

Let there be light!

Technical guide for visual colour evaluation

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1 Colour harmony under various lighting conditions

Uniform colour is directly associated with high quality and influences our purchasing decision. This is especially true for multi-component products consisting of different materials and or being produced by different suppliers. The human eye is often the final judge for approving a new design. Therefore, the visual inspection conditions need to be standardized to guarantee repeatable visual results. The most important colour match is under natural daylight. The CIE defined several standard D illuminants with D65 being the most important one. The lamps used in a light booth must simulate D65 as close as possible. Until now, fluorescent tubes were used to simulate D65. A new unique lighting setup is now able to achieve class A quality by simulating CIE D65 with a smart combination of filtered halogen lamps and LEDs.

2 Standardization of visual colour evaluations

Colour perception is dependent on personal experience as well as illumination and surrounding observing conditions. As the ambient conditions are highly variable and not consistent at all, it is required to standardize common lighting situations. The illumination should be easily switchable in order to observe and avoid so-called "Metamerism", i.e. differences in colour matching when lighting conditions change. In order to guarantee reliable testing and evaluation conditions, international standards specify testing procedures defining the following components: [1][2][6][7][10][12][13]

2.1

Observer

The observer must have normal colour vision and should be properly trained in evaluating colours. To avoid eye fatigue the colour decision should be made within seconds. Additionally, small breaks must be taken between evaluations. As people describe colour differently, the following order should be used for communication and documentation of colour: Hue -> Chroma -> Lightness.

2.2.

Object

The specimens should be flat and uniform in colour, gloss and surface texture. Standard and sample shall be placed next to each other without any distance in between and be reversed from time to time. The preferred sample size is approximately 10 cm to 15 cm. The viewing distance between eyes and the specimen should be 50 cm. This distance corresponds a 10° field of vision.

2.3

Surrounding

The visual field immediately next surrounding the specimen as well as the ambient visual field, used to let the observer's eyes rest, are of high importance for colour appraisals. The interior of the light booth should have a matte grey surface, and the appraiser should wear neutral coloured clothing to avoid disturbing chromatic reflections.

2.4

Illumination

The level of illumination at the colour-matching position shall be between 1000 lx and 5000 lx, depending on the respective international standard. A diffuser panel shall normally be used to avoid direct reflection and ensure a uniform distribution of lighting over the entire inspection field.

3 Terms for characterization of light

Light is electromagnetic radiation within a certain portion of the electromagnetic spectrum. The word light usually refers to radiation that is visible to the human eye (wavelength: 400nm to 700nm). In order to characterize light emitted by a light source several terms are used: colour temperature (CT) and correlated colour temperature (CCT), colour rendering index (CRI R_a) as well as spectral power distribution (SPD) and metamerism index MI_{vis} .

3.1

Colour Temperature (CT) and Correlated Colour Temperature (CCT)

The concept of colour temperature is based on the fact that the colour of an object changes when being heated because the emitted radiation changes. According to ISO/CIE 10526:1991 (E) a colour tempera-

ture T_c is defined as “The temperature of a Planckian radiator whose radiation has the same chromaticity as that of a given stimulus.”

Simply explained, the colour temperature is a temperature describing the colour characteristics of visible light based on the temperature of a Planckian black-body. Figure 1 shows the CIE x,y chromaticity space. The black line in the graph pictures the chromaticity values of black-body light sources of various temperatures.[8] [11][12][13]

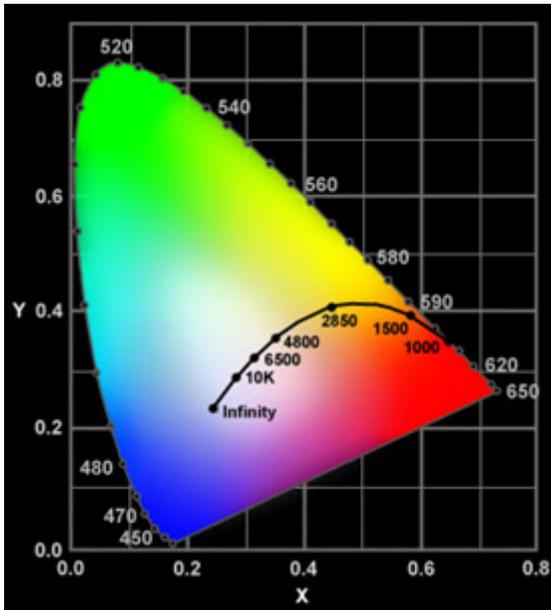


Figure 1:
Planckian locus in the CIE x,y chromaticity space

Colour temperature is usually expressed in Kelvins (K). The Kelvin scale is a measure for absolute temperature ($0^{\circ}\text{C} = -273\text{K}$). Colour temperatures over 5000K are defined as cool colours, with hues of bluish white, where lower colour temperatures (2700K – 3000K) are defined as warm colours, with hues of yellow and red. Most natural light sources (e.g. sun, stars) very closely follow the Planckian locus. When sources are to be described, which do not emit light exactly matching the black-body radiator, the term Correlated Colour Temperature is used. According to ISO/CIE 10526: 1991 (E) a correlated colour temperature, T_{cp} is defined as “The temperature of the Planckian radiator whose perceived colour most closely resembles that of a given stimulus at the same brightness and under specified viewing conditions.” [1] [2][8][13][12]

3.2 Spectral Power Distribution

Colour and colour temperature are not unique parameters to describe a light source. Two light sources with the same chromaticity coordinates xy and colour temperature might have a different spectral characteristic and therefore, create different colour impressions. Thus, the most accurate way of characterizing a light source or an illuminant is by their spectral power distribution curve (short: SPD curve). [1][2][8][6] [10][12][13].

The curve shows the radiant flux emitted by the light source at various wavelengths across the visible spectrum (amount of energy $[E(\lambda)]$). Mathematically the spectral power is written as:

$$E(\lambda) = \frac{\delta^2 \Phi}{\partial A \delta \lambda} \approx \frac{\Phi}{A \Delta \lambda}$$

Formula 2: Calculation of relative spectral power

Where

$E(\lambda)$ is the spectral power/energy,

Φ is the radiant flux,

A is the area over which the radiant flux is integrated and

λ is the wavelength.

Quite often, the relative spectral power is indicated by the ratio of the spectral power at a given wavelength $[E(\lambda)]$ to the spectral power of a reference wavelength $[E(\lambda_0)]$.

$$E_{rel}(\lambda) = \frac{E(\lambda)}{E(\lambda_0)}$$

Formula 2: Calculation of relative spectral power

Therefore, the SPD curve is normalized (see Formula 3) at the wavelength of 560nm so that the assessment is independent of the absolute level of illumination.

$$S_n(\lambda) = 100S(\lambda) / \sum_{400}^{700} S(\lambda) \bar{y}_{10}(\lambda) \Delta\lambda$$

Formula 3: Mathematical normalization of a spectral power distribution curve

3.3

Colour Rendering Index – CRI

The colour rendering index is a quantitative measure of a light source and its ability to reveal colours of objects in comparison with an ideal or natural light source. The term CRI is often used on commercially available lighting products. By proper definition, it should be called R_a – the General Colour Rendering Index, or R_i – the Special Colour Rendering Index, corresponding to the number of test-colour samples that are evaluated.

The CRI is calculated by comparing the colour rendering of the test source to that of a defined source. For test sources with a CCT under 5000K a black body radiator is used as the defined source. For test sources above 5000K daylight (D illuminants) are used. The detailed calculation of R_i and R_a is explained in the technical report of CIE 13.3-1995. [4] The test method is using a set of eight (R_a) or fourteen (R_i) CIE-1974 test-colour samples from an early edition of the Munsell Atlas. The first eight samples are moderate in saturation, cover the hue circle and are approximately the same in brightness. The other six samples provide supplementary information about the colour rendering properties of the light source.

3.4

Metamerism Index – MI

CIE publication 51.2 describes a method to rate the quality of daylight sources. For the visible range the method uses five theoretical sample pairs, where each pair consists of the standard and metameric sample with a $MI_{VIS} = 0$ for standard illuminant D65. The higher the mismatch between the MI_{VIS} of standard illuminant and MI_{VIS} of the daylight-simulating source, the worse is the quality of the light source. [5][13][12]

Pursuant to MI_{VIS} for the visible range, the CIE also defined MI_{UV} for the fluorescent range, with three theoretical metameric sample pairs. The formulas for MI_{VIS} and MI_{UV} are as followed:

$$MI_{VIS} = \sum_{t=1}^5 \Delta E_t / 5 \qquad MI_{UV} = \sum_{j=1}^3 \Delta E_j / 3$$

Formula 4: Calculation of the metamerism indices MI_{VIS} and MI_{UV}

Where ΔE_i and ΔE_j are the $L^*a^*b^*$ ($L^*u^*v^*$) colour differences between the i^{th} and j^{th} pair of metamers. The classification of MI_{VIS} and MI_{UV} is done according to the following table.

Category	CIELAB	CIEUV
A	< 0,25	< 0,32
B	0,25 to 0,5	0,32 to 0,65
C	0,5 to 1,0	0,65 to 1,3
D	1,0 to 2,0	1,3 to 2,6
E	> 2,0	> 2,6

Table 1: Categorization of MI_{VIS} and MI_{UV} depending on colour difference formula

As there are no actual D65 light sources available, the challenge is to develop a D65 simulator as close as possible to the CIE D65 illuminant. The quality of a simulator is objectively assessed with the CIE Metamerism Index MI_{VIS} , corresponding to quality classes A to E with class A being the most accurate simulation.

4 Quality measures for simulating CIE illuminants by artificial light sources

4.1

Definition light source and illuminant

When speaking about light sources and illuminants it is important to know what the difference between these two terms is. A simple and proper explanation comes from “Billmeyer and Saltzmann”, where a light source is explained as “Physically realizable light, whose spectral power distribution can be experimentally determined”. An illuminant is defined as “Light defined by a relative spectral power distribution that may or may not be physically realizable as a source.”

4.2

Standard illuminants

The CIE (Commission Internationale de l’Éclairage) defined a number of SPD curves to provide reference spectra for colourimetric applications, the so-called CIE standard illuminants.

4.2.1

CIE standard illuminant A

Standard illuminant A was introduced by the CIE in 1931 and represents an incandescent tungsten filament lamp. Its relative SPD is that of a Planckian radiator at an approximate temperature of 2856K. To simulate standard illuminant A in a light booth conventional light bulbs or nowadays quartz tungsten

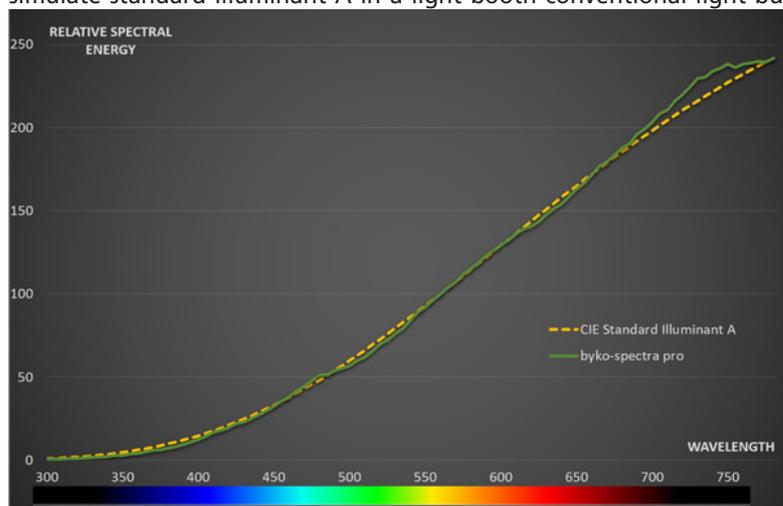


Figure 2: CIE standard illuminant A and its simulation with tungsten halogen lamps in byko-spectra pro

4.2.2

4.2.2

CIE standard illuminant series F

CIE defined 12 fluorescent lamp types, named F1 to F12, classified into three groups. They differ in the bandwidth and wavelength peak of their emission spikes. Consequently, different colour rendering indices and colour temperatures are achieved.

Classified Groups	Lamp types	Colour Temperature Tc	CRI Ra
Standard group	F1 – F6	2500 – 7000 K	60 - 80
Broad band group	F7 – F9	2500 – 7000 K	≈ 80
Three narrow band group	F10 – F12	2500 – 7000 K	80 - 95

Table 2: Classification of standard illuminant F series [16],[17]

Among these twelve, F2 and F11 are most commonly used in the industry. F2, also named “CWF” (cool white fluorescent) has a CT of about 4000K and a CRI $R_a \approx 60$. F11, also known under TL84, has a CT of about 4000K and a CRI $R_a > 85$. To simulate standard illuminant F series in a light booth, commercially available fluorescent tubes are used. [11] [16][17]

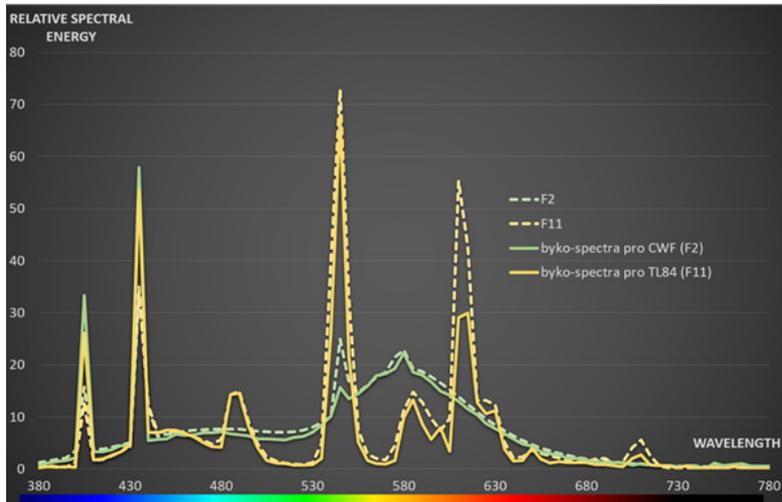


Figure 3: CIE illuminants F2 and F11 and their simulation with fluorescent tubes in byko-spectra pro

4.2.3

CIE standard illuminant D65

In 1964 CIE defined a series of daylight illuminants by numerous measurements of real daylight (see Table 3). Out of 622 measurements, the theoretical SPD curves of daylight from 330nm until 700nm were constructed. CIE standard illuminant D65 is the most important representation of an average daylight at 6504K corresponding to a midday light in Western/Northern Europe, comprising both direct sunlight and the light diffused by a clear sky including UV component.

Illuminant	Colour Temperature [K]	Common name
D50	5003	Warm daylight at sunrise or sunset
D55	5504	Mid-morning or mid-afternoon daylight
D65	6504	Noon daylight
D75	7500	Overcast daylight

Table 3: CIE standard illuminants D series, listed with CT and common name

In order to simulate daylight, different types of light sources are used in commercially available light booths/luminaires for visual appraisals. Depending on how good the match between artificial light source and standard illuminant CIE D65 is, a sample pair can look very different. In the following example, a sample pair is evaluated in light booth 1 with fluorescent tubes with a CT of about 6500K and a CRI R_a of about 96. The daylight simulation is an approximation of the CIE defined D65 with CIE MI_{vis} (see Chapter 3.4) Class B quality level (see Figure 4). The difference between this sample pair is very significant under these evaluation conditions.

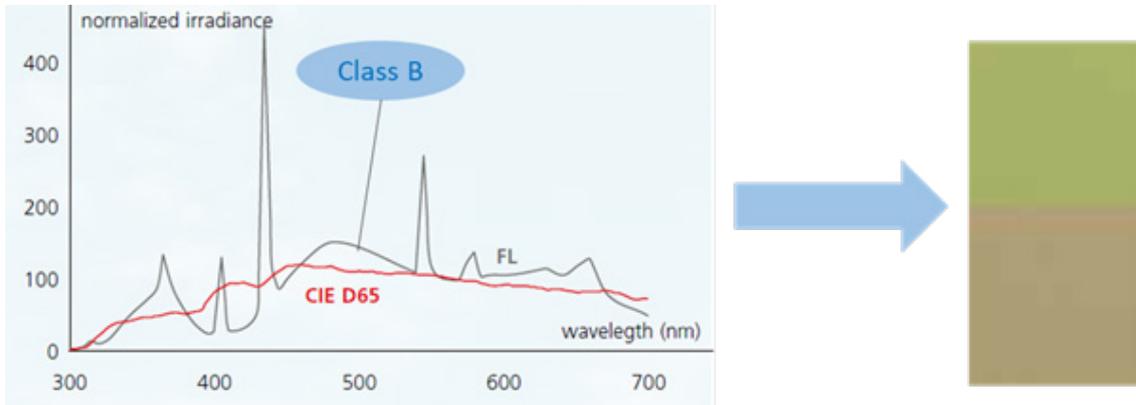


Figure 4: Daylight simulation with fluorescent tube

Next, the sample pair is evaluated in light booth 2, byko-spectra pro, using halogen lamps with a specially developed blue filter glass combined with an LED array. This combination creates an excellent simulation of CIE D65 without any spikes (see blue curve in Figure 5) resulting in a CIE MI_{vis} quality class A. Under these condition our sample pair will show only a small difference like under natural daylight.

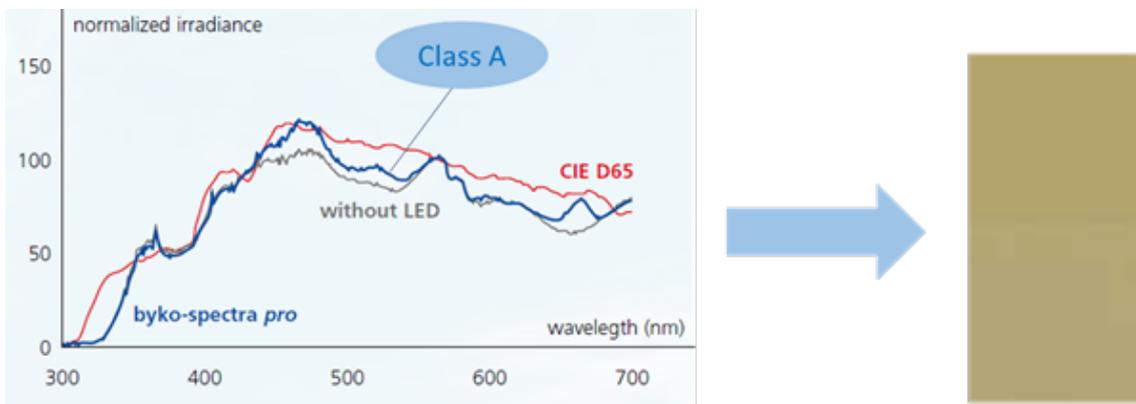


Figure 5: Daylight simulation with combination of filtered halogen lamps with and without LEDs

5 Best in Class Daylight with byko-spectra pro

BYK-Gardner's new light booth byko-spectra pro masters the challenge of bringing true daylight into the lab by a smart combination of filtered halogen lamps and LED array. This combination guarantees best in class daylight simulation – tested according to CIE.

Additionally, the built-in sensors in the light booth permanently control the lamp performance and automatically adjust the voltage to guarantee lamp stability. In order to control the lamp condition and trigger lamp replacement actual colour temperature, light intensity and lamp operation time are

shown on the display of the light booth. To reduce maintenance interval, the class A daylight lifetime is extended to 600 hours.

Depending on a product's usage, colour needs to match under a variety of illuminations. To be prepared for metamerism the light booth byko-spectra pro offers two daylight illuminants with class A performance (D65 and D75), incandescent lighting (A), three fluorescent illuminants (CWF, TL84, U30) and a UV light for evaluation of fluorescent samples.

As diffused light is essential in the evaluation of solid colours, diffuser panels mix the light to ensure uniform lighting over the entire inspection field. To comply with international standards, the interior walls are painted with a matte light grey colour to eliminate influence of the surrounding on the observer.

Technical performance is not the only key criteria for a light booth. Efficient and comfortable operation also play an important role for the user. The large colour display not only allows the switching of illuminants, but also enables an easy menu guided operation. The included remote control allows switching illuminants from a distance of up to 10 m. An Auto Sequence Mode progresses automatically through the user-defined sequence of illuminants for hands free operation.

byko-spectra *pro* is available as a regular light booth and as luminaires. The luminaires can be hung from the ceiling as a set or as multiple units to outfit an entire colour harmony room to evaluate system components or complete products, e.g. car bodies. Luminaires also have the same class A illumination specifications as the light booth, ensuring the needed precision in visual colour appraisals. ■



Figure 6: byko-spectra *pro* light booth



Figure 7: byko-spectra *pro* luminaire

More information is available from BYK-Gardner GmbH, P.O. Box 970, 82534 Geretsried, Germany: By fax: +49 8171 3493-140, the free service no. 0 800 gardner (0 800 4273637) or on the Internet at www.byk.com/instruments.



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Standards

- [1] **DIN EN ISO 3668:2001-12:** Paints and varnishes – Visual comparison of the colour of paints
- [2] **ASTM D 1729: 1982:** Standard Practice for Visual Appraisal of Colours and Colour Differences of Diffusely-Illuminated Opaque Materials
- [3] **ISO/CIE 10526:1991:** CIE Standard Colourimetric Illuminants
- [4] **CIE 13.3 – 1995:** Method of Measuring and Specifying Colour Rendering Properties of Light sources
- [5] **CIE 51.2 – 1999:** A Method for Assessing The Quality of Daylight Simulators for Colourimetry
- [6] **CIE 15:2004, 3rd edition:** Colourimetry
- [7] **CIE DS 014-1.2/E:2004:** Colourimetry – Part 1: CIE Standard Colourimetric Observers
- [8] **CIE DS 014-2.2/E:2004:** Colourimetry – Part 2: CIE Standard Illuminants
- [9] **CIE S 014-3/E:2011:** Colourimetry – Part 3: CIE Tristimulus Values
- [10] **DIN 6173 – 2: 1983-12:** Colour matching: lighting conditions for average artificial light
- [11] **CIE 192:2010:** Practical daylight sources for colourimetry
- [12] **SAE J361TM – 04/2017:** Surface Vehicle Recommended Practice: Procedure of Visual Evaluation of Interior and Exterior Automotive Trim, Chapter 4.1.3

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- [13] Yuk Ming Lam, John H Xin, Kwan Moon Sin: Study of the influence of various D65 simulators on colour matching, *Colour. Technol.*, **117**, 2001
- [14] Roy S. Burns: "Billmeyer and Saltzman's Principles of Colour Technology", Third Edition, 2000 by John Wiley and Son's, Inc.
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