FN-Optiklabor-Lichtquellen-EN-v0.1-2026-05-17

Research Note — Light Sources

Author: Thomas Schüller · forschung@tschueller.com · ORCID 0009-0003-9799-6747 **Affiliation:** privately funded, no institutional affiliation **Licence:** CC BY 4.0 · **Version:** 0.1 · **Date:** 2026-05-17 **Strand:** FORSCHUNG / Höhlengleichnis-Optiklabor / 07 Light Sources **Tool:** LUX · **Document type:** Research note (Template v1.0) **Status:** completed test with documented assessment

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1. Thesis

Module 09 (Colour Mixing) showed that colour is a perceptual response of three cone types. Module 07 uses this tristimulus metric to test the intuitive assumption “every white light source is equivalent”. The assumption turns out to be doubly wrong: **first, different white light sources have completely different spectra (continuous for the black body, gappy for LED and fluorescent), and second, they render object colours differently well.** A light source has two independent properties: how it looks itself (colour temperature) and how well it shows object colours (colour rendering index, CRI). These two properties are decoupled — two sources can appear equally white and yet render object colours completely differently.

2. Assumptions

1. Planck’s radiation law for thermal emitters (black body).
2. CIE 1931 standard observer for colour perception (from Module 09).
3. Lambert-Beer-like reflection: object colour = source spectrum × reflectance.
4. Idealised emission spectra: LED as pump peak + phosphor bump, fluorescent as mercury lines + phosphor, sodium as doublet.
5. McCamy approximation for correlated colour temperature (CCT).
6. Simplified CRI via mean colour shift of eight test colours against a black-body reference.

3. Mathematical model

M1 — “white = white”: Every white light source is equivalent and interchangeable.

M2 — black body (Planck): thermal emitter with spectrum

$$B(\lambda, T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{hc/(\lambda k_B T)} - 1}.$$

Wien’s displacement law: peak at $\lambda_{\max} = b/T$ with $b = 2898\,\mu\text{m·K}$. Colour temperature T determines the colour.

M3 — line and band spectra: LED, fluorescent, sodium as sums of narrow Gaussian bands or lines plus optional phosphor continuum. Gappy spectra that can still appear white (because the eye registers only three tristimulus values, Module 09).

M4 — colour rendering (CRI): Object colour under source S is $S(\lambda)\,R(\lambda)$ for reflectance R. The colour rendering index measures the mean colour shift of test colours between source and reference emitter:

$$\text{CRI} \approx 100 - k\,\langle \Delta_{xy}\rangle,$$

where Δ_{xy} is the chromaticity shift per test colour.

Symbol	Meaning	Unit
$B(\lambda,T)$	Planck radiance	W/(m²·sr·m)
T	temperature	K
$\lambda_{\max}$	peak wavelength	nm
$S(\lambda)$	source spectrum	rel.
$R(\lambda)$	object reflectance	0..1
CCT	correlated colour temperature	K
CRI	colour rendering index	0..100

4. Parameters

Three scenarios:

Scenario	Setup
A black body	Planck at 2700 K, 5500 K, 6500 K
B three white sources	incandescent (2700 K Planck), warm-white LED, fluorescent
C CRI	above sources + sodium vapour, reference 2700 K black body, 8 test colours

Tolerance set in advance: $\varepsilon = 5\%$ chromaticity distance for A/B; for C, M1 is refuted if CRI range > 20 points.

5. Prediction

Scenario	Expectation
A	2700 K clearly more yellowish than 6500 K, distance $> \varepsilon$
B	All three appear whitish, but spectra completely different (smooth vs. lines)
C	CRI varies strongly: incandescent ≈ 100, sodium very low

6. Falsification criterion

M1 (“white = white”) is refuted if **any** holds: - Two black bodies of different temperature have chromaticity distance $> \varepsilon$ (colour temperature is real). - Two “white” sources have strongly different spectra at similar colour (spikiness ratio > 2). - The CRI varies between sources by more than 20 points (colour rendering is source-dependent).

7. Competing models

- **K1 — “white = white” (M1):** tested baseline model.
- **K2 — black-body emitter (M2):** incandescent, sun, stars.
- **K3 — line/band emitter (M3):** LED, fluorescent, gas discharge.
- **K4 — CRI / colour rendering (M4):** quality metric.
- **K5 — TM-30 (modern colour rendering):** gamut index + fidelity index, supersedes CRI.
- **K6 — spectral rendering:** full spectra instead of CCT+CRI — for accurate simulation.
- **K7 — daylight model (CIE D series):** standardised daylight spectra, not exactly Planck.

8. Domain of failure

- **Very low temperatures ($T < 1000$ K):** radiation almost entirely infrared, barely visible.
- **Very high temperatures ($T > 20000$ K):** peak in UV, colour saturates towards blue.
- **Non-thermal sources:** laser, LED, gas discharge do not follow Planck — CCT is only an approximation (“correlated” colour temperature).
- **Metameric failure:** two sources with the same CCT can render object colours differently (exactly the CRI point).
- **Fluorescent objects:** emit light at a different wavelength — breaks the simple reflection computation.
- **Extremely narrowband sources (sodium):** CRI concept reaches its limits because almost no colour is distinguishable.

9. Simulation

Numerical evaluation in `lichtquellen_simulation.py`:

1. Planck spectra at various temperatures, normalised.
2. Idealised LED, fluorescent, sodium spectra as Gaussian sums.
3. Spectrum → XYZ → sRGB via CIE 1931 CMFs (from Module 09).
4. CCT estimation via McCamy formula.
5. CRI: eight test colours as broad Gaussian reflectances; object colour under source vs. reference, mean chromaticity shift.

Results in `lichtquellen_results.json`. Plot as `lichtquellen_szenen.svg` (four subplots: black body, three white sources, sodium, Wien’s law).

10. Result

10.1 A black-body comparison

Temperature	Chromaticity xy	estimated CCT	appears
2700 K	(0.459, 0.412)	2726 K	warm yellow
5500 K	(0.330, 0.342)	~5500 K	neutral white
6500 K	(0.313, 0.329)	~6500 K	bluish white

Distance 2700↔6500	0.16 (≫ ε)	—	**refuted**

10.2 B three white sources

Source	Chromaticity xy	CCT	spikiness
Incandescent 2700 K	(0.459, 0.412)	2726 K	2.22
Warm-white LED	(0.403, 0.387)	3538 K	1.90
Fluorescent	(0.352, 0.398)	4909 K	**4.97**

Spikiness ratio 4.97 / 1.90 = 2.6 (> 2) → **refuted**: similarly white, completely different spectra.

10.3 C colour rendering CRI

Source	CRI (approx.)	max. colour shift
Incandescent 2700 K	100 (reference)	0.000
Warm-white LED	77.2	0.090
Fluorescent	60.0	0.136
Sodium vapour	49.1	0.203

CRI range 100 − 49 = 51 points (≫ 20) → **refuted (fundamental)**.

Plot: `lichtquellen_szenen.svg`.

11. Assessment

M1 ("white = white") is refuted in all three scenarios — scenario C provides the sharpest refutation via colour rendering.

Scenario A establishes colour temperature as a real, measurable property. A black body at 2700 K (incandescent) is clearly more yellowish than at 6500 K (overcast sky) — the chromaticity distance of 0.16 is huge compared to the discrimination threshold. The estimated CCT matches the input almost exactly (2726 K for 2700 K input), validating the McCamy formula. Wien's displacement law explains why: at higher temperature the spectral peak shifts to shorter wavelengths (more blue).

Scenario B is the first surprising finding: incandescent, warm-white LED and fluorescent all appear whitish but have drastically different spectra. The incandescent is a smooth continuum (spikiness 2.2), the LED has a blue pump peak plus phosphor bump (spikiness 1.9), the fluorescent is full of sharp mercury lines (spikiness 4.97). That they still look similarly white is only possible because the eye reduces the spectrum to three tristimulus values (Module 09) — different spectra, similar colour (metamerism).

Scenario C is the practically most important finding: the **colour rendering** distinguishes the sources dramatically. Under the incandescent (CRI 100 by definition) object colours look "natural" because its smooth spectrum delivers all wavelengths. Under sodium vapour (CRI 49) object colours are barely distinguishable — the notorious orange of older motorway lighting, under which a red and a green car appear equally grey because the source delivers practically only one wavelength (589 nm) and thus no colour information. LED (77) and fluorescent (60) lie in between: usable, but with visible colour distortions, especially for saturated reds (a known weakness of early LED lighting).

The central methodological lesson: A light source has **two independent properties**. First, its own colour (colour temperature, CCT) — how it looks when you look into it. Second, its colour rendering (CRI) — how well it shows object colours. These two are decoupled: a warm-white LED (2700 K) and an incandescent (2700 K) have the same CCT but different CRI. The schoolroom confusion “is this warm or cool light?” misses the more important question “how well does it show colours?”.

Connection to previous modules: - **Module 09 Colour Mixing** provided the tristimulus metric, without which CCT and CRI cannot be defined. Module 07 is the direct application. - **Module 08 Stage Lighting** assumed simple RGB model sources; Module 07 shows that real sources have much more complicated spectra — stage practice (CRI of spotlights) depends directly on this. - **Module 05 Lenses (chromatic aberration)** is affected: a source with line spectrum (fluorescent) shows discrete colour fringes, one with continuum (incandescent) shows smeared ones. - **Module 03 Single Slit:** the physical spectrum of a source is objectively measurable (spectroscopy); its colour and colour rendering are derived perceptual quantities.

12. Next test

Module 06 Prisms as next step: the prism spatially decomposes exactly these source spectra. An incandescent spectrum shows a continuous band, a fluorescent spectrum discrete lines, sodium a single line. Prism spectroscopy is the historical method by which these spectra were discovered at all (Fraunhofer lines). Requires Module 05 (refraction) and Module 07 (source spectra).

Possible extension Module 07 v0.2: TM-30 colour rendering (modern replacement of CRI), daylight model (CIE D series), sunlight with atmospheric absorption (why sunsets are red).

Appendix A — Cross-references

- Practice explanation: `PRAXIS-Lichtquellen-EN.md` (follows)
- Companion paper: `BEGLEITPAPIER-Lichtquellen-EN.md` (follows)
- Tool: `LUX.html` (follows) — *Lat. lux, the light*
- Code: `lichtquellen_simulation.py`
- Plot: `lichtquellen_szenen.svg`
- Result data: `lichtquellen_results.json`
- Predecessor modules: Module 09 Colour Mixing (tristimulus), Module 08 Stage Lighting, Module 05 Lenses
- Related modules: Module 06 Prisms (forthcoming), Module 03 Single Slit (spectrum)

Appendix B — External stocktaking

- **Wyszecki & Stiles (2000)** *Color Science* — colour temperature, CRI.
- **CIE 13.3:1995** *Method of Measuring and Specifying Colour Rendering Properties* — official CRI definition.
- **CIE 015:2018** *Colorimetry* — CCT, daylight.
- **IES TM-30-20** — modern colour rendering metric.
- **Planck (1901)** *On the Theory of the Energy Distribution Law of the Normal Spectrum* — original work.
- **PhET “Blackbody Spectrum”** — didactic black-body simulation.

What the workshop note adds: three contrasting scenarios in falsification format; the central separation of colour temperature (own colour) and CRI (colour rendering); real Planck and CIE numerics; bridges to modules 09, 08, 05, 06.

Appendix C — Sources

- Wyszecki, G.; Stiles, W. S. (2000). *Color Science*, 2nd ed. Wiley.
- CIE (1995). *Method of Measuring and Specifying Colour Rendering Properties of Light Sources*, CIE 13.3.
- CIE (2018). *Colorimetry*, 4th ed. CIE 015:2018.
- IES (2020). *TM-30-20: Method for Evaluating Light Source Color Rendition*.
- Planck, M. (1901). On the Theory of the Energy Distribution Law of the Normal Spectrum. *Ann. Phys.* 4:553.
- McCamy, C. S. (1992). Correlated color temperature as an explicit function of chromaticity coordinates. *Color Res. Appl.* 17:142.

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