LED EVENT 2016
Design en engineering trends voor LED-applicaties

BE WOENSDAG 30 NOVEMBER 2016
TECHNOPOLIS, MECHELEN
NL DONDERDAG 1 DECEMBER 2016
CONGRESCENTRUM 1931
BRABANTHALLEN, DEN BOSCH

TE LINTELO SYSTEMS BV
Gigahertz-Optik

Spectral Handheld Light Meters for accurate measurements of LED lighting

Mike Clark, Gigahertz-Optik GmbH

on behalf of Te Lintelo Systems BV

MESSEN VON LICHT - MESSEN MIT LICHT
Qualität „Made in Germany".
Gigahertz-Optik

www.gigahertz-optik.de

TE LINTELO SYSTEMS BV
photonics is our passion!
+31 316 340804
www.tlsbv.nl - contact@tlsbv.nl

Talk Aims

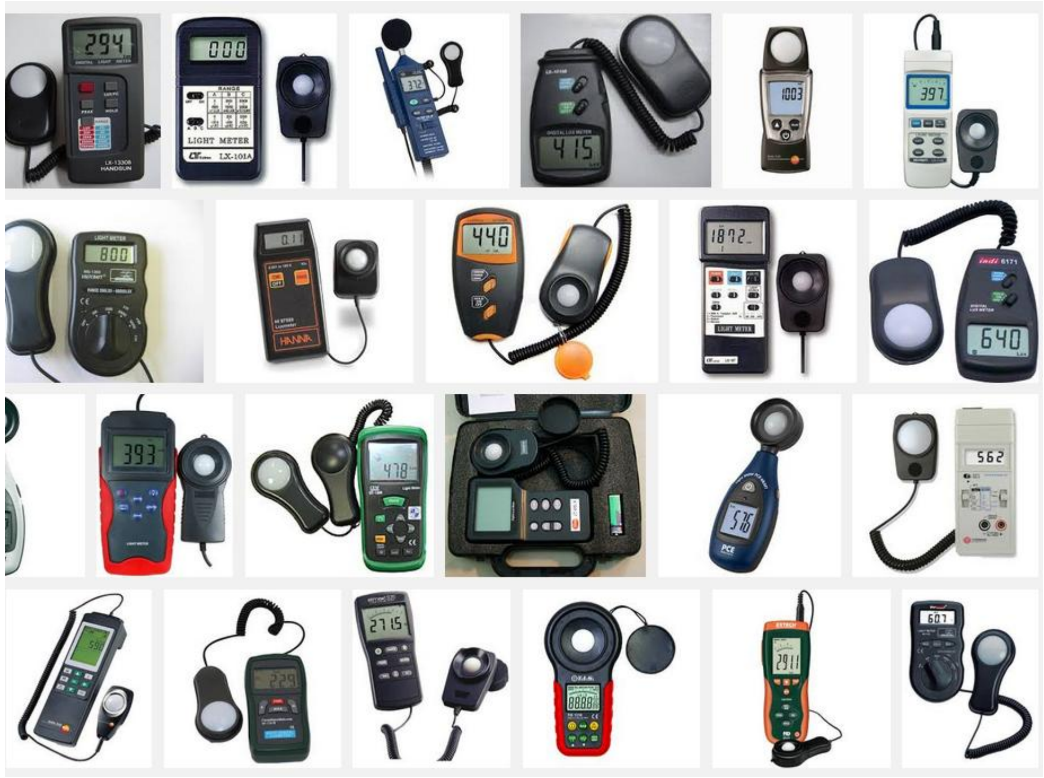
What are the weaknesses and problems associated with using traditional light meters to measure LED based lighting products?

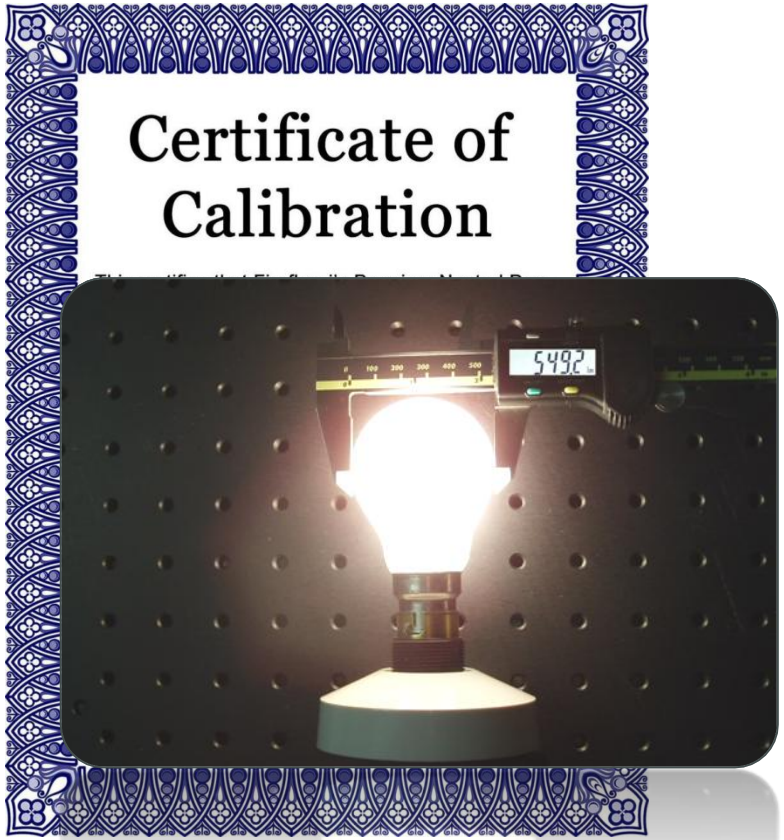
What’s different about contemporary spectral light meters and what are the advantages and benefits of using them?

How do spectral light meters help us exploit the many opportunities offered by LED lighting

Photometers

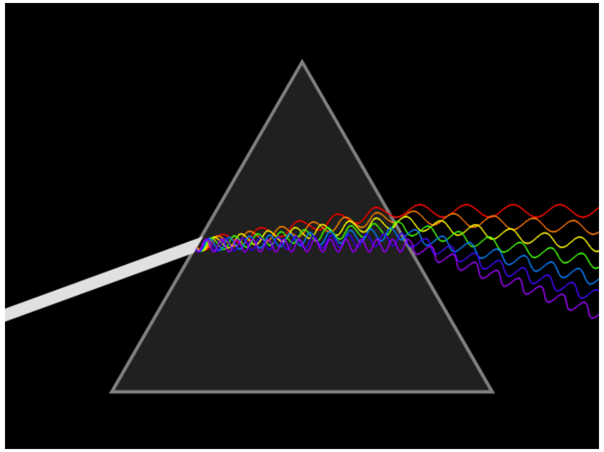
So what's wrong with using a traditional lux meter to measure LED lighting?



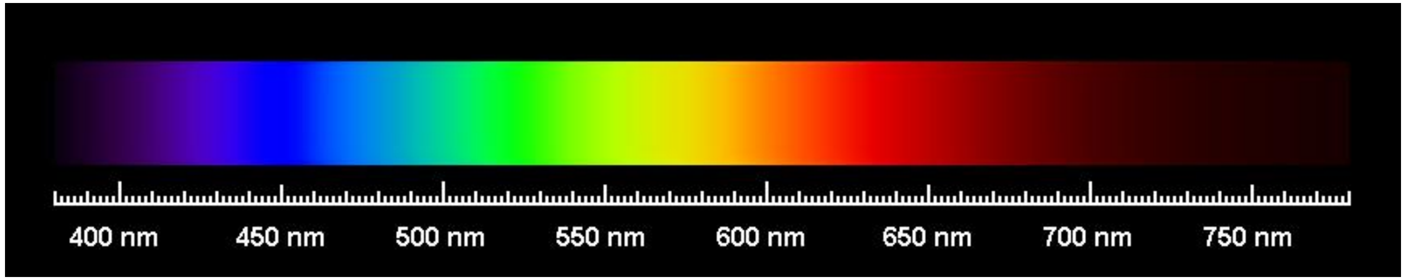


Just because something has been 'calibrated', it doesn't necessarily make it suitable for a particular measurement task.

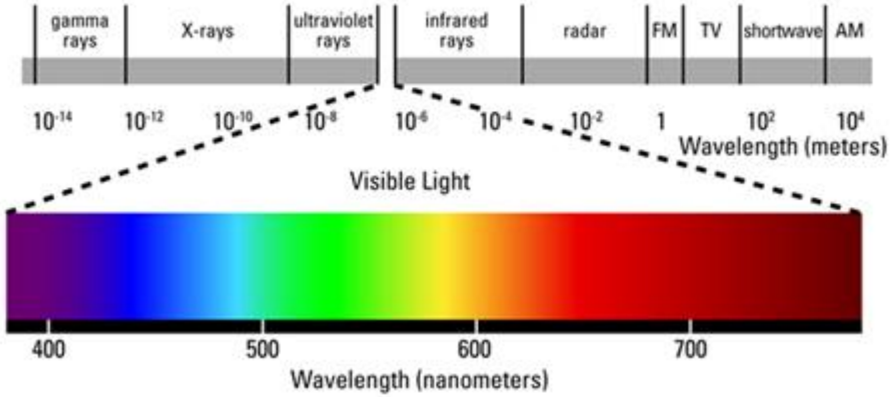
Visible Light

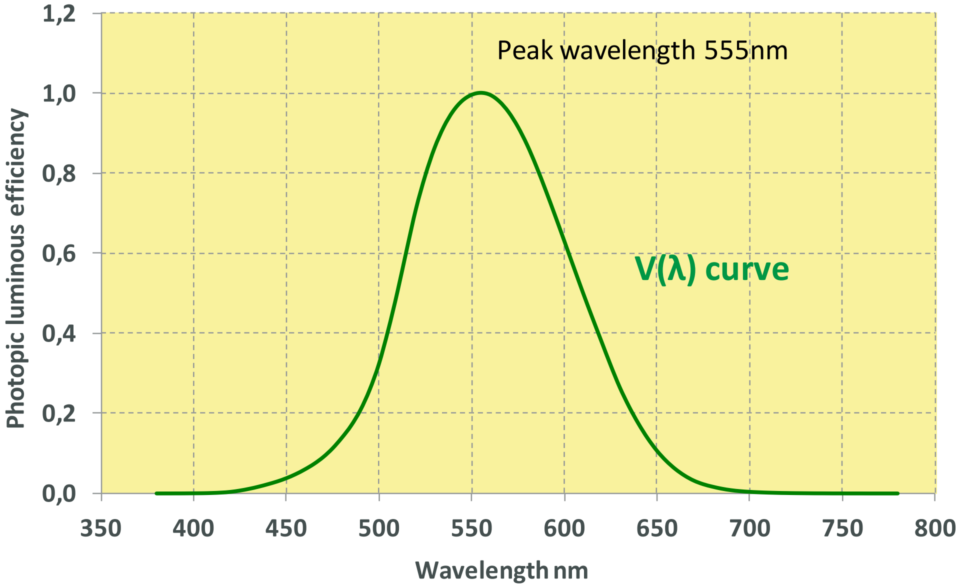


https://en.wikipedia.org/wiki/Prism



Light is visible to humans in the 380nm to 780nm wavelength range….





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

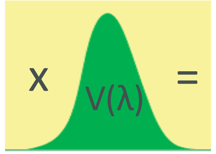
The CIE V(λ) curve describes the average spectral sensitivity of human visual perception of brightness. In use since 1924.

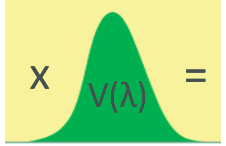
ISO 23539:2005 (CIE S010/E:2004)

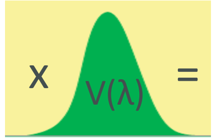
….but not all wavelengths with the same sensitivity

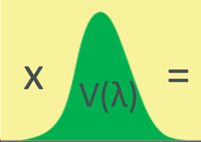
Photometric Units

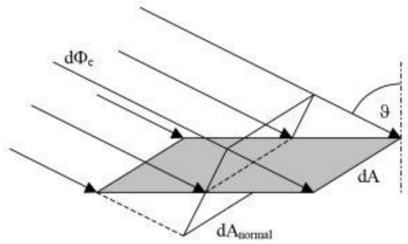
Radiometric Quantity	Radiometric Unit	Photometric Quantity	Photometric Unit
Irradiance	W/m^2	Illuminance	lux
Radiance	$W/(sr.m^2)$	Luminance	cd/m^2
Radiant intensity	W/sr	Luminous intensity	cd
Radiant flux	W	Luminous flux	lumens

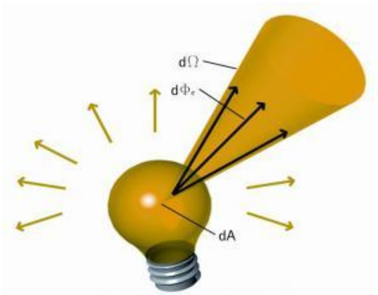






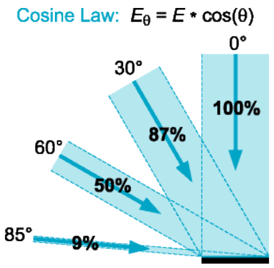


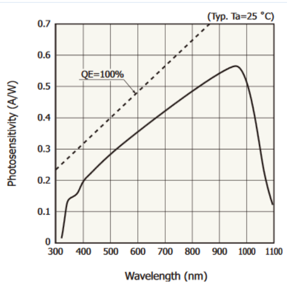


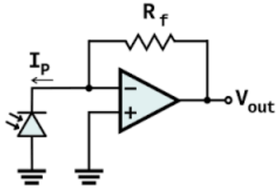


www.gigahertz-optik.de/en-us/basics-light-measurement

Photometers



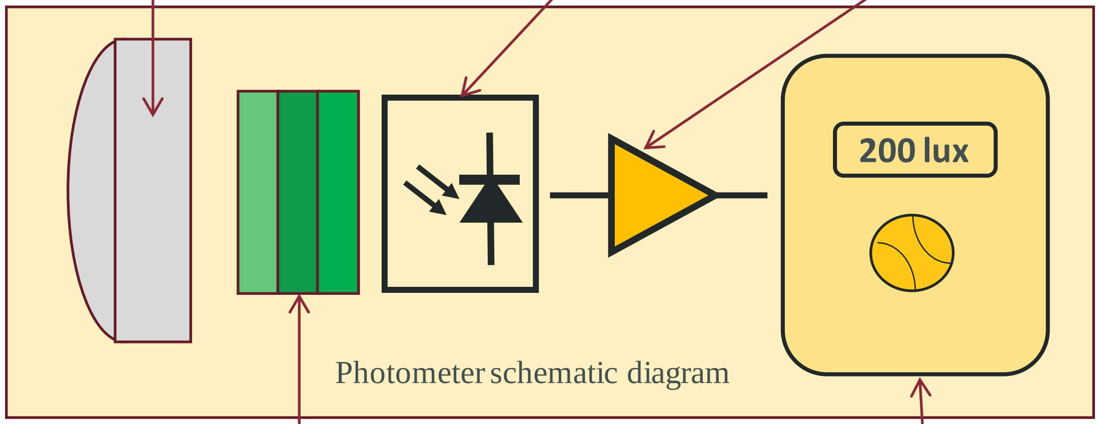




Entrance optic
(e.g. cosine diffuser)

Si photodiode

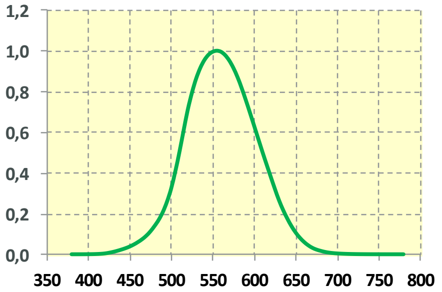
Trans-impedance
amplifier



Photometer schematic diagram

CIE V(λ) Photometric
curve matching filter

Display meter with
gain ranges



ISO/CIE 19476:2014 (CIE S 023/E:2013)
Characterization of the performance of illuminance meters and luminance meters

Quality Indices	Notation
V(λ) Mismatch	f_1'
UV Response	f_{UV}
IR Response	f_{IR}
Cosine Response (i)	f_2
Linearity	f_3
Display Unit	f_4
Fatigue	f_5
Temperature Dependence	$f_{6,T}$
Humidity Resistance	$f_{6,H}$
Modulated Light	f_7
Polarization	f_8
Spatial Non-uniformity	f_9
Range Change	f_{11}
Focusing Distance (ii)	f_{12}

(i) Illuminance meters only *(ii) Luminance meters only*

Spectral Mismatch Error

V(λ) Mismatch	f_1'

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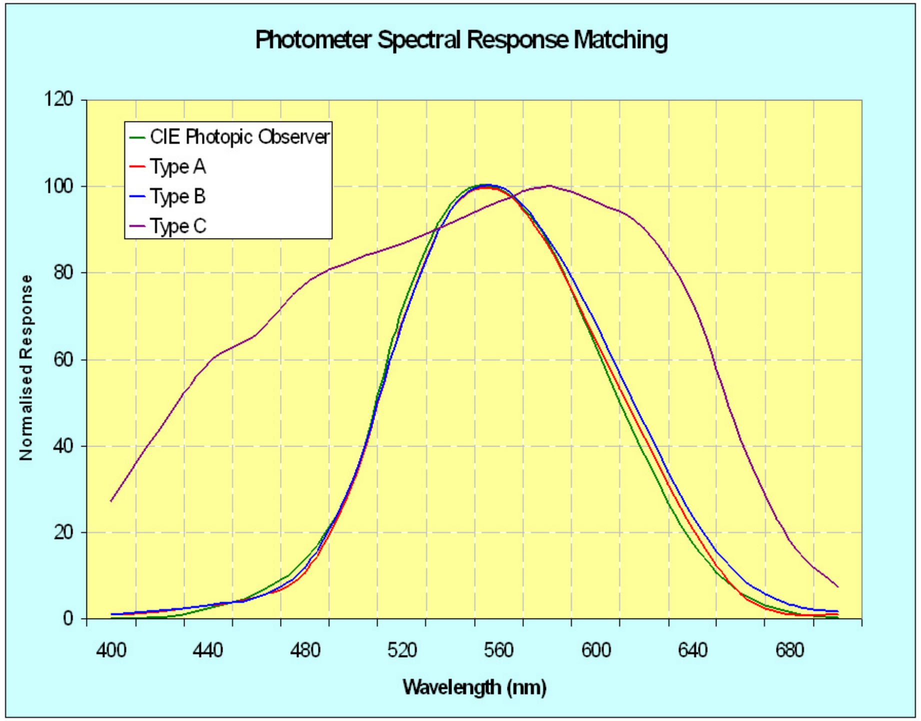
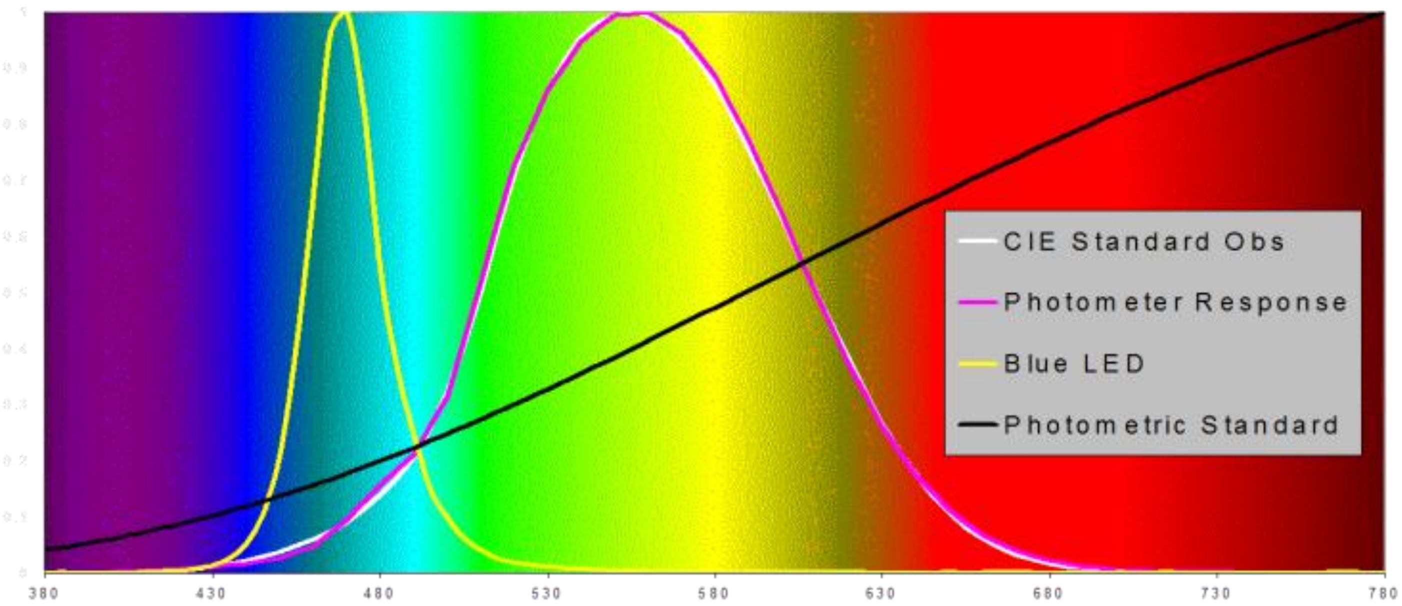
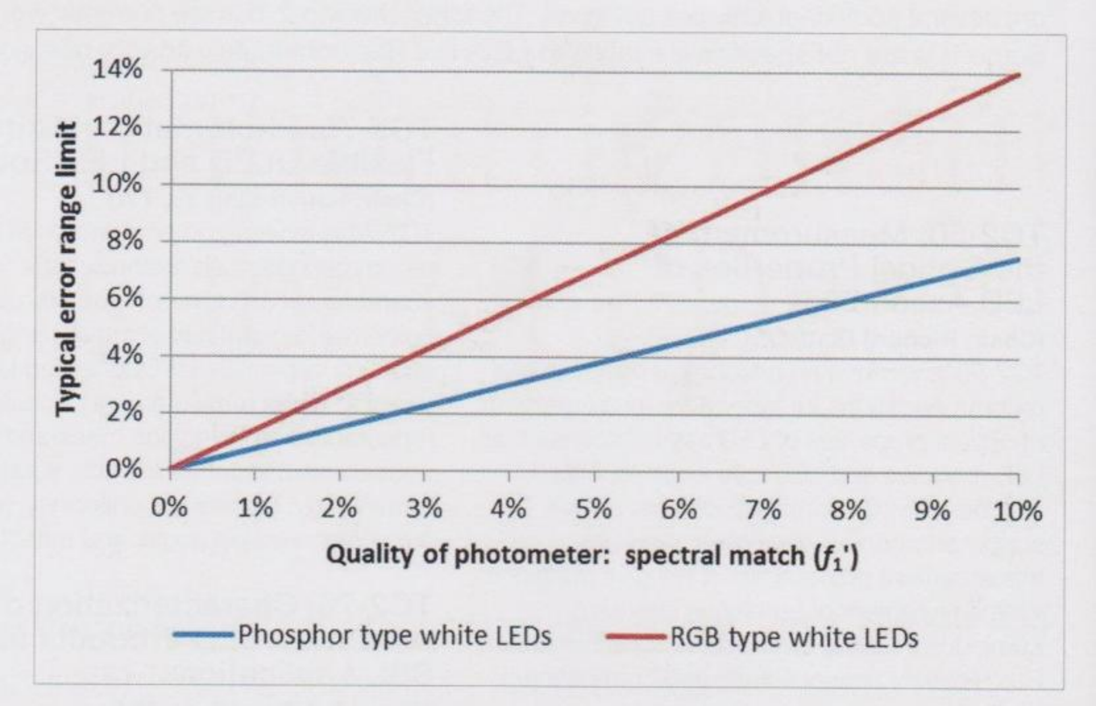


Standard calibration of photometers is made with the CIE Illuminant A (2856K incandescent source)

Spectral mismatch is usually the most significant error source when photometers are used to measure LEDs

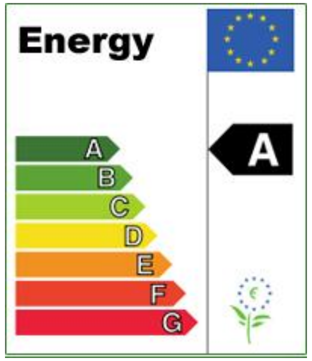


Spectral Mismatch Error



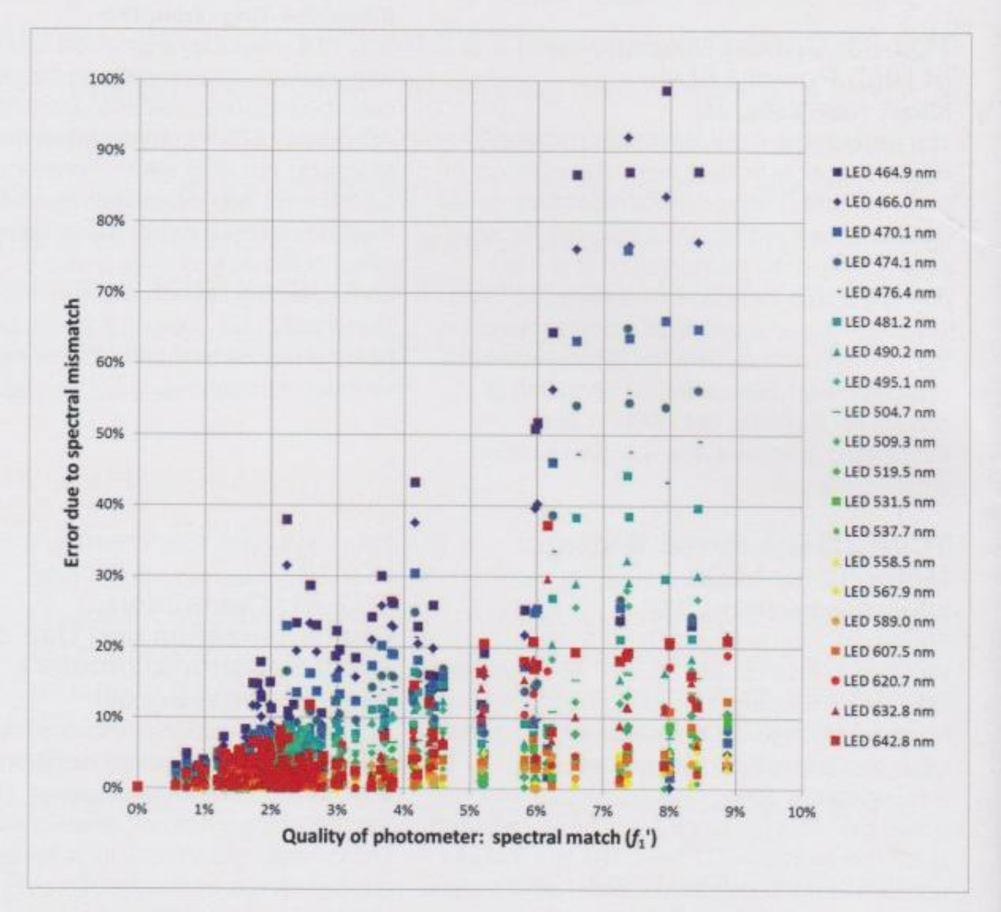
Tony Bergen & Peter Blattner CIE Div 2, *Photometry Standardization Developments for OLEDs and LEDs*, LED Professional Review, Issue 41, Jan 2014.

f1' not a direct measure of LED measurement error, but can indicate likely error range for white LEDs



~10% significant for energy bills and global warming

Spectral Mismatch Error



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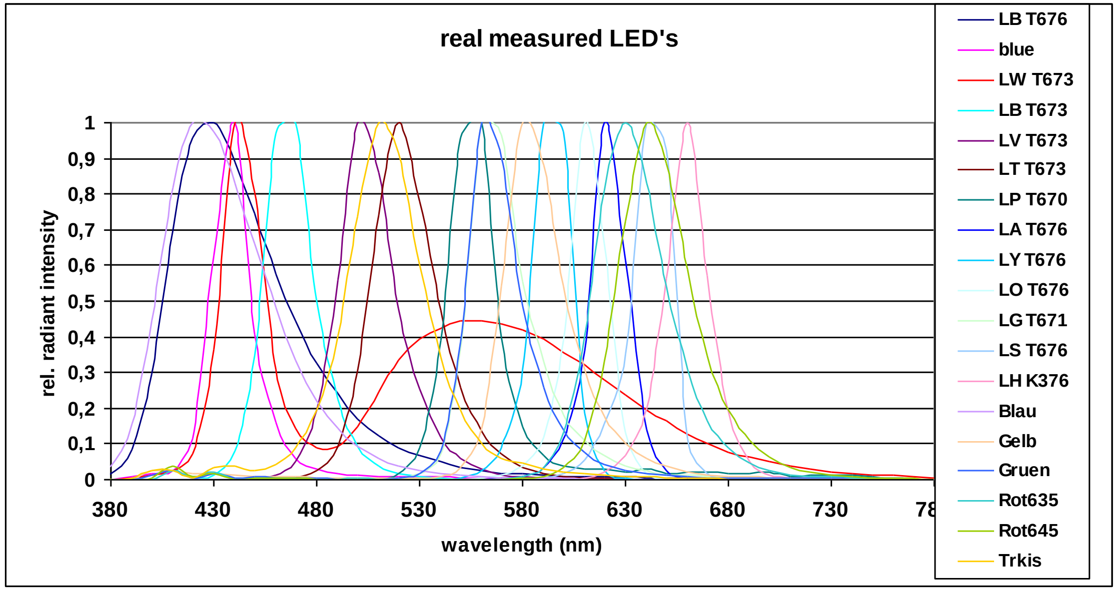
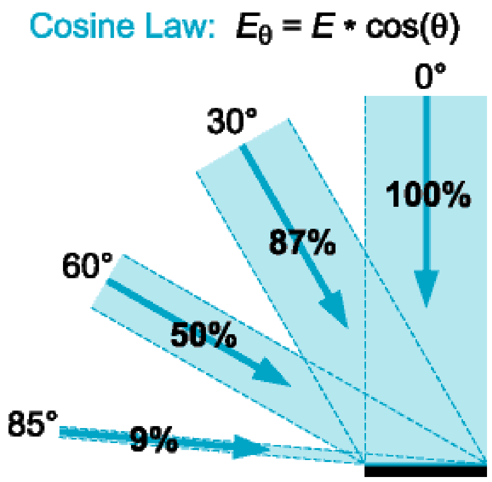
V(λ) Mismatch	f_1'



Photometer errors when measuring coloured LEDs can be very much worse than white LEDs

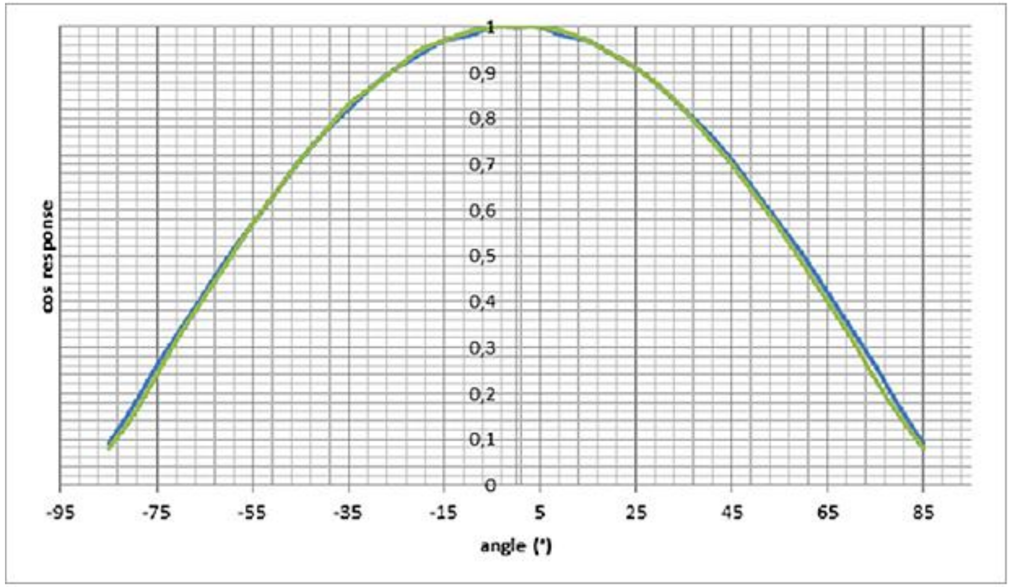
Cosine Error

Cosine Response	f_2



As a beam of light deviates from normal incidence, its area increases on the surface. The resulting reduction in irradiance is determined by the cosine of the angle of incidence.

Lux meter errors resulting from poor cosine response can be most significant when measuring extended light sources



Independent of lighting technology – not specific to LEDs

Quality Indices	Notation
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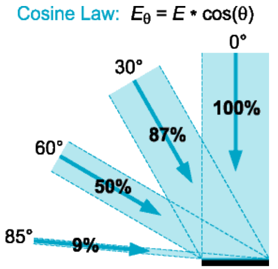
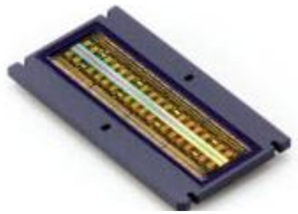
Spectral Light Meters

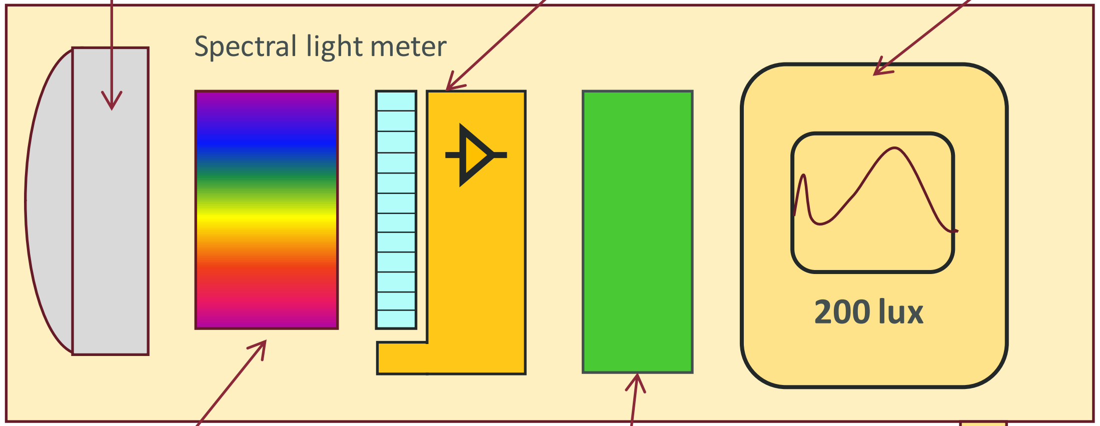




Entrance optic (e.g. cosine diffuser)

Array detector (typically CMOS)

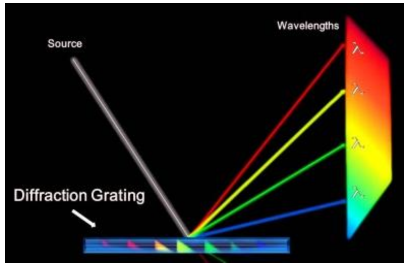
Meter with graphical display for spectra

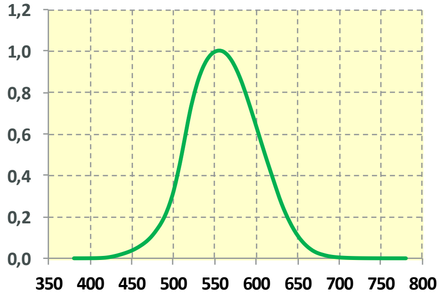


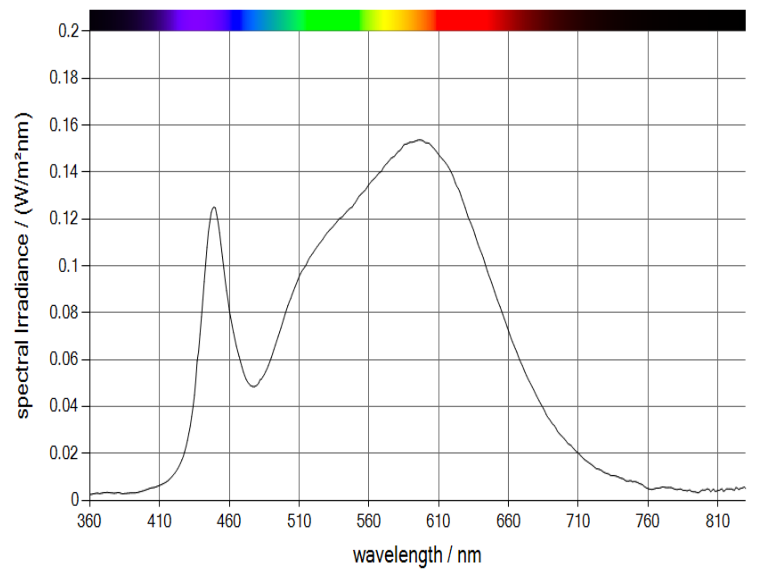
Wavelength dispersion (i.e. diffraction grating)

CIE V(λ) Photometric response - calculated

USB / Wi-Fi / etc





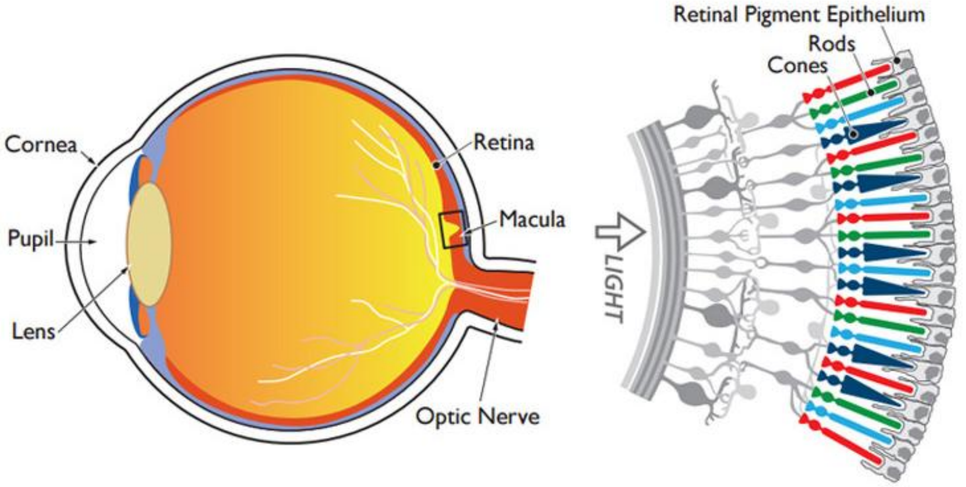


Spectrum enables measurement of **quality** and **effectiveness** of light – not just efficiency

i.e. typically colour

Filter responses other than photometric V(λ)

Colour Measurement

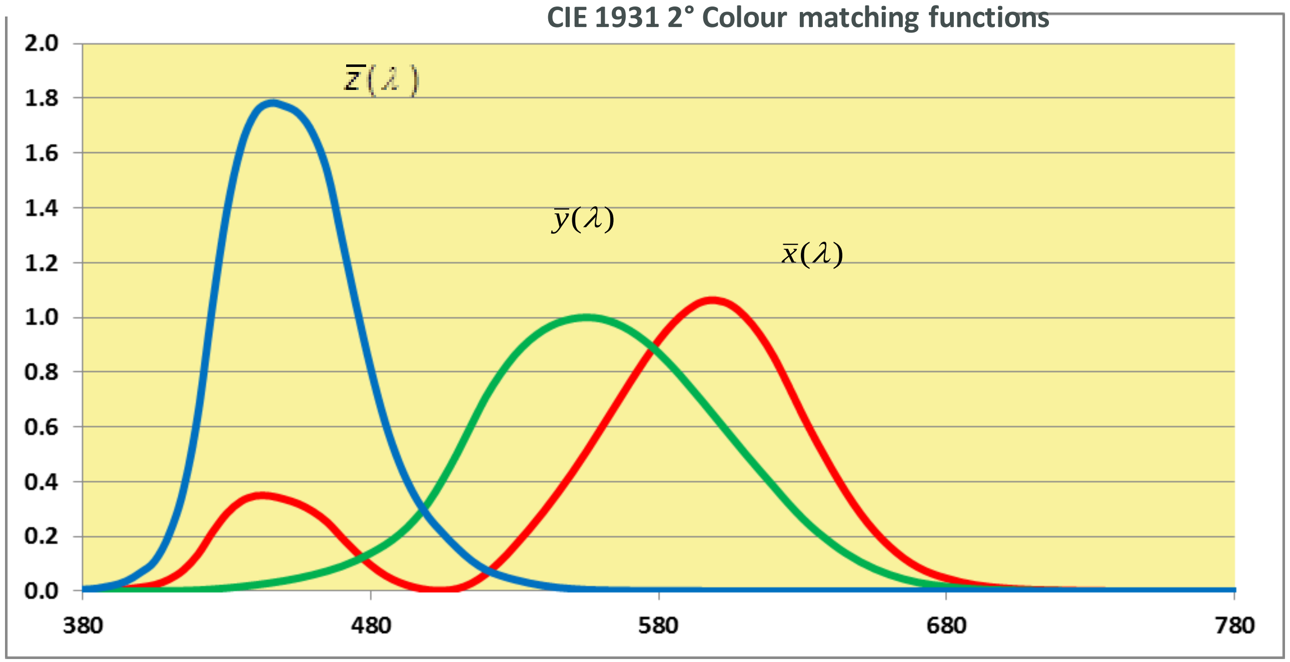


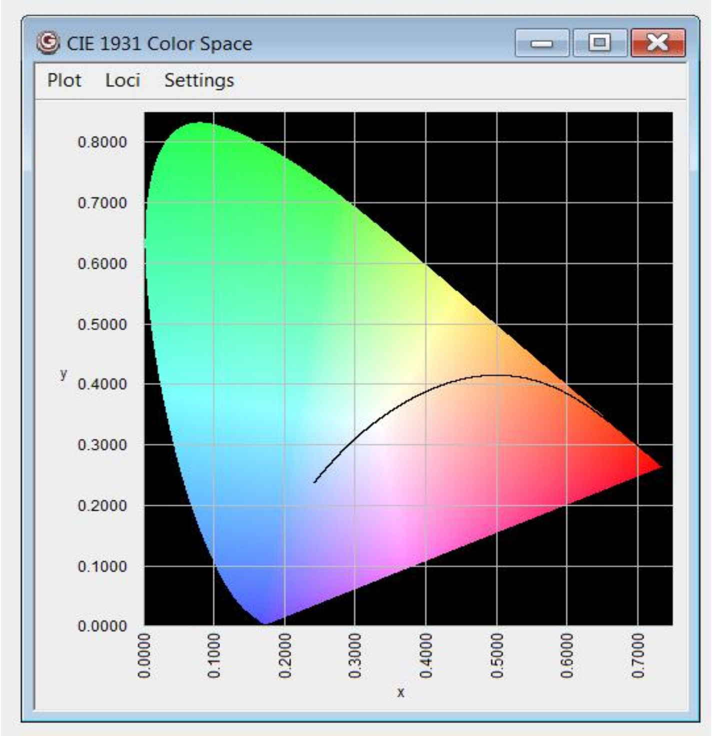
Human eye has two types of photoreceptors for vision – Rods (~120 million) and Cones (~6 million).

We have 3 types of cones – blue, green and red sensitive. Colour perception is via cones only.

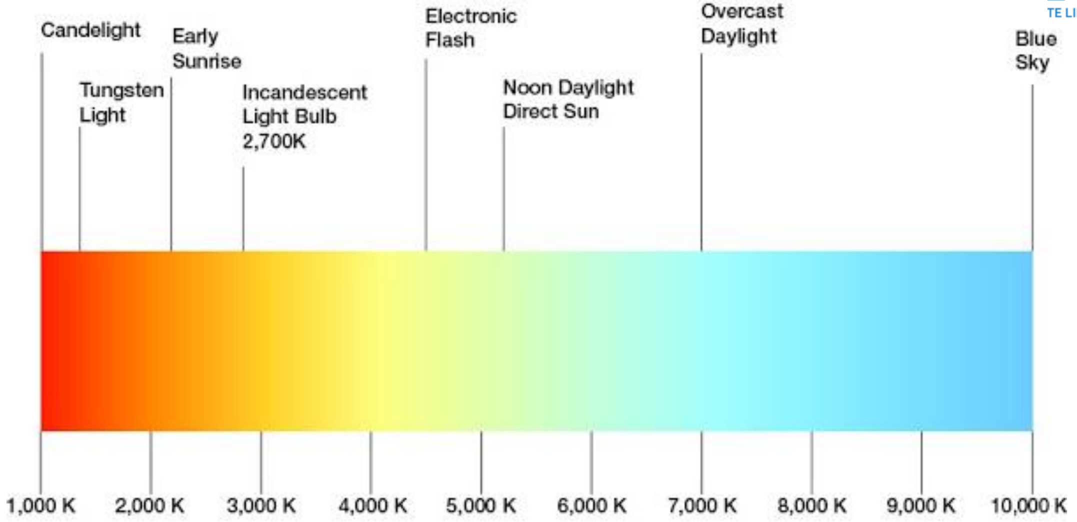
1931 CIE released first standard observer for a 2° FOV – still in widespread use.

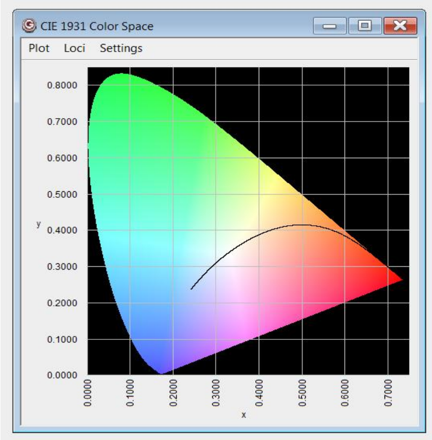
The CIE 1931 colour matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ can be implemented much more accurately in a spectral light meter rather than coloured filters in a tri-stimulus meter.

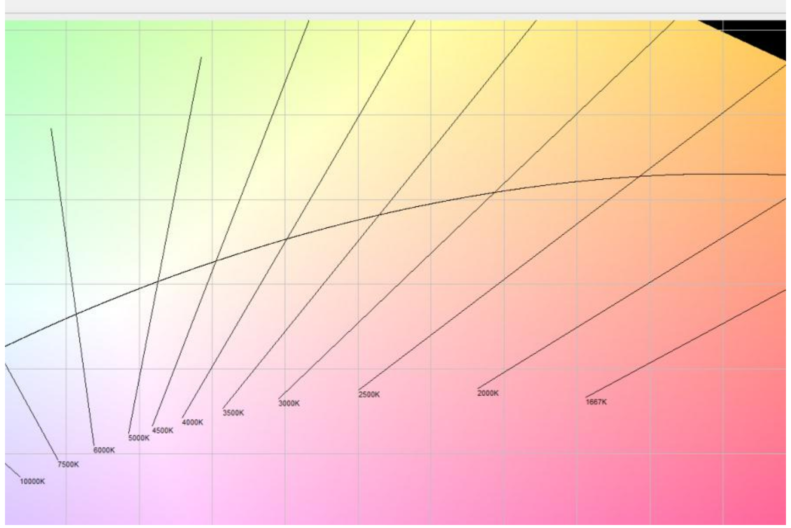




Colour Temperature







Correlated colour temperature (CCT) is a measure of light source's colour appearance defined by the proximity of its chromaticity coordinates to the blackbody locus.

Different colour light sources can have the same CCT.

Limited accuracy and range of CCT with tri-stimulus meters

Colour Rendering - CRI

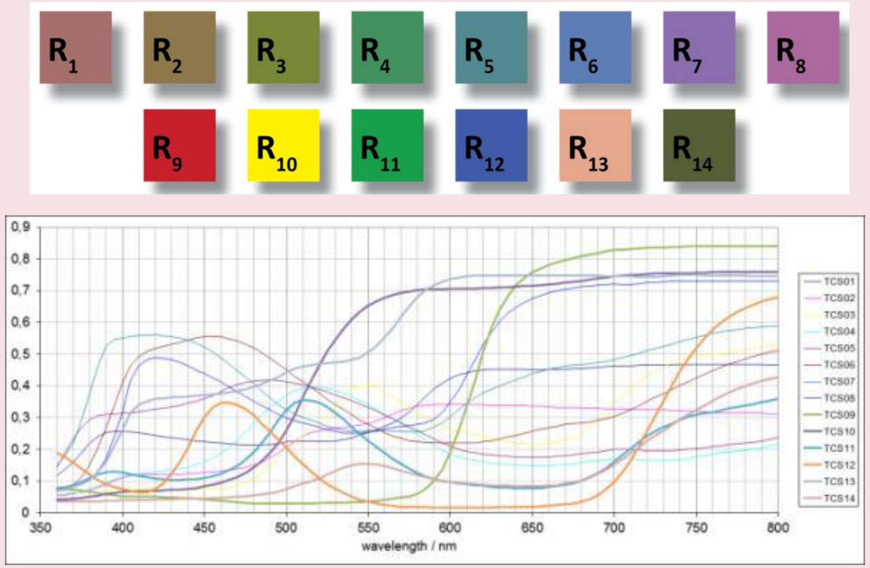
The colour rendering of a light source is a measure of its ability to realistically reproduce the colour of an object.

CIE 13.3-1995 *"Method of measuring and specifying colour rendering properties of light sources"*

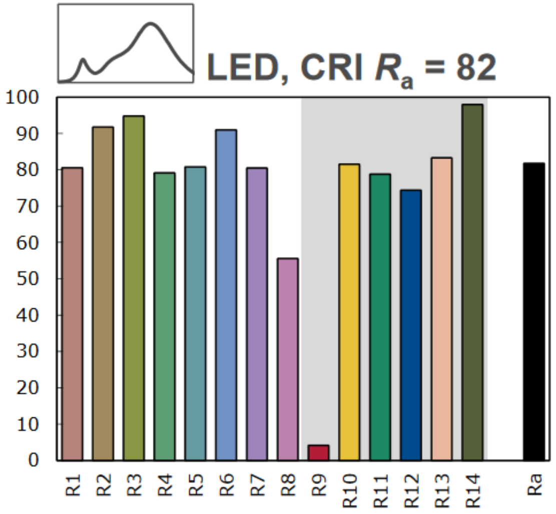
Colour fidelity metric only. First released 1965, updated in 1974. R_a is average of R_1 - R_8

The CIE General Colour Rendering Index, R_a, does not agree well with perception of some light sources, notably LED light sources that contain narrow spectral bands.

CIE Colour Rendering Indices, CRI



Test colour samples according to CIE 13.3



CRI can only be determined with spectral data of light source

Colour Rendering – TM30

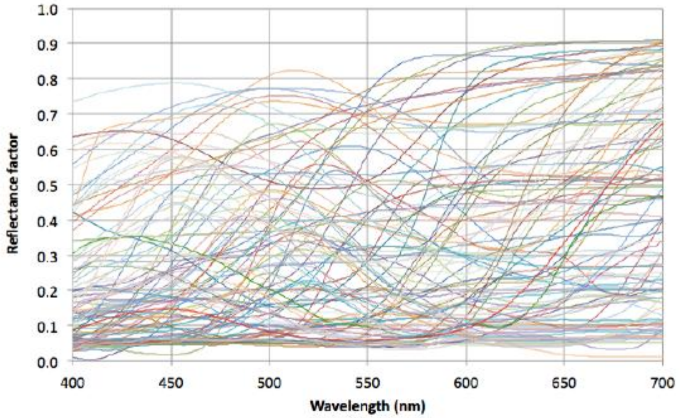
TM-30-15 IES *"Method for Evaluating Light Source Color Rendition"*

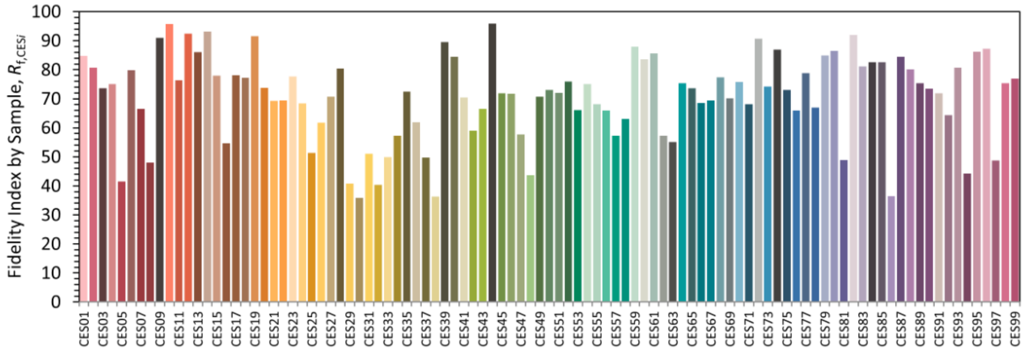
Illuminating ENGINEERING SOCIETY

http://www.ies.org

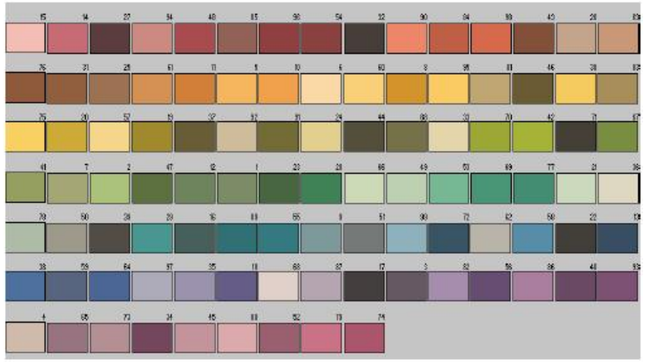
TM-30-15 uses 99 colour samples to characterize the difference between the test source and reference illuminant. Uses CIECAM02 (uniform colour space).

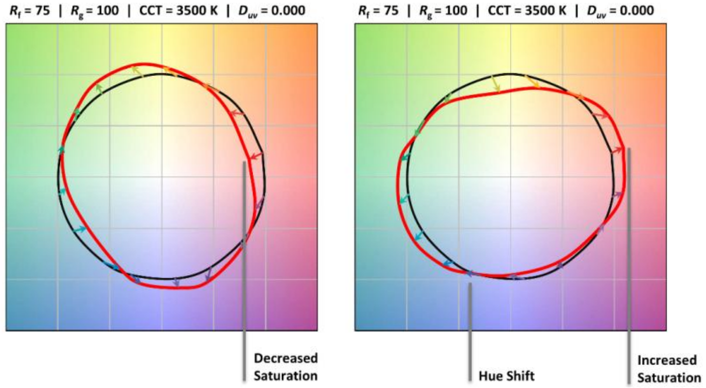
More comprehensive set of numerical and graphical outputs than CIE CRI system





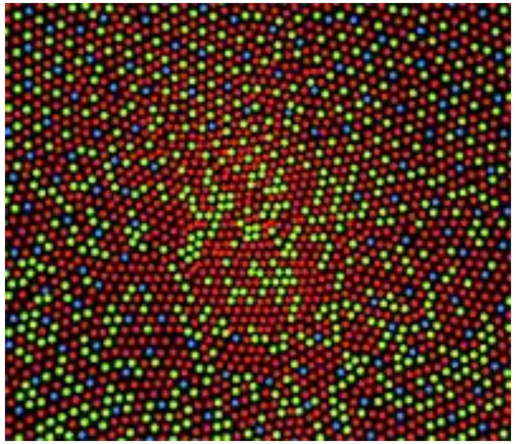
Fidelity Index, R_f
Gamut Index, R_g
Color Vector/Saturation Graphics
16 hue-based fidelity indices
16 hue-based chroma indices
1 skin-specific fidelity index
99 individual fidelity value





TM-30-15 metrics can only be determined with spectral data of light source

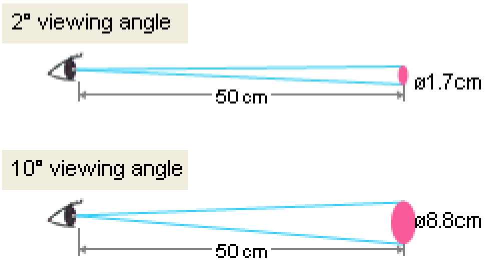
Observer's field of view



CIE 1931 2° Standard Observer

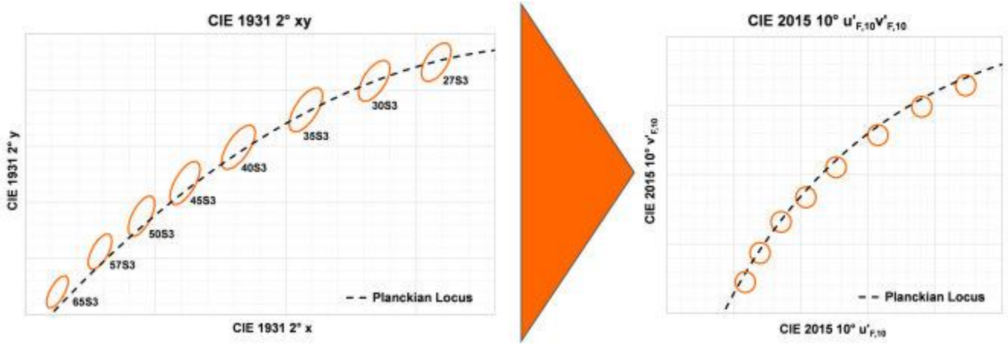
CIE 1964 10° Standard Observer

CIE 170-2:2015

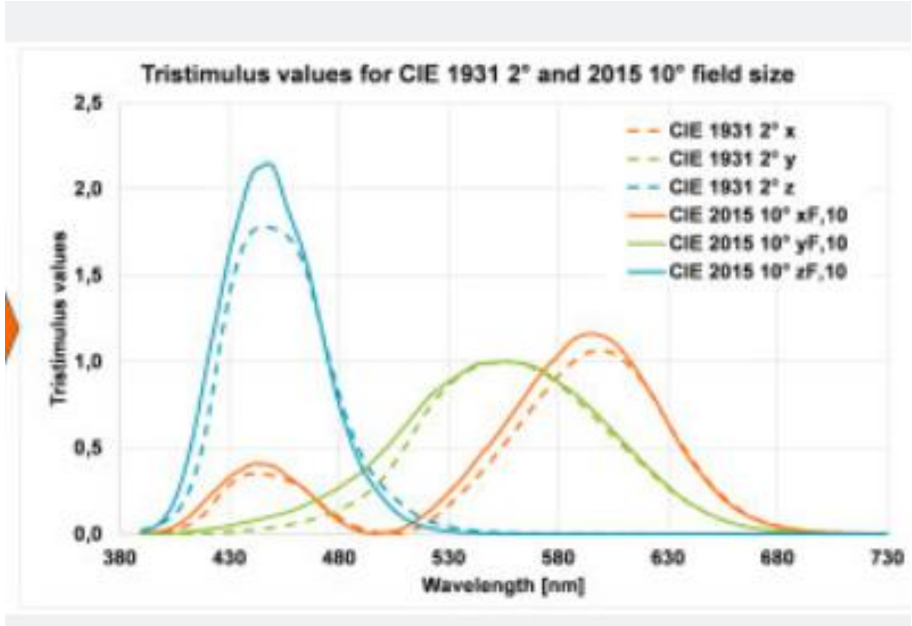


Only with spectral data can these different weighting functions be implemented

Cones are not uniformly distributed within the fovea – few blue cones in the central region.



http://www.osram-os.com/osram_os/en/applications/general-lighting/ten-binning/index.jsp



$\bar{x}(\lambda)$

Scotopic Vision

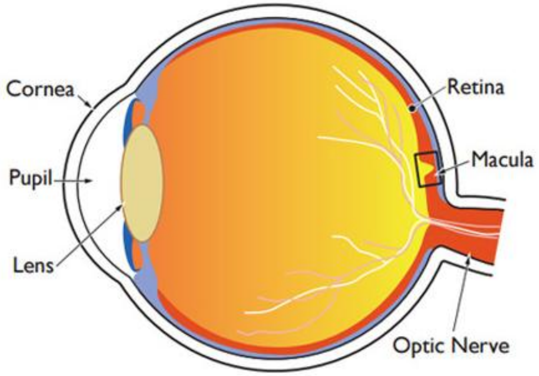
Under low light (scotopic) conditions only rods produce a visual signal.

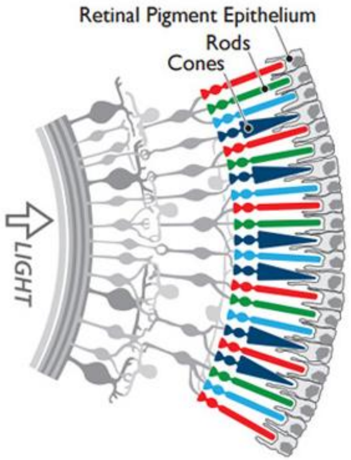
In normal (photopic) conditions only cones produce visual signal (rods are saturated).

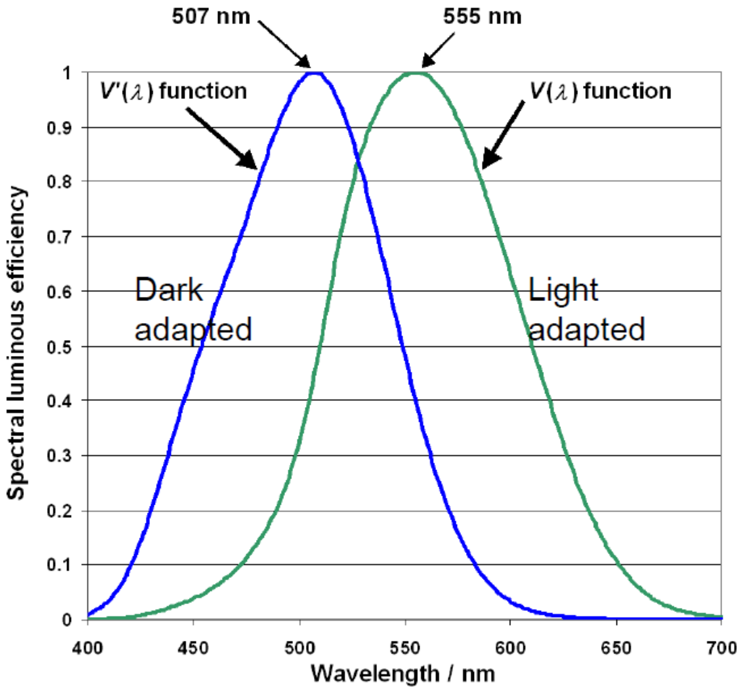
Photopic lighting condition ~>3cd/m^2 Scotopic lighting condition ~<0.03cd/m^2

The standard scotopic luminosity function or V' (λ) was adopted by the CIE in 1951

Scotopic response is simply implemented with spectral meter







Mesopic Vision

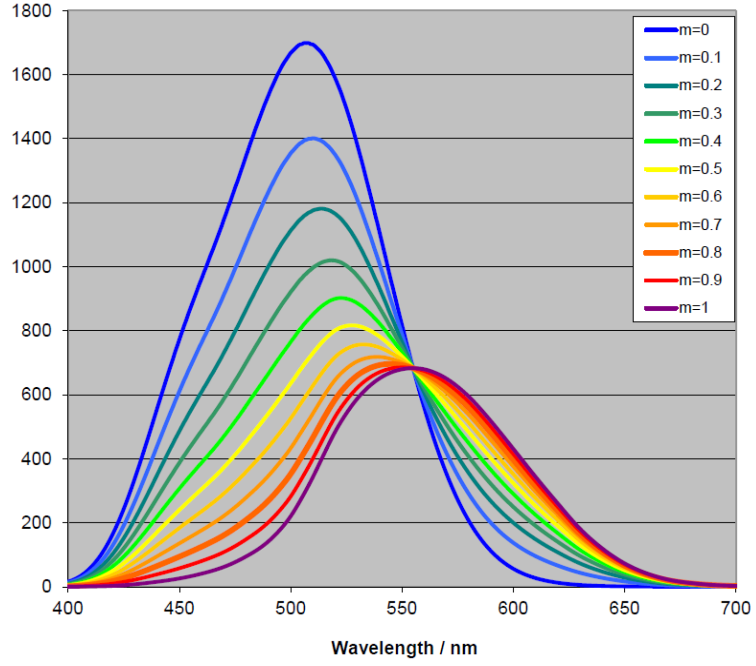
Scotopic Vision	Mesopic Vision	Photopic Vision
Illuminance <0.05 lux to ~3µlux	Illuminance 3µlux to 50 lux	Illuminance levels >50lux
Rods only, no colour perception	Eye not in stable state	Cone receptors yield colour

The eye operates in the mesopic region in many important situations:

- Night time driving;
- Emergency escape lighting;
- Marine signalling.

LED lighting has potential to offer good colour rendering with high mesopic efficiency. Using the mesopic system to calculate the effective luminance of cool white light sources results in significant changes in their apparent efficacy.

CIE 191: System for mesopic photometry

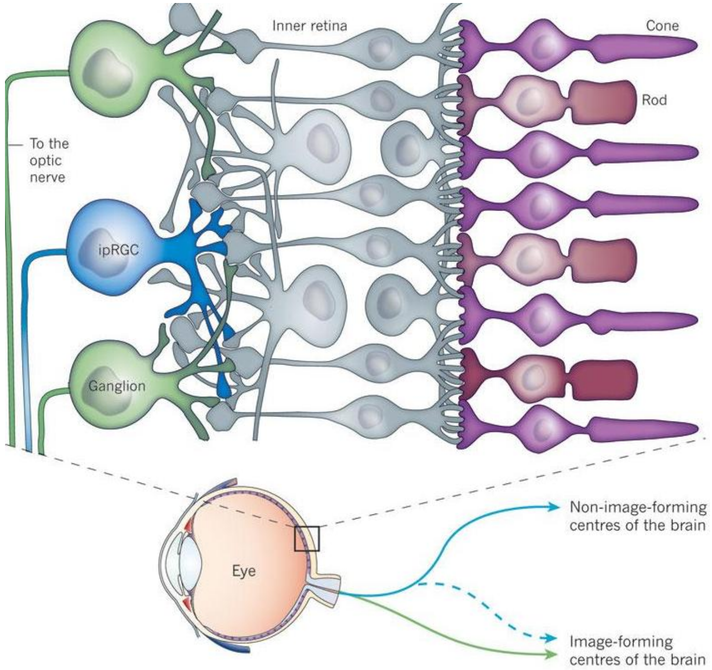


Spectral weighting function depends on visual adaptation (determines value of *m*)

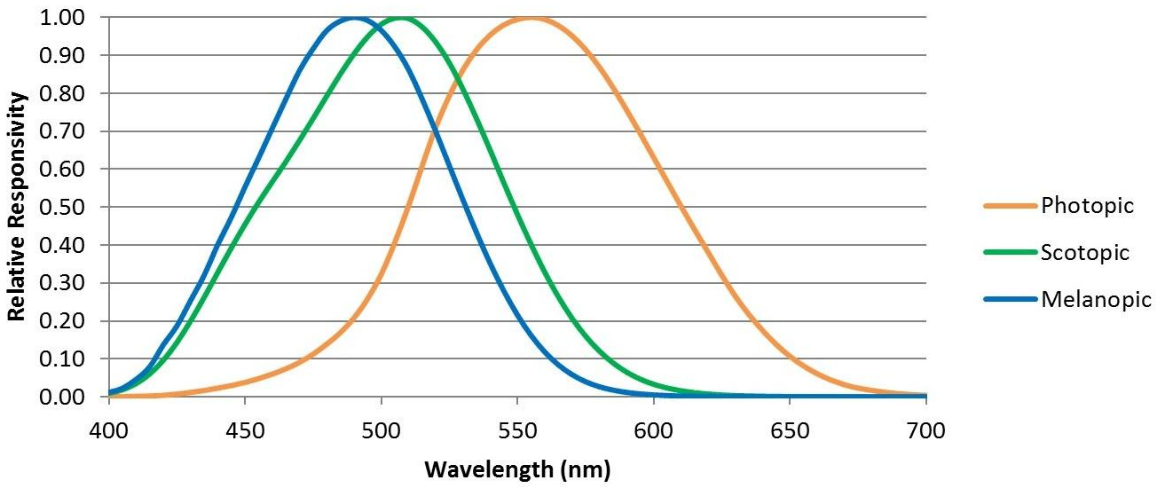
Human Centric Lighting / Circadian Lighting

Research over the past 15+ years has shown that as well as the rod and cones responsible for our vision, our retinas also have intrinsically photosensitive retinal ganglion cells (ipRGCs) that play a major role in entraining our circadian rhythms.

Much activity in this field due to the ease with which the spectral output and intensity of LEDs can be controlled as well as the flexibility in constructing luminaires (and the commercial opportunities this gives rise to!).



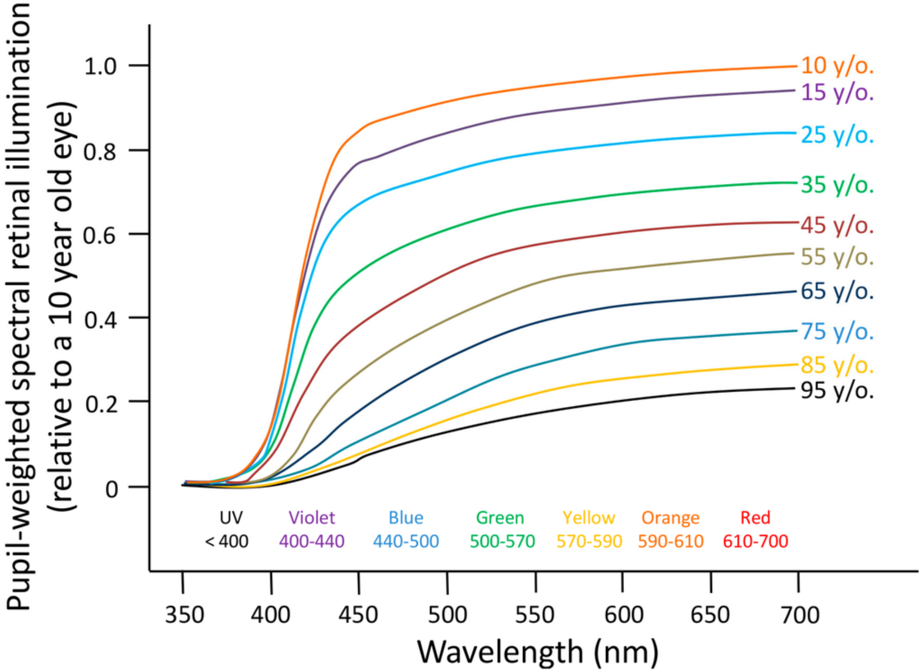
Lucas et al (2014) *Trends in Neurosciences* 37(1):1-9



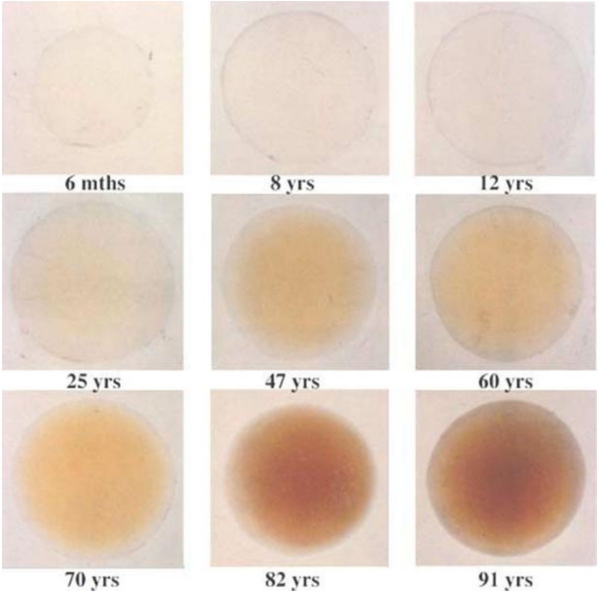
http://lucasgroup.lab.ls.manchester.ac.uk/research/measuringmelanopicilluminance/

Human Centric Lighting – age considerations

Clouding of the lens in the eye with age results in lower light transmission, particularly in the blue region.



Int. J. Mol. Sci. **2014**, *15*(12), 23448-23500; doi:10.3390/ijms151223448



Another effect requiring spectral data!

Human Centric Lighting -standards

Research is still in relatively early stages but guidelines and standards for the measurement and incorporation of circadian lighting are emerging.

CIE Technical Note CIE TN 003:2015 Report on the First International Workshop on Circadian and Neurophysiological Photometry.
http://files.cie.co.at/785_CIE_TN_003-2015.pdf

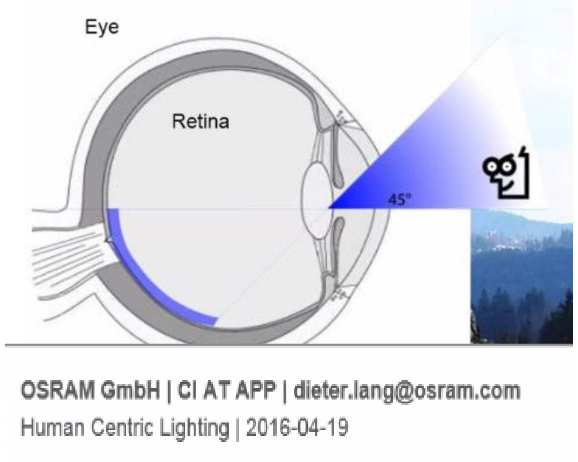
prEN 16791 Quantifying irradiance for eye-mediated non-image forming effects of light in humans

DIN SPEC 5031-100 Melanopic effects of ocular light on human beings - Quantities, symbols and action spectra

EN 12464-1:2011 Lighting of indoor work places (gives some guidance only)

The WELL Building Standard https://www.wellcertified.com/
(specifies lighting conditions in terms of Equivalent Melanopic Lux)

DIN SPEC 67600:2013-04 (E) Biologically effective illumination - Design guidelines
(bases its recommendations solely on melanopic illumination)



Vertical illumination levels (at eye level) more important in HCL due to distribution of ipRGC's – we are optimised for blue light from the sky!

http://humancentriclighting.org/measuring-and-design-of-lighting-for-hcl-applications/

Horticultural Lighting

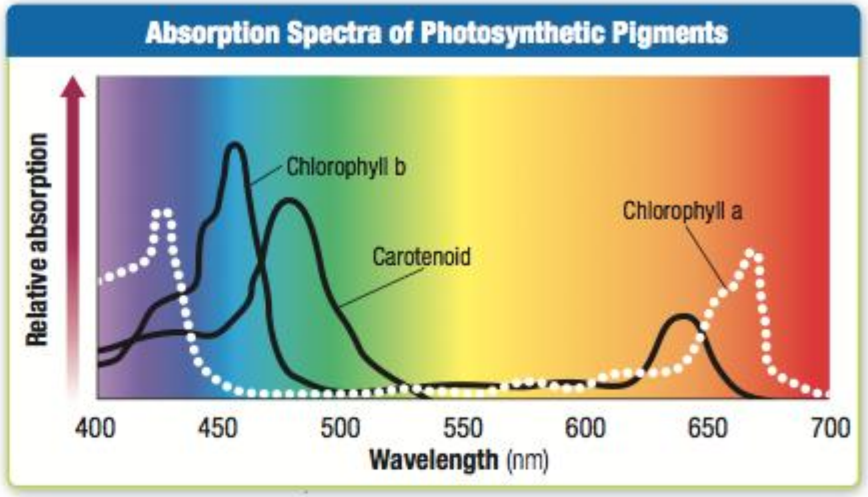
Much research and IP regarding optimum spectral content of grow lights.

Blue and red LEDs may offer greatest PAR efficacy , but is this best for crop yields?

Its complicated - temperature, humidity, air circulation, soil moisture and mineral content, etc are all factors too ☹

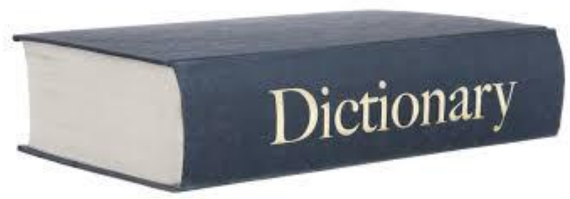
Photosynthetically Active Radiation, PAR, 400-700nm

Lux and lumens are not meaningful for plants.



Photosynthesis depends on the amount of photons.
Planck–Einstein relation, $E = hc/\lambda$, allows us to determine this from the spectral data.

<u>Horticultural Lighting – PAR metrics</u>



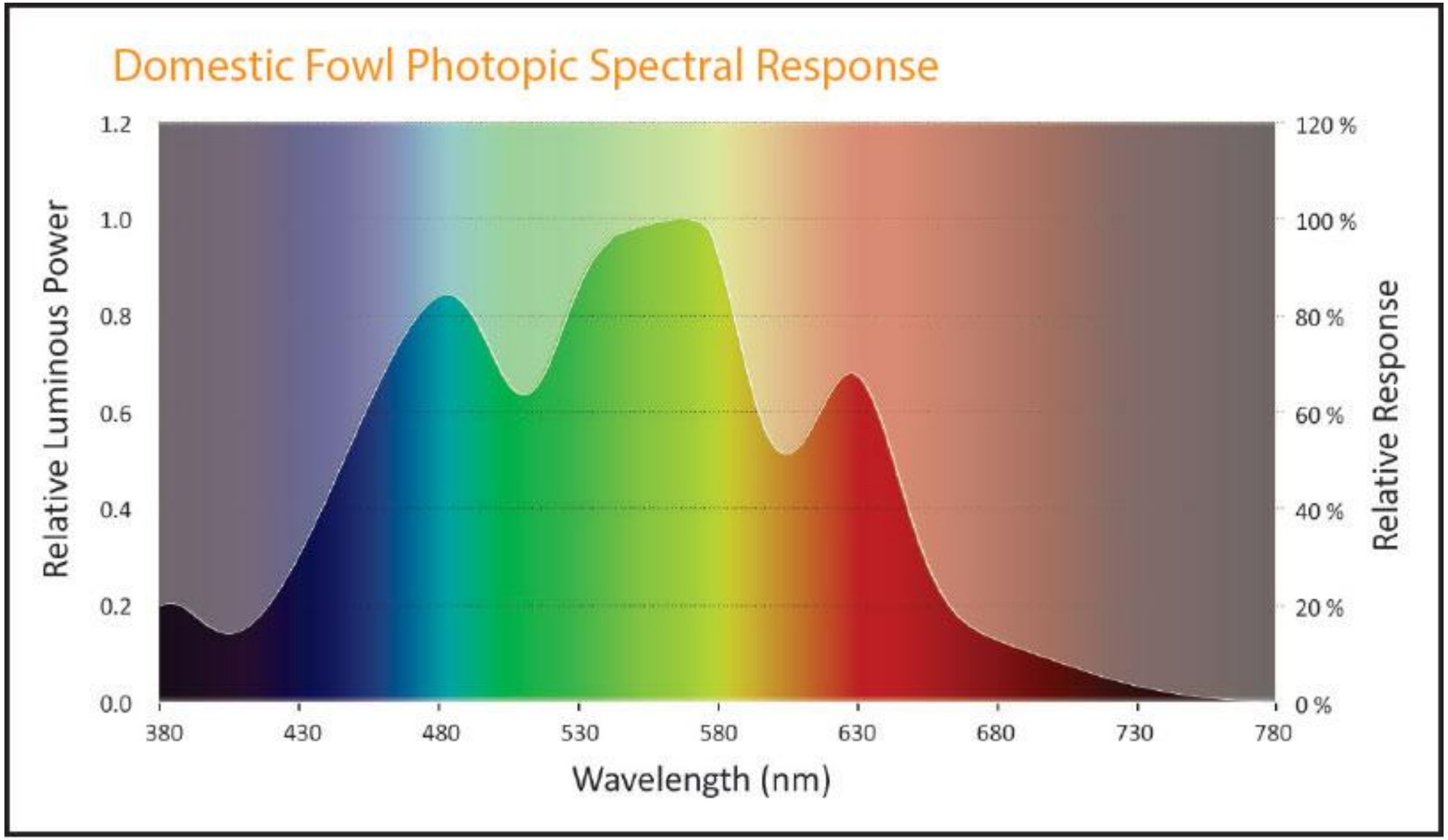
PAR is a much misused term – not quantitative, just descriptive - **P**hotosynthetically **A**ctive **R**adiation. Generally accepted as radiation within 400-700nm

Photosynthetic Photon Flux (PPF) : measurement of the total number of photons emitted by a light source each second within PAR wavelength range. Measured in **µmol/s**. Analogous to ‘lumens’ for visible light.

Photosynthetic Photon Flux Density (PPFD) : measurement of the total number of photons within PAR wavelength range that reach a surface each second measured over a one square meter area. Measured in **µmol/m²/s**. Analogous to ‘lux’ for visible light.

Day Light Integral (DLI) : cumulative measurement of the total number of photons within PAR wavelength range that reach a surface during 24 hour period, measured over a one square meter area. Measured in **mol/m²/d**.

The mole is the SI base unit (symbol **mol**) for the amount of a substance i.e. photons in this context.
1 mol = 6.0221415×10^{23} (“Avogadro’s number”)

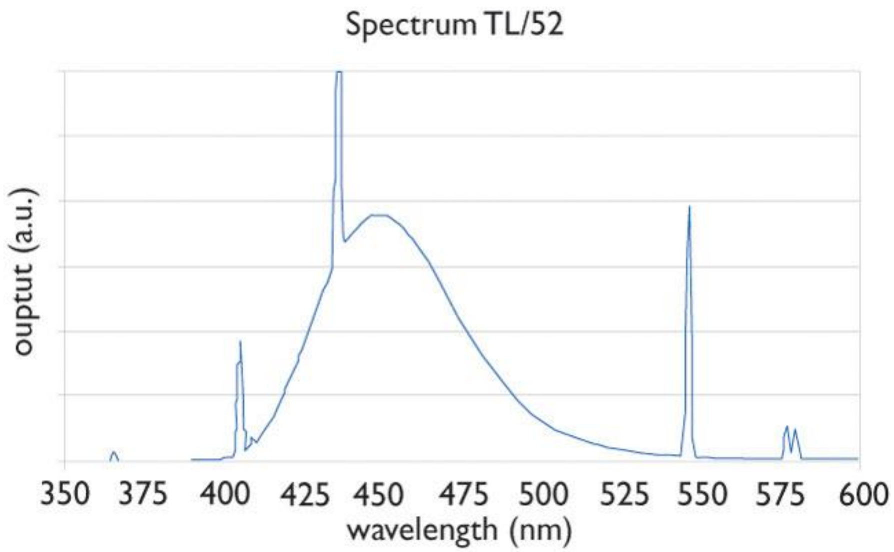


Data source: "Spectral sensitivity of the domestic fowl (Gallus g. domesticus)" N. B. PRESCOTT AND C. M. (1999)

Phototherapy

Light is used for therapeutic purposes such as the treatment of jaundice (hyperbilirubinemia) in new born infants

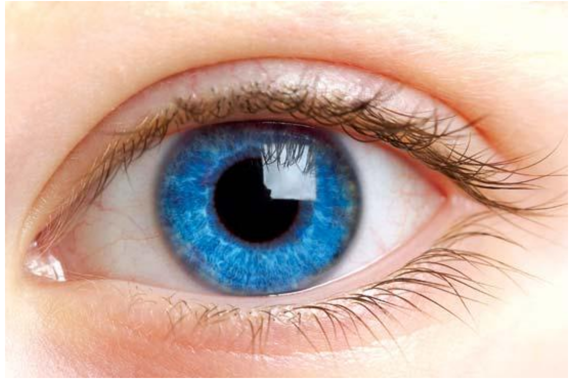
Spectral light meters enable the accurate measurement of phototherapy sources according to all international standards.



The European market specifies:
Total irradiance for bilirubin, E_{bi} in accordance with IEC 60601-2-50:2009+A1:2016
E_{bi} = integrated irradiance 400 to 550nm, in mW/cm^2

Whereas the USA market requires:
Average spectral irradiance over the 460 to 490nm range in accordance with American Academy of Pediatrics latest recommendations, in $\mu W/cm^2/nm$

Blue Light Hazard



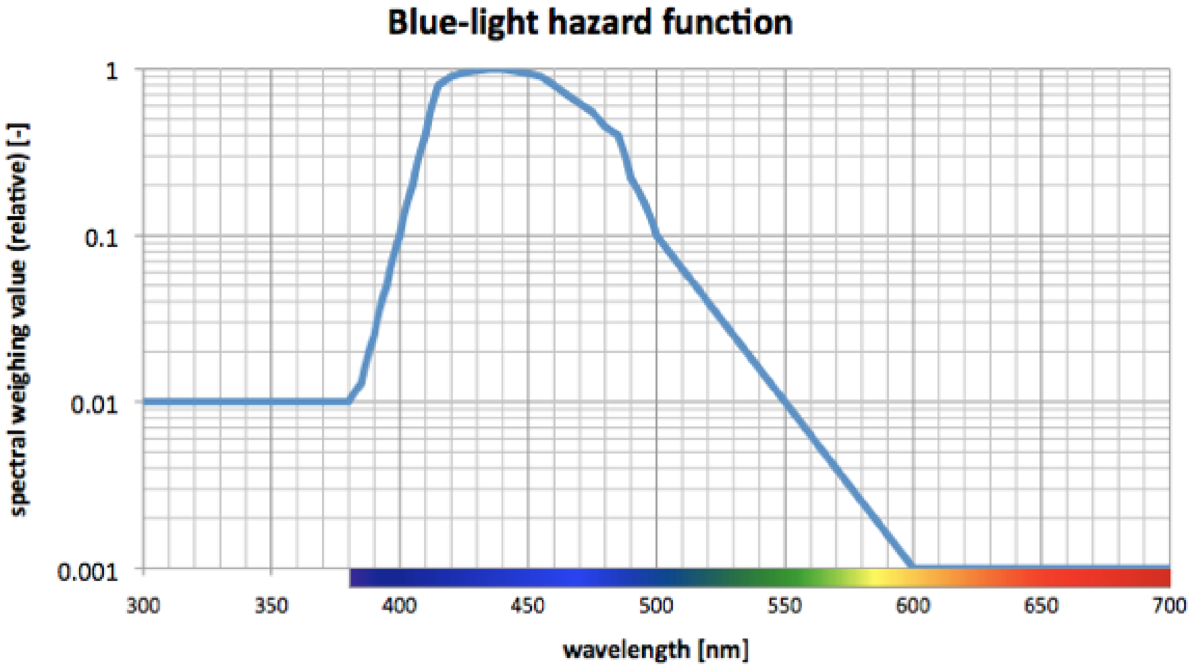
More specialist application - extended wavelength range 300-700nm
Standards require particular measurement geometries

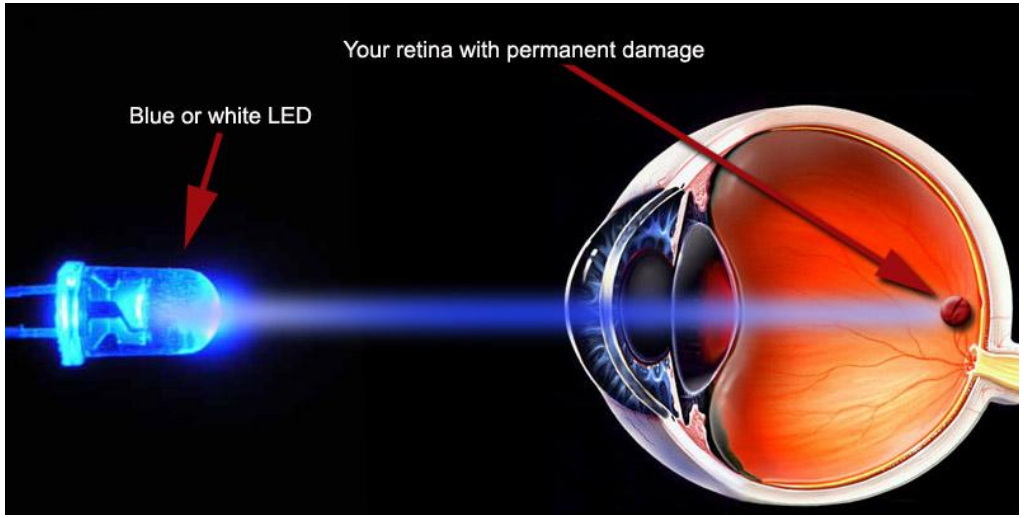
IEC TR 62778:2014 Application of IEC 62471 for the assessment of blue light hazard to light sources and luminaires

Blue light weighted radiance 300-700nm at 200mm in an 11mrad FOV

IEC 62471:2006 Photobiological safety of lamps and lamp systems

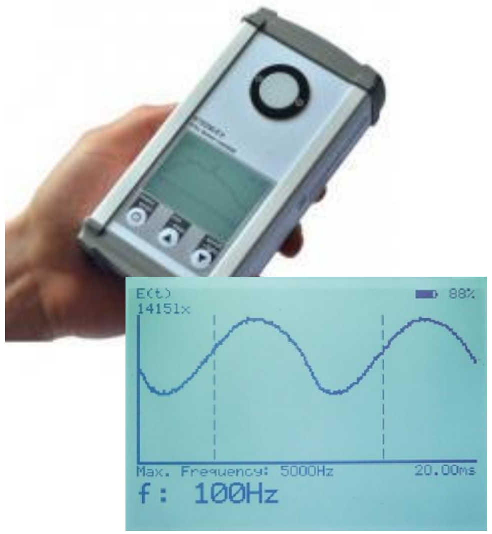
Includes UV and IR hazards too, 200-3000nm

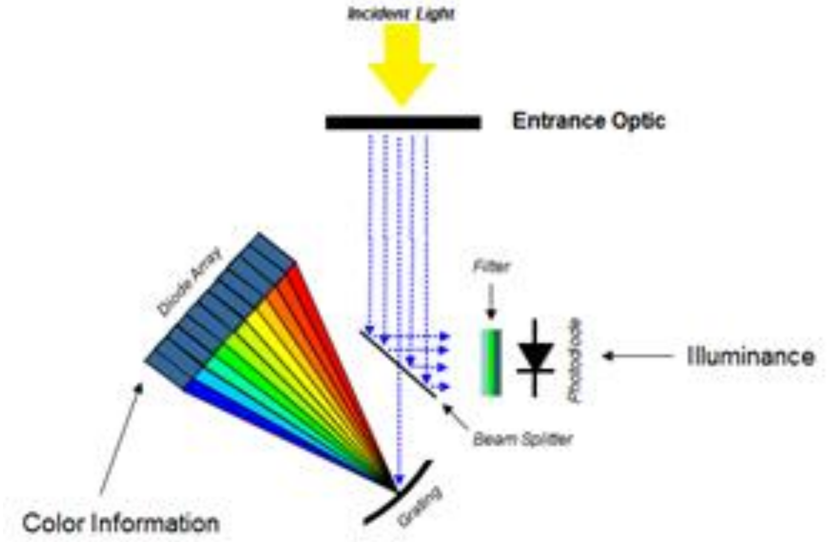




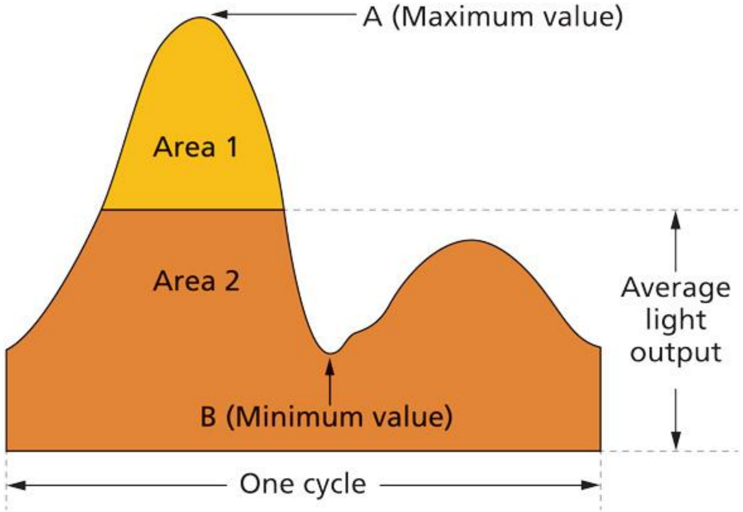
https://www.hdwarrior.co.uk/2009/05/09/led-light-damage/

Enhanced Spectral Light Meters





LED Flicker – detrimental health effects such as triggering photosensitive epilepsy and stroboscopic effects. Results from drive and control circuitry



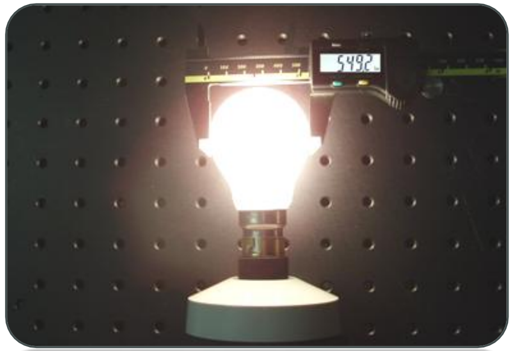
Source: IESNA Lighting Handbook, 10th Edition

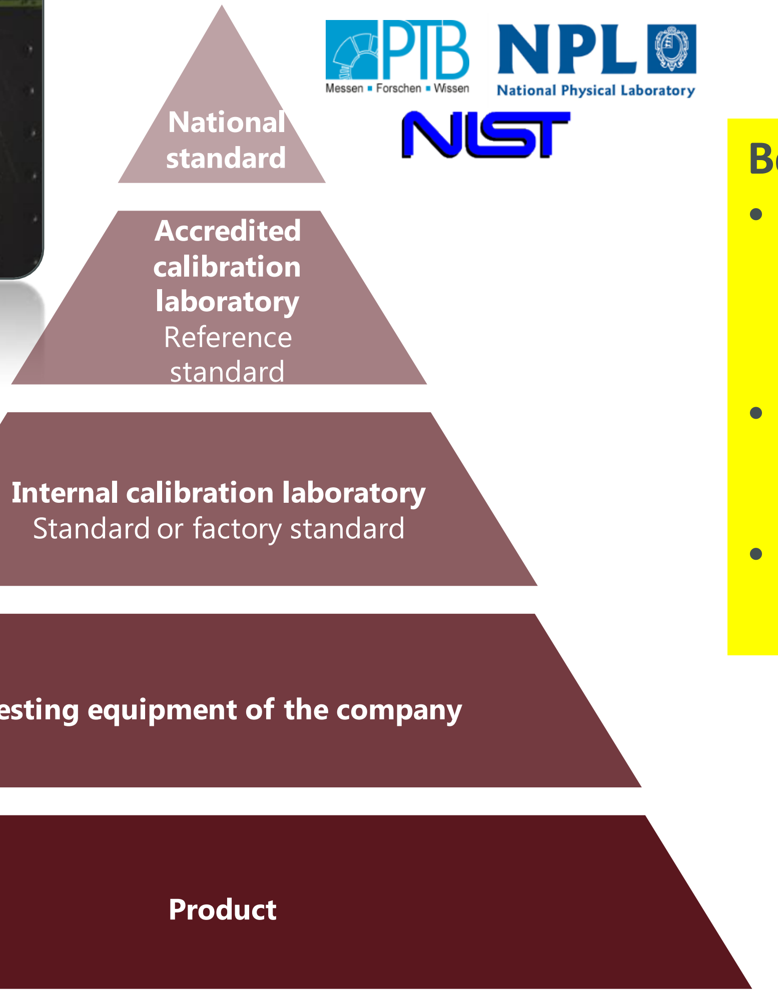
- additional measurement capabilities such as Flicker measurement;
- higher levels of accuracy resulting from improved stray light rejection and linearity correction.

IEEE Std 1789 (2015) "Recommended Practice for Modulating Current in High-Brightness LEDs for Mitigating Health Risks to Viewers"

CIE TN 006:2016 Visual Aspects of Time-Modulated Lighting Systems – Definitions and Measurement Models http://files.cie.co.at/883_CIE_TN_006-2016.pdf

Traceable Calibration



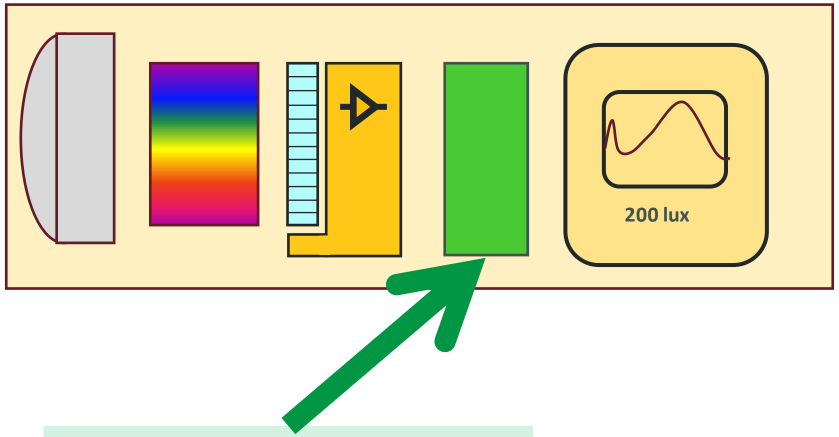


CAUTION

Be cautious about:

- Manufacturer's claims of 'traceable' calibration. *Check for relevant accreditation by DAkkS, UKAS, etc to ISO 17025;*
- Simple % 'accuracy' claims. *Look for details of calibration conditions and uncertainty;*
- Unrealistic accuracy claims – *how does it relate to uncertainty from National Measurement Institutes*

Summary



Spectral matching to:

- Photometric curve V(λ)
- Scotopic curve V'(λ)
- Colour matching
- Mesopic
- Melanopic
- PAR
- Bilirubin
- Blue light hazard
- Chicken vision
- Etc, etc …

To conclude:

- Spectral mismatch errors with photometers are often significant when measuring LEDs/SSL;
- Spectral light meters remove spectral mismatch error and enable colour measurements;
- Any action spectra (filter function) may be applied within its spectral range;
- Enable development and testing of LED products for non-GLS / novel / high value applications;
- Traceable calibration is essential.

Thank you for your attention.

Mike Clark
m.clark@gigahertz-optik.de

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TE LINTELO SYSTEMS BV

Te Lintelo Systems BV
Mecurion 26a
6903 PZ Zevenaar
The Netherlands

✆ +31 316 340804

www.tlsbv.nl
contact@tlsbv.nl

photonics is our passion!