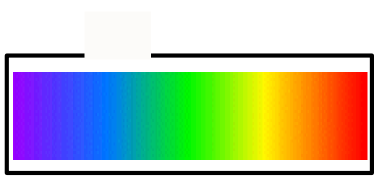
Measurement devices



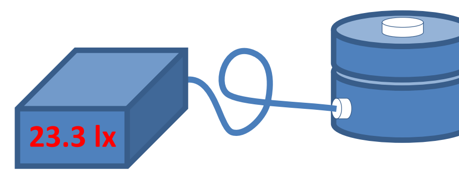
Spectral information





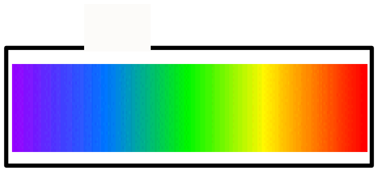


Spectroradiometer



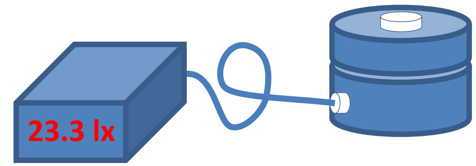
Radiometers with specific filter spectral response matching

Spectroradiometer Versus Filter-Radiometer



Spectral measurements + numerical integration

+spectral match
+different spectral weighting possible
+different input optics
-wavelength accuracy/stability
-responsivity stability
-price
-fragile
-size
-straylight



Single cell filter-radiometer

+sensitivity
+fast
+easy to use / mobile
+quite stable responsivity
-spectral match
-no spectral information

-> both have their „place“

Combination of both: most accurate solution in most applications

How accurate are measurements/ measurement devices?

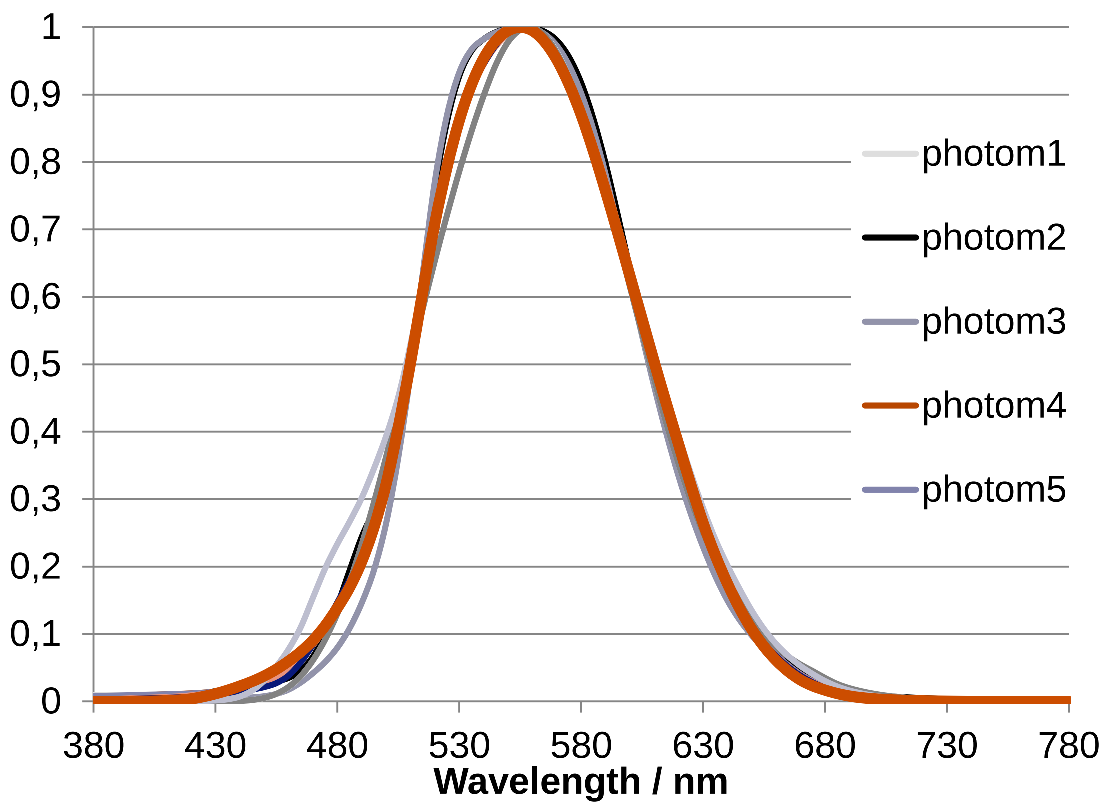
- “accuracy” shouldn’t be used for quantification … (CIE TN in preparation by DR2-75)
- depends on measurement task (definition of quantity)
- depends on measurement task measurement conditions
- depends on quality of device (spectral match, wavelength, linearity, geometrical match, straylight,…)

Quality of measurement devices

CIE defines sets of quality indices

- Photometers: CIE S023 (ISO /CIE 19476)
  - spectral match (f_1')
  - spatial properties (f_2, $f_{2,g}$, $f_{2,u}$)
  - linearity f_3
  - …
- Colorimeter: CIE 179
- UV Radiometer: CIE 220
- Radiometers: CIE 53
- Imaging Luminance Measurement Devices (ILMDs): CIE TC2-59
- Array-Spectroradiometer: CIE TC2-51
- CIE TRs on: bandpass effects CIE 214, spectral response CIE 202, Uncertainty CIE 198…

Example: Spectral Match of Photometer

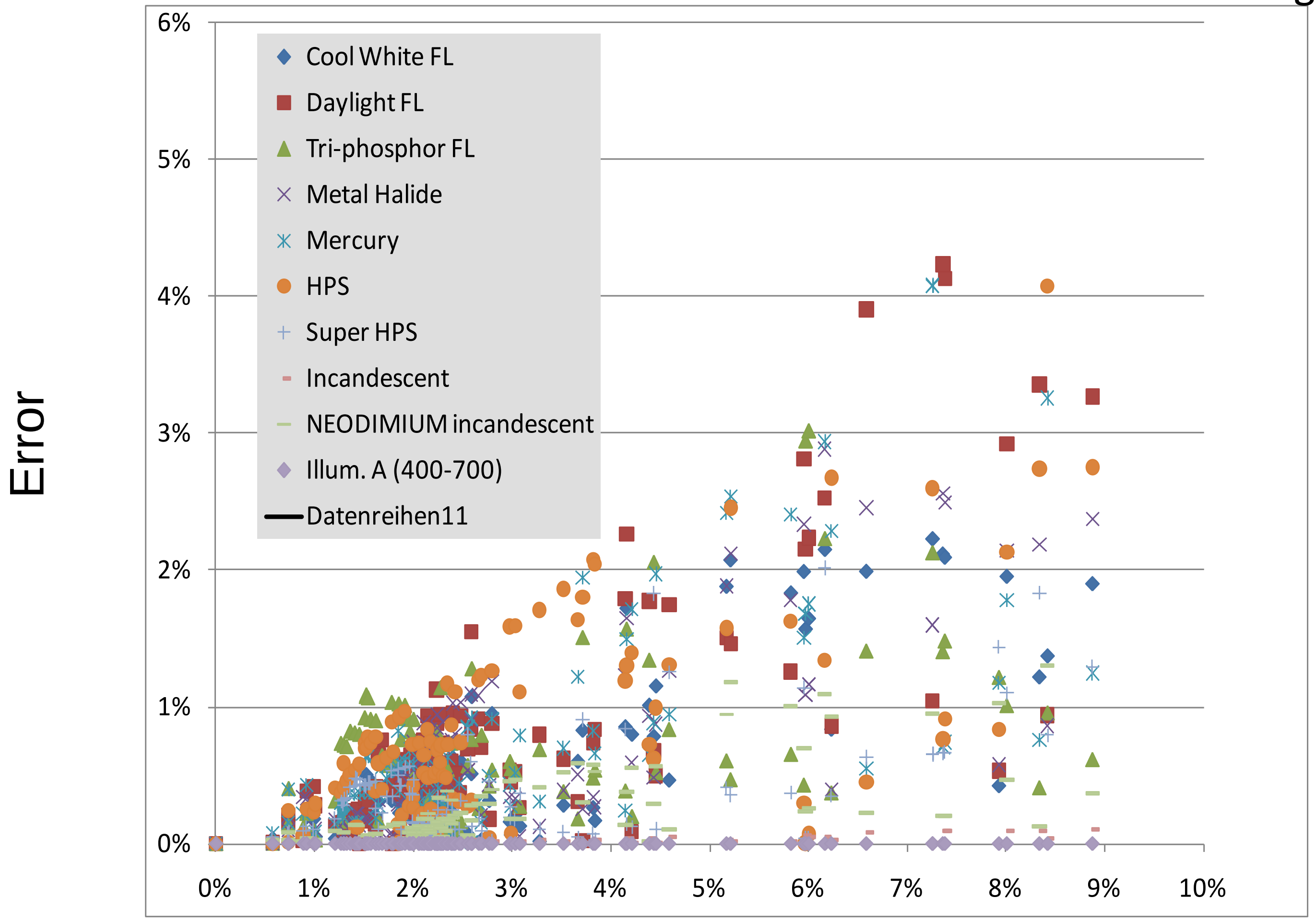


-> Quality index for spectral match (f_1')

$$f_1' = \frac{\int_{380\,\text{nm}}^{780\,\text{nm}} \left| s^*_{\text{rel}}(\lambda) - V(\lambda) \right| \mathrm{d}\lambda}{\int_{380\,\text{nm}}^{780\,\text{nm}} V(\lambda)\,\mathrm{d}\lambda}$$

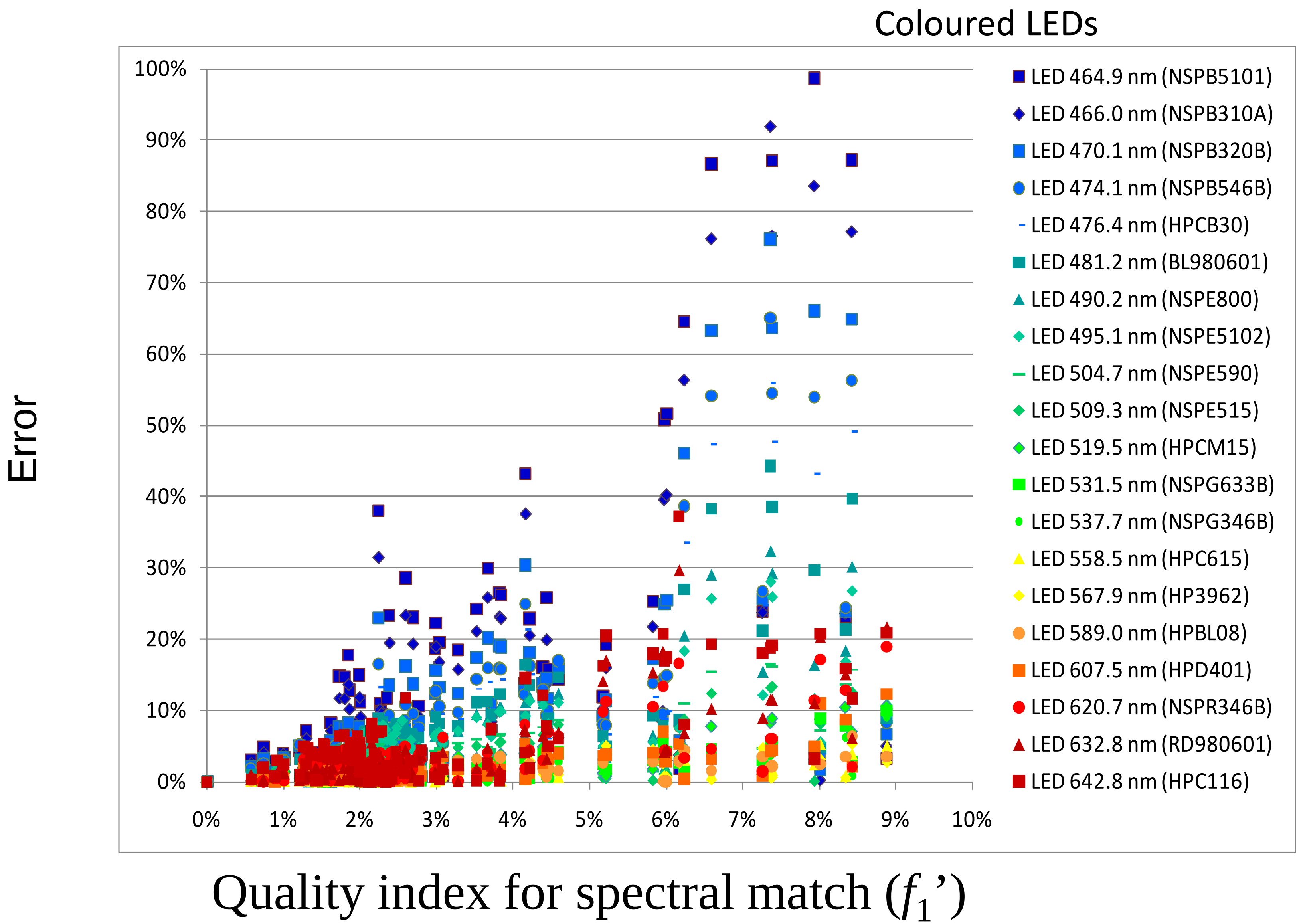
Error due to spectral mismatch

“classical light sources”



Quality index for spectral match (f_1’)

Error due to spectral mismatch



Conclusions

- Use existing concepts (quantities, units)
- Pay attention to the quality of your measurement equipment (c.f. CIE quality indices)
- Spend some time on the characterization of the measurement devices (linearity, dark signal, geometrical response,…)
- Describe well your set-up (information on the field of view, exposure duration, adaptation, light history, measurement equipment, calibration…)
- Estimate and state the measurement uncertainty

- Give feedback on CIE DS 026 to your CIE National Committee by 2018-10-28

Thank you for your attention

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Reserve

Calibration certificate

Extent of the Calibration

Calibration of the displayed value of the luminance between 0.5 cd/m² and 20 cd/m².

Measurement Procedure

The calibration factors are determined by comparing the displayed value of the device under test to the reference luminance source METAS N° 4746. The measurement procedure is described in the internal instruction 118.31K02 and is in accordance with CIE publication CIE S023:2013. A luminous field of 30 mm diameter is generated by the output port of an integration sphere. The spectral distribution of the luminous field is of type CIE Standard Illuminant A (tungsten lamp of distribution temperature 2856 K). The measurement field of the luminance meter is under filling the luminous field.

Measurement Conditions

The ambient temperature during the measurement was (23.4 ± 0.5) °C and the relative humidity was (41 ± 5) %. Settings on the DUT were as follows: Measuring mode: ABS; Response: fast; Calibration: Preset.

Measurement Results

L_0	L_a	K
0.507	0.507	1.000
1.003	1.002	1.001
2.228	2.216	1.005
2.794	2.782	1.004
4.935	4.916	1.004
10.037	9.982	1.005
15.20	15.11	1.006
20.12	19.99	1.006

L_0: Reference value of luminance in cd/m²
L_a: Displayed value of DUT in cd/m² regarding the dark current of 0.001 cd/m²
K: Factor of calibration

The luminance (L_0) is calculated by multiplying the displayed value of the luminance meter (L_a) with the calibration factor K.

Uncertainty of Measurement

$U = 0.030 \cdot K$

The reported uncertainty of measurement is stated as the combined standard uncertainty multiplied by a coverage factor $k = 2$. The measured value (y) and the associated expanded uncertainty (U) represent the interval ($y \pm U$) which contains the value of the measured quantity with a probability of approximately 95 %. The uncertainty was estimated following the guidelines of the ISO (GUM:1995).

Consider the measurement conditions

Use the measurement results

Observe the measurement uncertainty

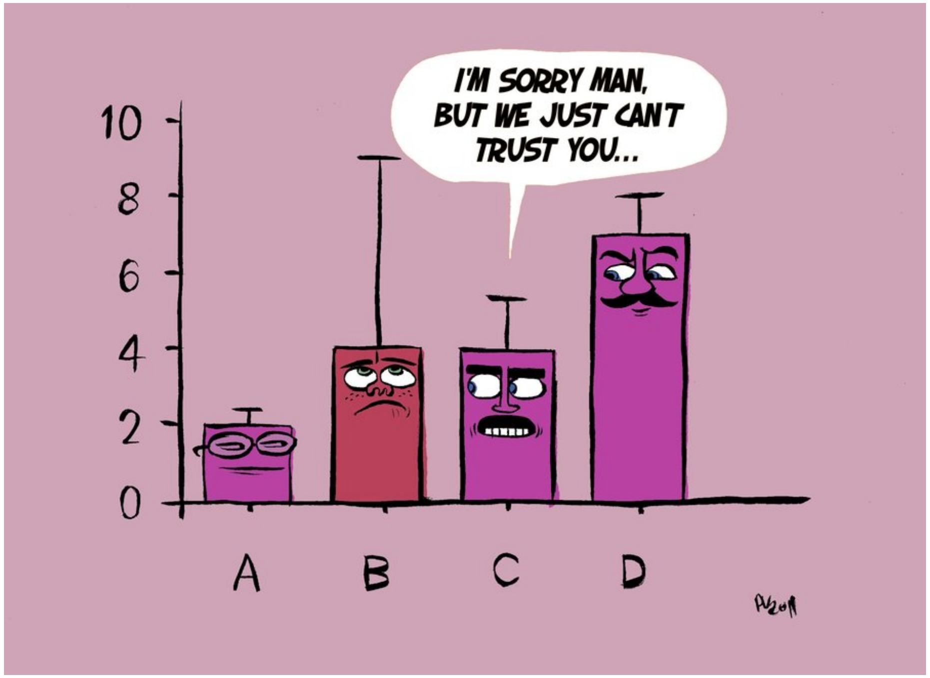
Metrological Traceability

- International Vocabulary of Metrology[1]:
- property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty
- Usually no legal requirement but required by application standards - > quality insurance

[1]International Vocabulary of Metrology –
Basic and General Concepts and Associated Terms
JCGM 200:2012
https://www.bipm.org/en/publications/guides/vim.html

Motivation to state measurement uncertainties

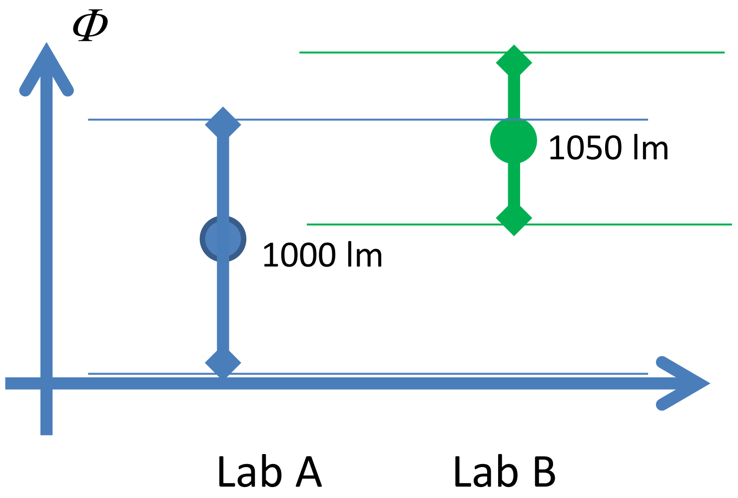
1. Quantifying the quality of a measurement...



... and the device under test (DUT) as properties of the DUT is included in the measurement uncertainty

Why uncertainties matter?

2. Comparing results



Without considering measurement uncertainty: Lab A differs from Lab B

Considering measurement uncertainty:

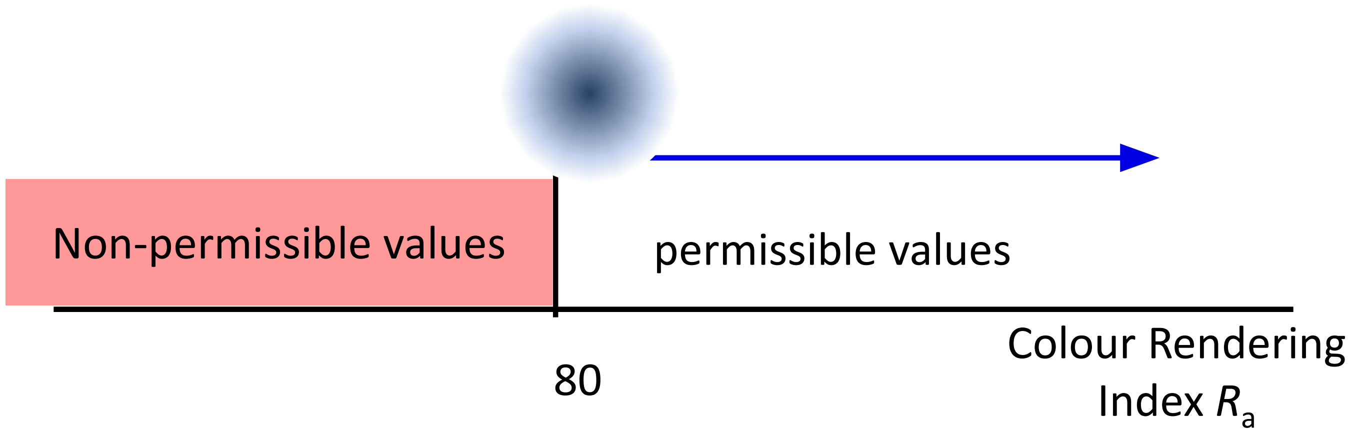
Degree of equivalence between Lab A and Lab B can be quantified!

Why uncertainties matter?

3. Conformity statements

EU Regulation 1194/2012 for LED lamps

General colour rendering index R_a ≥ 80



Without considering measurement uncertainty: Yes products fulfils

Considering measurement uncertainty: **conformance probability**

JTC9 – Age-dependent Corrections

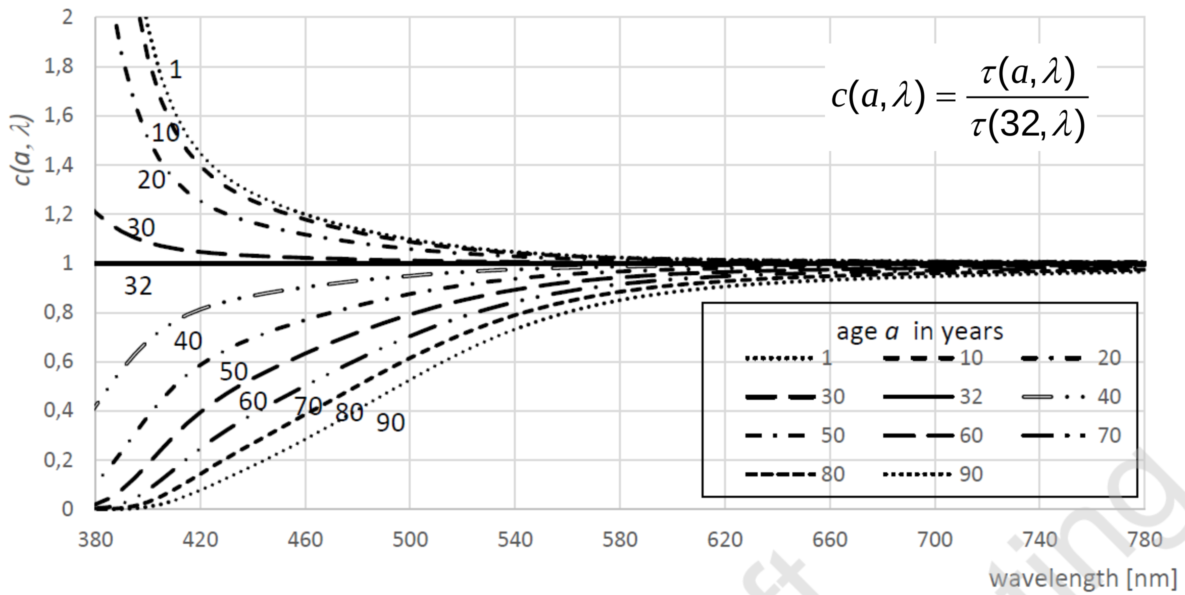


Figure A.1 — Spectral correction function $c(a, \lambda)$ for different ages

Typical correction for melanopic irradiance (NB depends on spectral distribution)

	25 years	35 years	50 years	75 years	90 years
$k_{\text{mel},\tau}(a)$	1.045…1.055	1	0.83…0.86	0.57…0.65	0.44…0.55