Color Vision Deficiency and Color Rendering Indices

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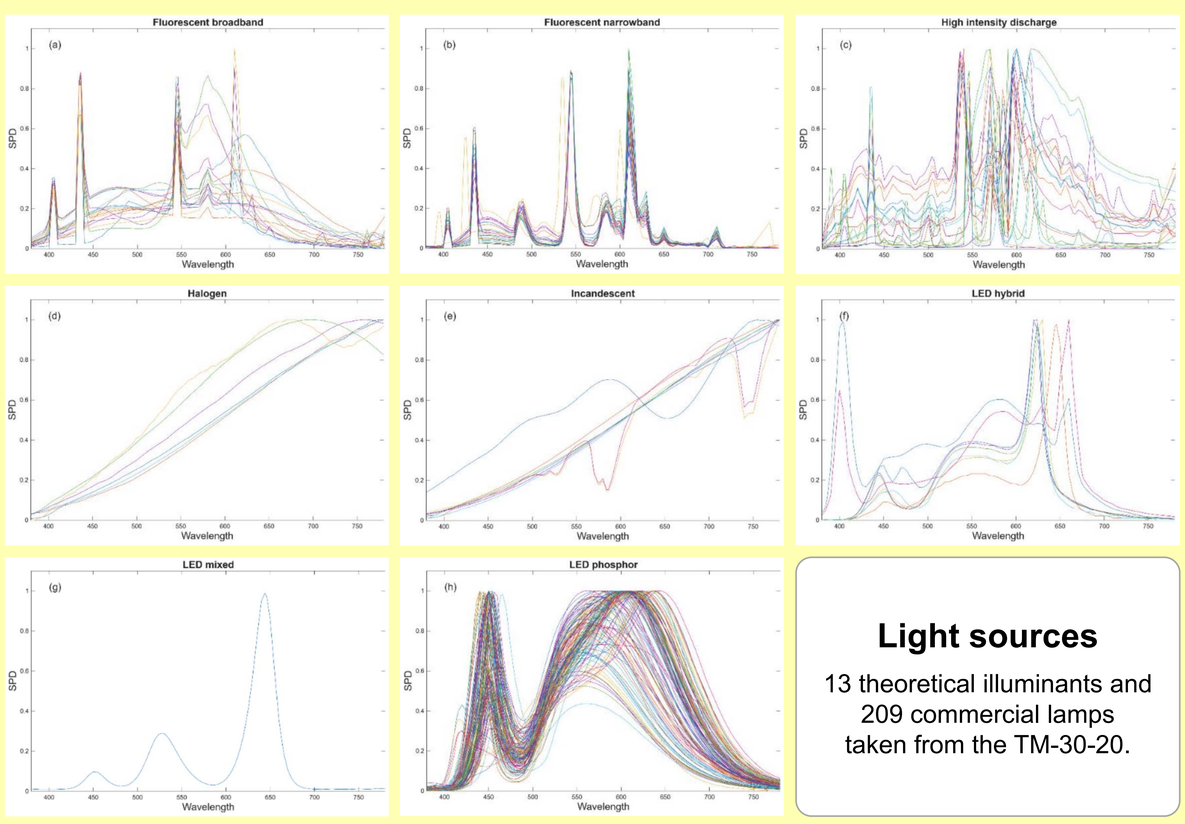
Objective

To analyze how the color rendering indices R_a, Q_a, R_f and R_g change for observers with color vision deficiency (CVD), simulating protan and deutan conditions of different severities.



Light sources

13 theoretical illuminants and 209 commercial lamps taken from the TM-30-20.

Figure 1. SPDs of the light sources in the 8 groups considered.

Method

- Light sources

  SPDs from the TM-30-20 calculation tools [5,9]: equal-energy illuminant and CIE F1–F12 (theoretical) plus 209 commercial lamps in 8 groups (Fig. 1). Data from 380 to 780 nm in 2 nm (R_a,Q_a) or 1 nm (TM-30-20) steps; spline interpolation, no extrapolation.
  Reference illuminant: Planckian radiator for CCT<5000 K and CIE daylight phase for CCT≥5000 K (R_a,Q_a). TM-30-20 uses a Planckian radiator up to 4000 K, daylight from 5000 K and a proportional mix in between.

- Simulation of color vision deficiency

  Lucassen et al. model [12]: L- and M-cone responses are weighted by a parameter d (XYZ→LMS transformation after Golz and MacLeod [13]). Severity: d=0: normal vision; d=0.3 and d=0.6: mild and medium protanomaly or deuteranomaly; d=1: protanopia or deuteranopia.
  The resulting LMS values are transformed back to XYZ and the indices are computed with the same color models as for normal vision.

- Color rendering indices:

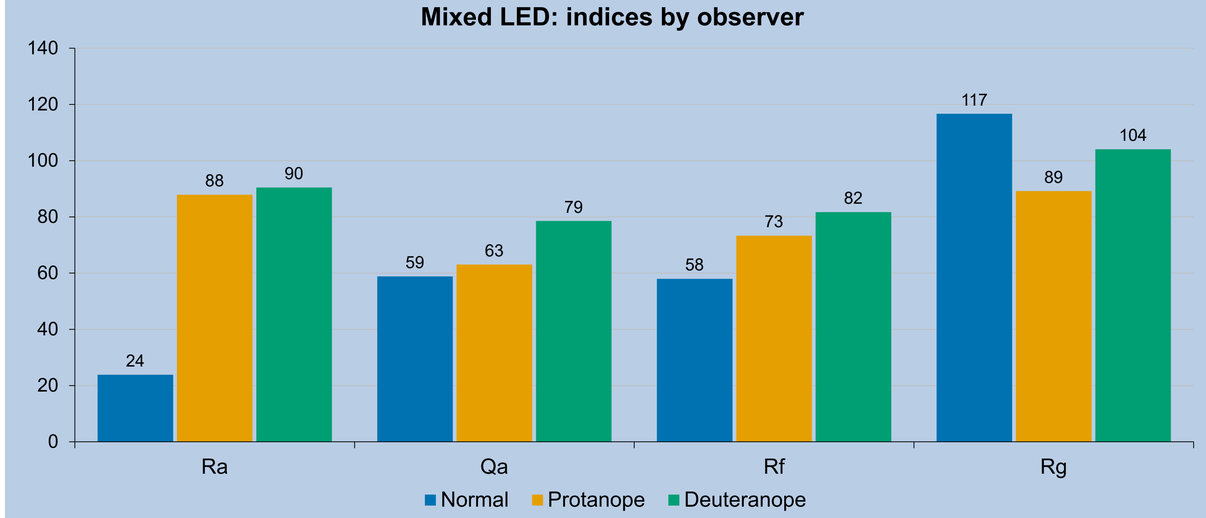
Index	Samples	Color space / adaptation	Score
R_a (CIE 13.3)	8	CIE 1964 U*W*V*, von Kries	R_i=100−4.6 ΔE_i
Q_a (CQS)	15	CIELAB, CMCCAT2000, saturation factor	$Q_{a,rms}$=100−3.1 $\Delta E_{_rms}$
R_f (TM-30-20)	99	CAM02-UCS *J'a'b'*, CAM02 adaptation	R'_f =100−6.73 · mean ΔE
R_g (TM-30-20)	99	CAM02 *a'b',* gamut polygons	100×area (test) / area (reference)

Results

- Fidelity indices (R_a,Q_a,R_f) rise systematically with CVD severity: a reduced color gamut means fewer spectral regions need accurate reproduction.
- Mixed LED: R_a jumps from 23.86 (normal vision) to 87.89 (protanope) and 90.46 (deuteranope), while Q_a and R_f rise much less.
- Q_a and R_f are more robust than R_a; the 99 samples of R_f avoid the “lucky match” of the 8-sample R_a.
- R_g is the most informative index: protans lose gamut (mixed LED: 116.67→89.17) whereas deutans may gain saturation (narrowband fluorescent: 100.1→105.9).
- Standard deviations drop sharply with severity: severe dichromats respond homogeneously to spectral changes.
- HID lamps show the widest spread; phosphor LEDs are stable (R_a,R_f ≈ 80–92) for all observers.

Lamp group	R_a			R_g		
	Normal	Protan.	Deuter.	Normal	Protan.	Deuter.
EE	95.28	94.90	95.83	102.7	90.4	104.1
CIE F	75.24	92.00	91.36	93.1	93.5	105.6
FB	80.97	92.23	91.51	96.2	93.4	105.5
FN	81.54	90.84	91.88	100.1	93.5	105.9
HID	67.35	88.39	88.71	90.1	93.1	105.7
H	98.74	98.95	99.04	98.1	90.1	105.3
I	92.67	98.07	98.15	99.9	90.1	105.3
LEDH	89.56	96.12	96.42	98.5	91.1	104.8
LEDM	23.86	87.89	90.46	116.7	89.2	104.0
LEDP	79.41	92.55	92.61	94.8	91.5	104.2

Mean R_a and R_g per lamp group for normal vision, protanopes and deuteranopes.
EE: equal energy; CIE F: F1–F12; FB/FN: fluorescent broad/narrowband;
HID: high intenstity discharge; H: halogen; I: incandescent;
LEDH/M/P: hybrid/mixed/phosphor LED.



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Conclusions

- Standard fidelity metrics (R_a, Q_a, R_f) are inflated for CVD observers and are not inclusive of the ≈8% of men with CVD.
- Fidelity alone is insufficient: R_g best differentiates protans (desaturation) from deutans (possible saturation boost).
- Mixed LEDs and HID lamps, with sharp emission peaks, are unreliable for CVD observers; phosphor LEDs are the safer choice for inclusive lighting.
- The validity of applying color models after an LMS transformation is arguable: experimental work is still needed.

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