ICC-Spectral Imaging Experts' Day @ NTNU Gjovik

New tools for Spectral colour management

Ronnier Luo

9/9/2024

Colour Engineering Lab

Zhejiang University

Thouslite

Thousand Lights Lighting (Changzhou) Limited

SCOPE

- Background
- Camera characterisation models
  - Colorimetry
  - Spectrophotometry
- Tools for spectral colour reproduction

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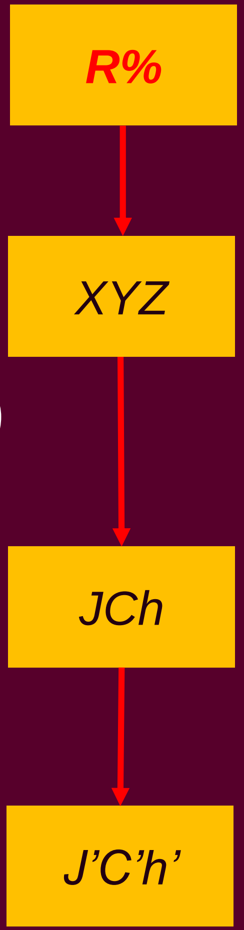
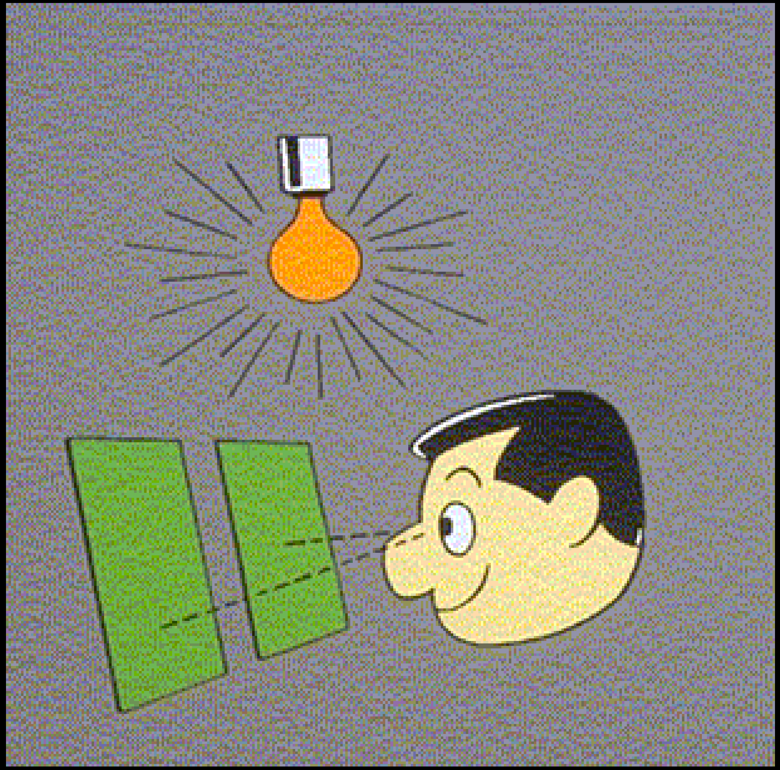
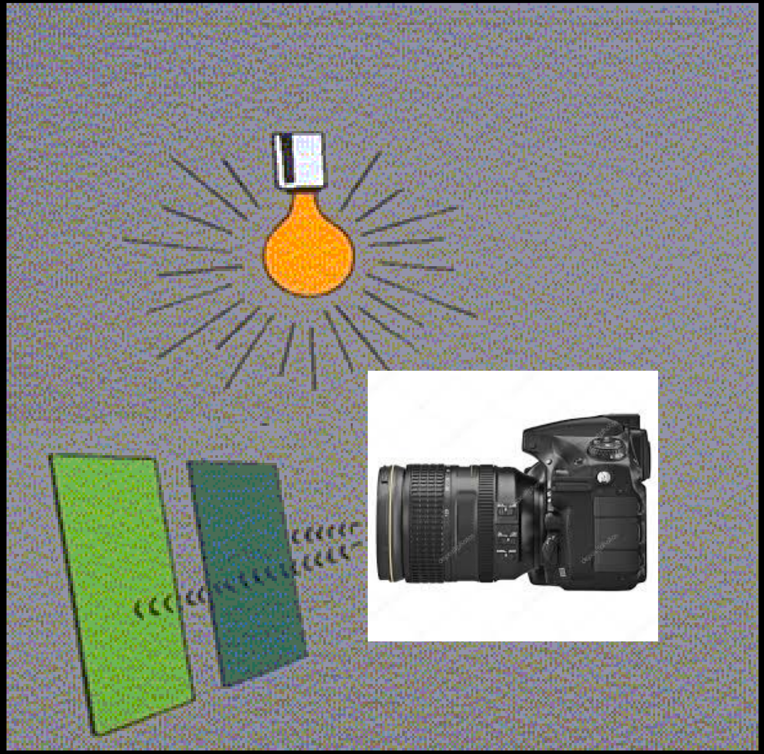
Types of olour reproduction

1. **Spectral *(R%)***
2. **Relative Colorimetric *(XYZ)***
3. **Absolute Colorimetric *(X_L Y_L Z_L)***
4. **Appearance *(JCh)***
5. **Preference *(JCh)***



Observer Metamerism





Observer Metamersim

$$Human: \quad X_i = \int_{\lambda_{min}}^{\lambda_{max}} M_i(\lambda)E(\lambda)r(\lambda)d\lambda$$

$$Camera: \quad D_i = \int_{\lambda_{min}}^{\lambda_{max}} S_i(\lambda)E(\lambda)r(\lambda)d\lambda$$

Matrix − expression

$X = M\,E\,r$ *and* $D = S\,E\,r$

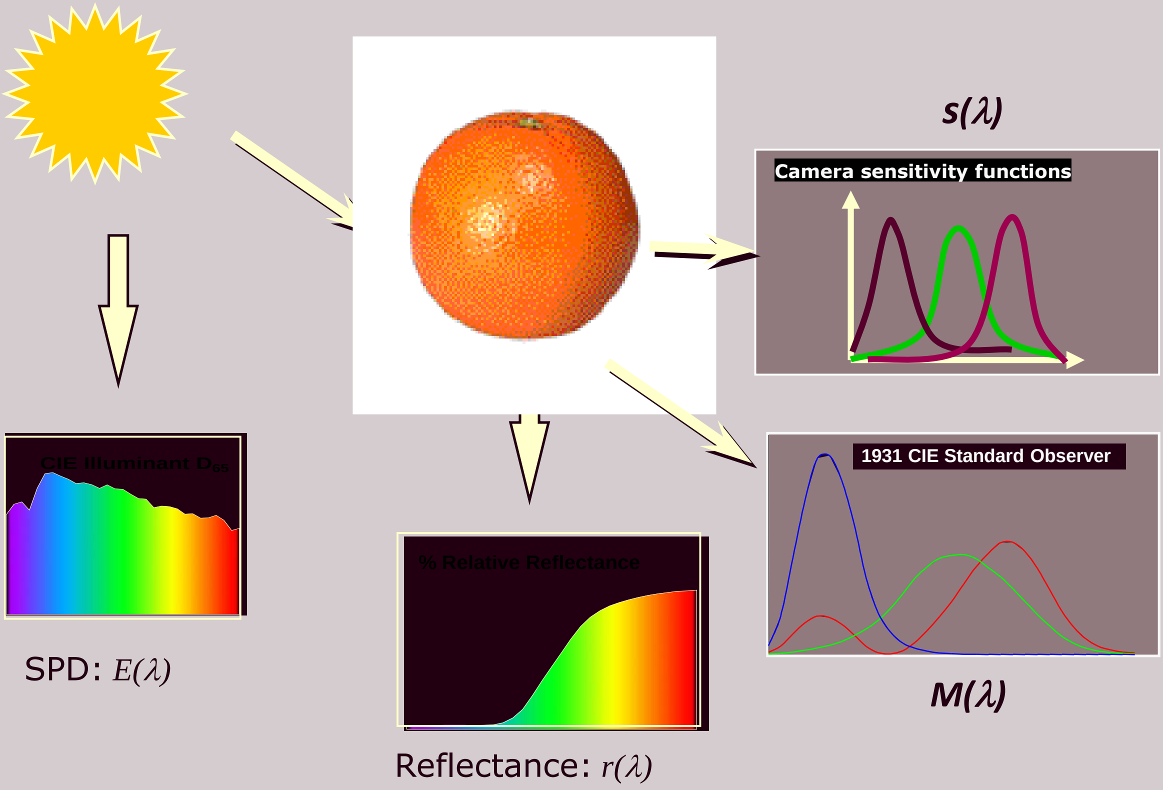
where

$X = [X, Y, Z]^T$ *and* $D = [R, G, B]^T$,

$r = [r_1 \ldots\ r_{31}]^T$,

$$E = \begin{bmatrix} E_1 & 0 & . & 0 \\ 0 & E_2 & . & 0 \\ . & . & . & . \\ 0 & 0 & . & E_{31} \end{bmatrix},$$

$$M \begin{bmatrix} \bar{x}_1 & \ldots & \bar{x}_{31} \\ \bar{y}_1 & \ldots & \bar{y}_{31} \\ \bar{z}_1 & \ldots & \bar{z}_{31} \end{bmatrix} \quad or \quad S \begin{bmatrix} \bar{r}_1 & \ldots & \bar{r}_{31} \\ \bar{g}_1 & \ldots & \bar{g}_{31} \\ \bar{b}_1 & \ldots & \bar{b}_{31} \end{bmatrix}$$



$E(\lambda)$: spectral power distribution of illuminant
$r(\lambda)$: spectral reflectance of an object
$M_i(\lambda)$: CIE colour matching functions
$S_i(\lambda)$: camera spectral sensitivity functions

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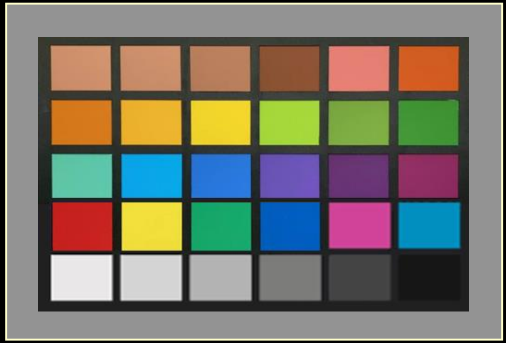
Reference target based characterization   X = A D



Calibration target

$$\begin{bmatrix} R_1 & G_1 & B_1 \\ R_2 & G_2 & B_2 \\ \ldots\ldots & & \\ R_n & G_n & B_n \end{bmatrix}$$

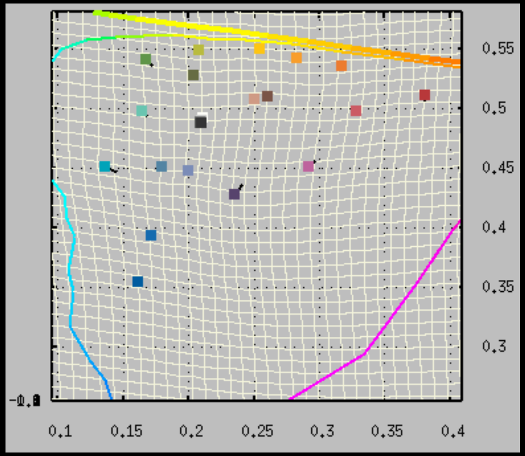
Polynomial

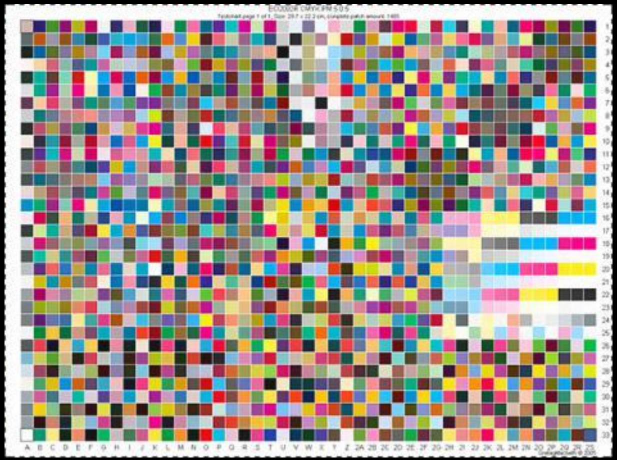
Neural Network

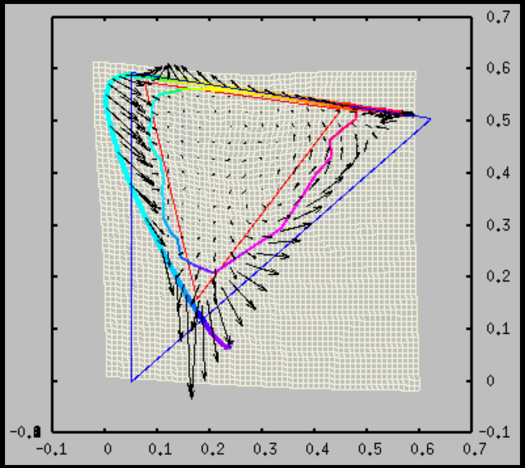
Look-up-table

$$\begin{bmatrix} X_1 & Y_1 & Z_1 \\ X_2 & Y_2 & Z_2 \\ \ldots\ldots & & \\ X_n & Y_n & Z_n \end{bmatrix}$$

Building a 3D-LUT from PMCC colours X = A D

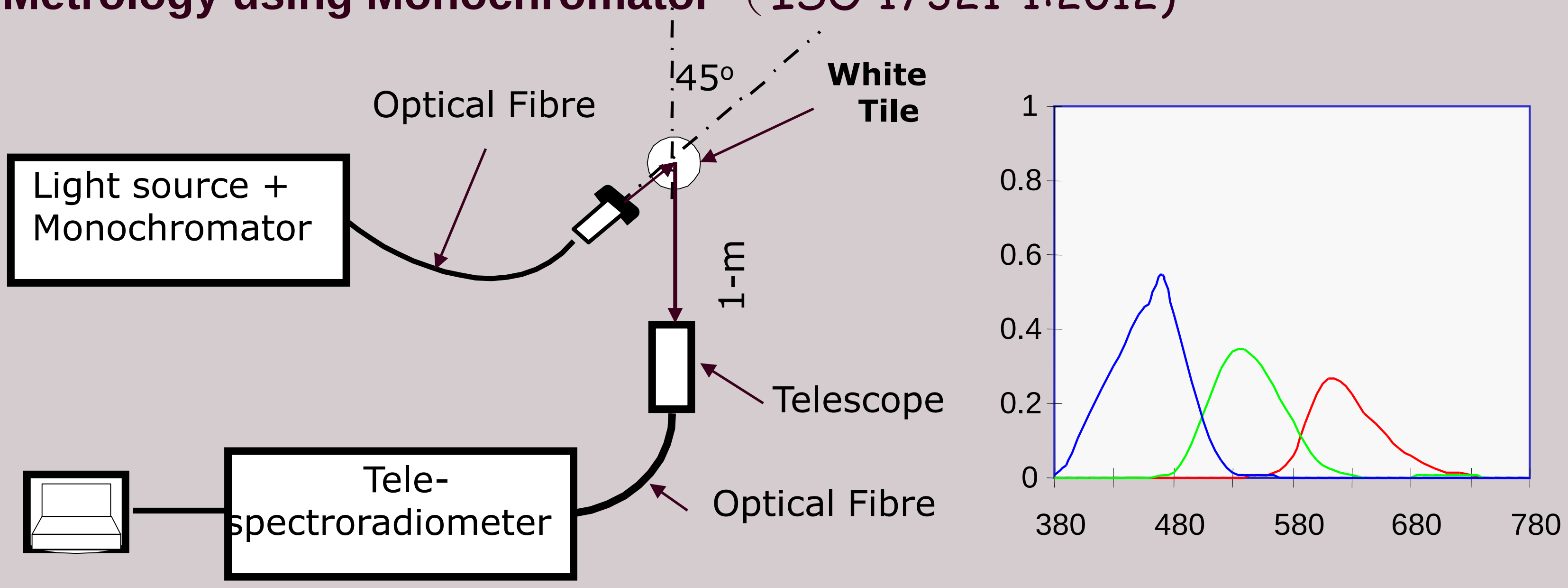






Measuring Spectral Sensitivities
D= S E r

- **Metrology using Monochromator** (ISO 17321-1:2012)



Xenon continuous source + monochromator with a 5-nm bandwidth
TSR: 5-nm interval and bandwidth.

Measuring Spectral Sensitivities D= S E r

- Optimised PCAs for camera spectral sensitivity, H. Fan, etc, JOSAA 40(2023) 1515-1526
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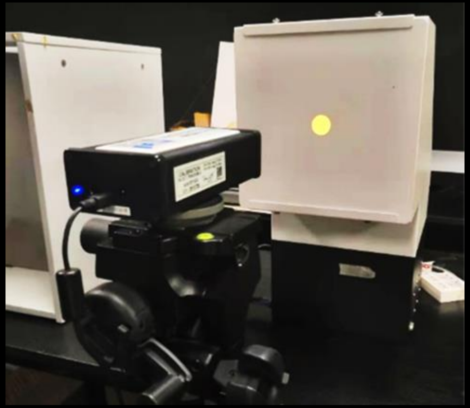
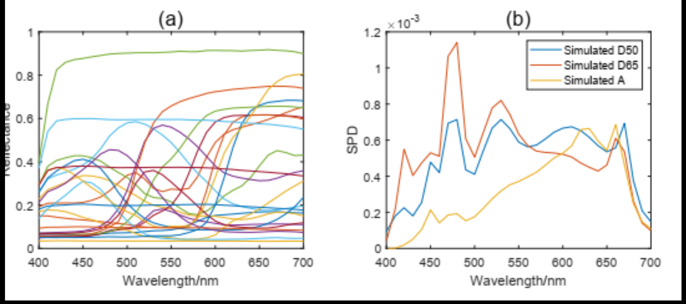
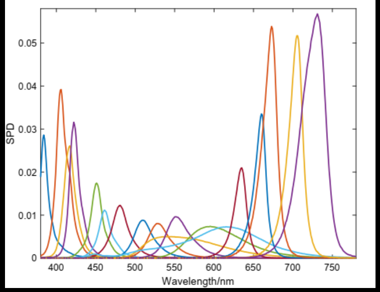
Table 4. Accuracy of Spectral Sensitivity Estimation Using Different Methods and Different Color Samples in the Practical Experiment

Samples	Method (Order)	SE R	SE G	SE B	SE Mean	RGB Error	ΔE_{00}	Vora
LED	Classical PCA (2)	17.3%	8.6%	6.3%	10.7%	1.72%	1.23	0.988
	Weighted PCA (2)	7.4%	7.0%	**4.3%**	**6.2%**	1.37%	1.11	0.997
	Classical PCA (4)	**6.4%**	7.4%	6.4%	6.7%	1.77%	0.83	0.997
	Weighted PCA (4)	8.7%	6.9%	5.6%	7.1%	1.31%	**0.68**	**0.998**
	Fourier (10)	12.4%	**6.7%**	7.6%	8.9%	1.29%	1.22	0.994
	Polynomial (11)	13.0%	7.3%	8.3%	9.5%	1.15%	0.90	0.993
	Radial (8)	10.0%	7.0%	7.2%	8.1%	**1.14%**	1.07	0.995
	Regularization	10.5%	6.9%	9.1%	8.8%	1.43%	1.27	0.994
MCCC	Classical PCA (2)	13.3%	8.9%	**7.1%**	9.8%	1.42%	0.98	0.990
	Weighted PCA (2)	**6.9%**	**7.3%**	7.2%	**7.1%**	**1.35%**	0.66	**0.996**
	Classical PCA (4)	16.4%	9.6%	9.2%	11.7%	1.56%	0.75	0.986
	Weighted PCA (4)	7.3%	9.2%	9.4%	8.6%	1.45%	**0.60**	0.993
	Fourier (7)	20.3%	9.2%	8.6%	12.7%	1.54%	0.65	0.989
	Polynomial (7)	49.2%	13.2%	13.8%	25.4%	2.70%	3.80	0.906
	Radial (6)	12.4%	8.8%	14.2%	11.8%	1.52%	0.84	0.988
	Regularization	23.6%	13.6%	19.3%	18.8%	1.56%	2.50	0.966







Linear modelling via basis functions

- The colour formation equation: **D= SEr**
- We can express reflectance **r** as:

$$r(\lambda) = a_1B_1(\lambda) + a_2B_2(\lambda) + a_3B_3(\lambda) + \ldots + a_nB_n(\lambda)$$

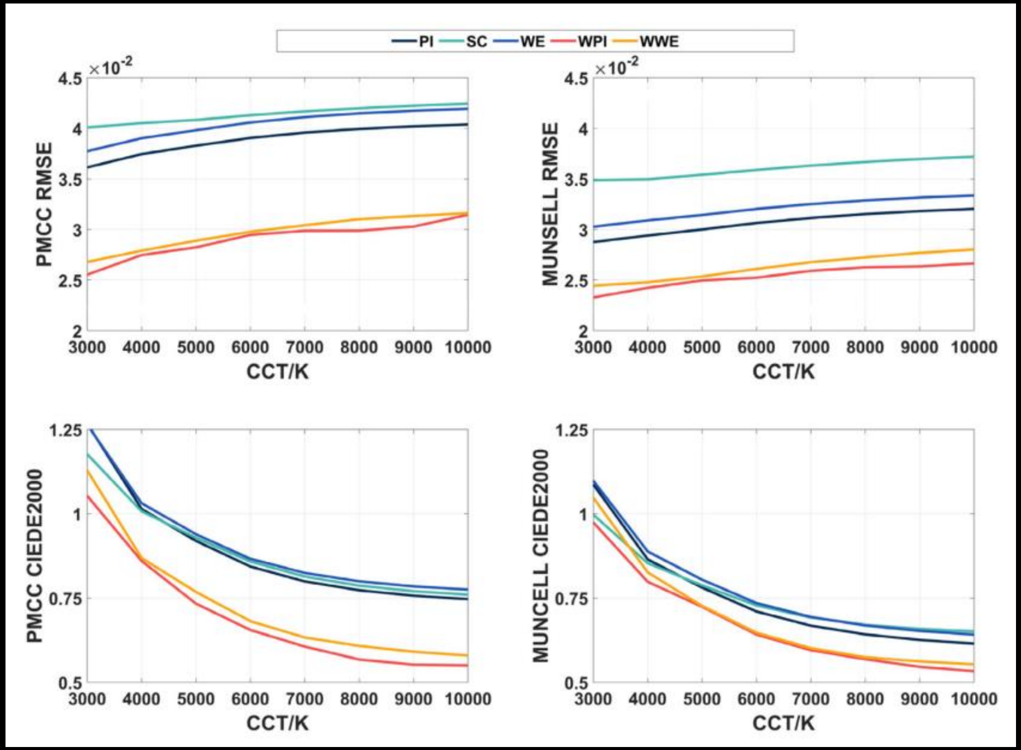
  - B = [**$B_1(\lambda)$, $B_2(\lambda)$ $B_3(\lambda)$, $B_n(\lambda)$**] set of **Basis functions** common for all reflectances based on material datasets
  - a =[**a_1 a_2 a_3 … a_n**] set of **weights** specific to a given reflectance

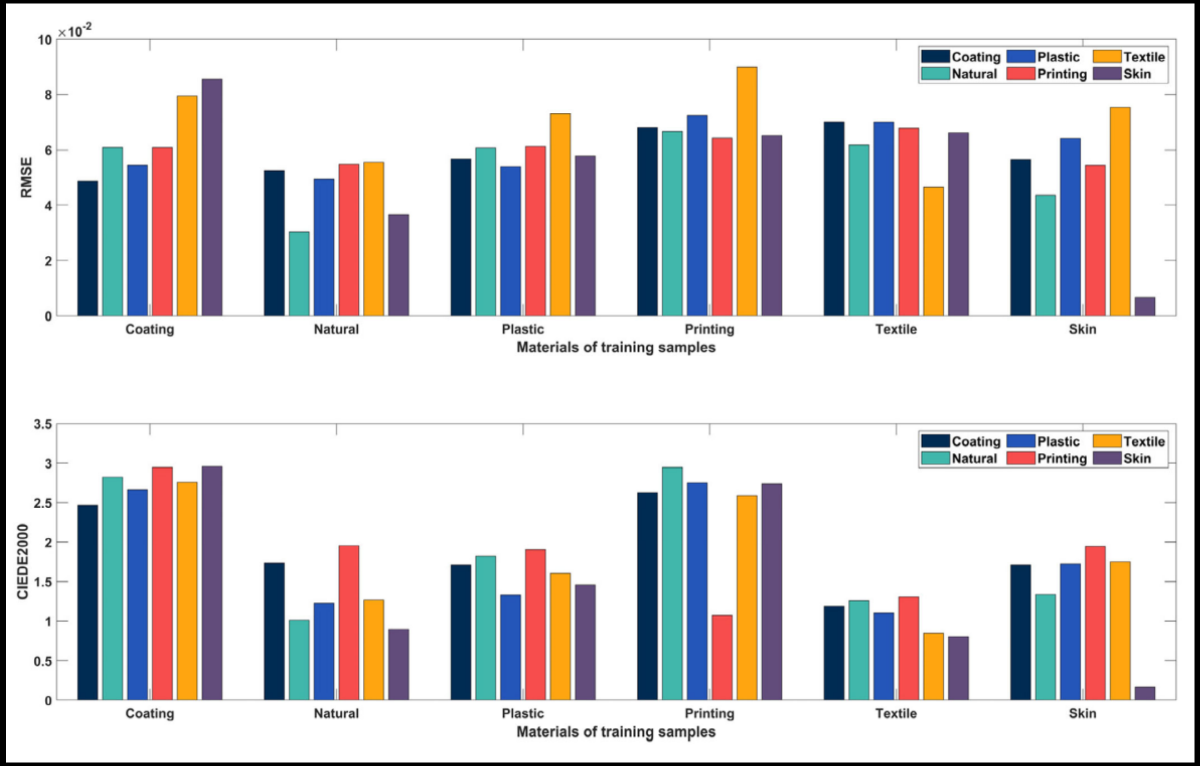
- **$D = SE\,Ba^T \rightarrow a^T = [S\,E\,B]^{-1}R \rightarrow r = Ba^T$**

Methods to estimate spectral reflectance using databases under different illuminants Xu et al. CRA (2023) DOI:10/1002/col.22859

D= SEr

- Smooth constrained (Sc); Pseduo Inverse (PI) method; Weiner (W) method; Weighted PI (WPI); Weighted W (WW)





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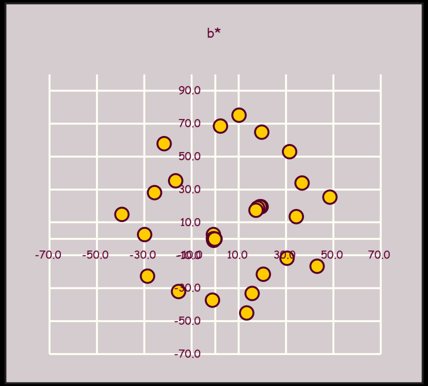
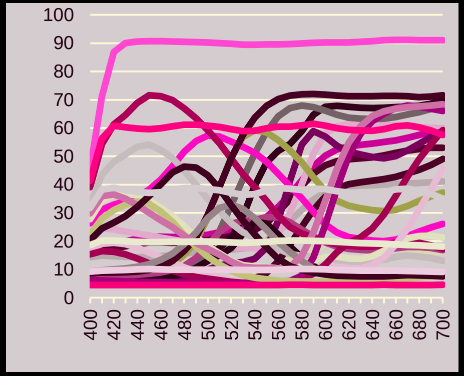
The new preferred memory color (PMC) chart

M. R. Luo, (2024) CRA, https://doi.org/10.1002/col.22940

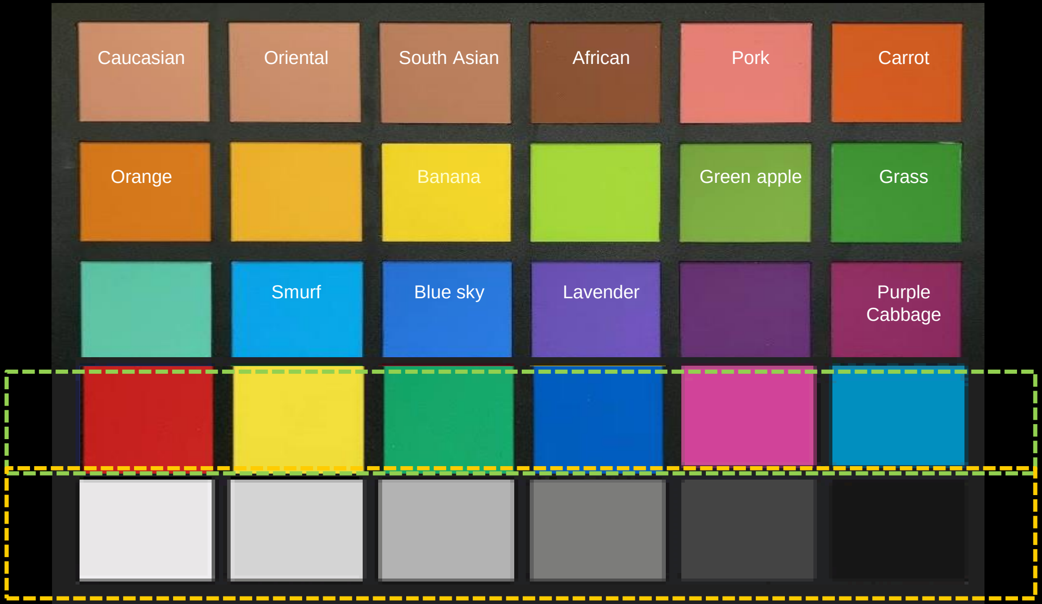
X = M E r





X = M E r

D = S E r



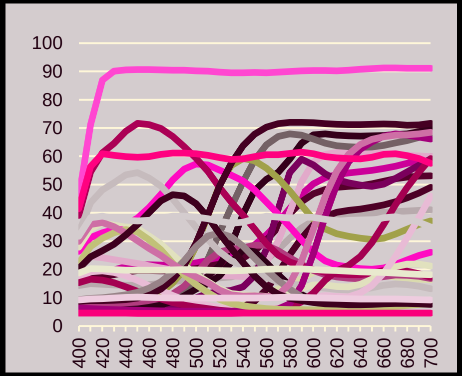
Memory colours

Reference gamut

Neutral colours

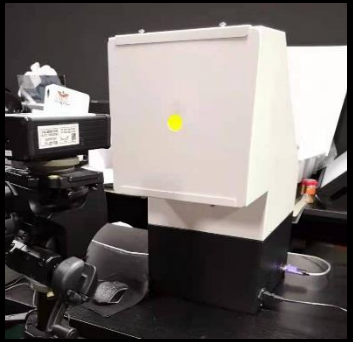
Preferred Memory Calibration Chart (PMCC)

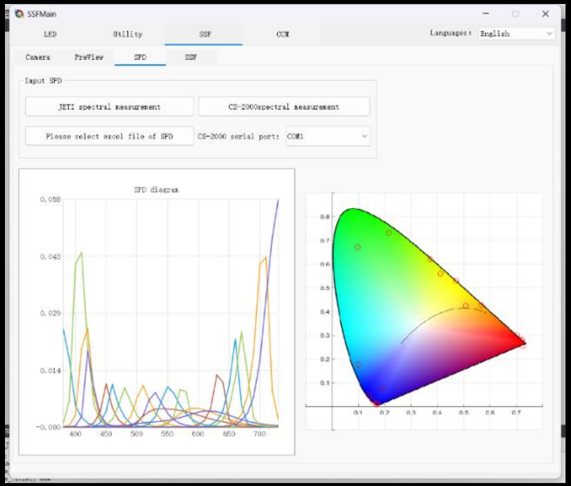
X = M E r = = M L

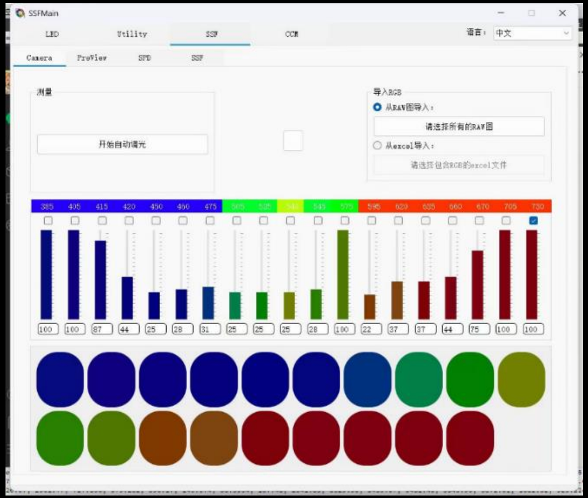


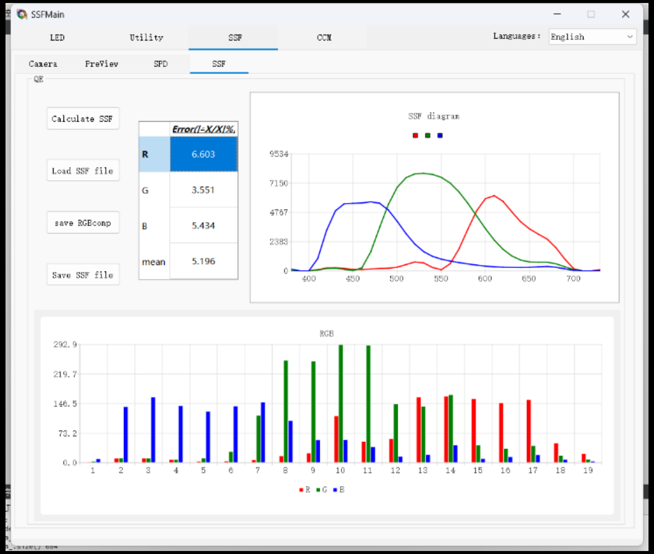
Measuring camera SSF in operation

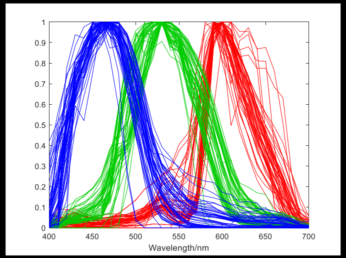
$$D = S\,E\,r$$











Camera characterization

From SSF to compute CCM for an illuminant, material set, a CMF

CMF

SPD

R

PMCC

MCCC	PMCC	printing	coating	plastic	textile	skin	natural	Total
24	30	67568	6187	5338	11773	9267	743	100930

Study at ZJU-CEL

❑ Colour science and engineering

- UCS: Comprehensive/Simple, Uniformity/hue linearity
- CAM: HDR, Un/related, 2D, CC
- Platform: CM, AWB, CAM, GMA, PCR
- CMF: CVDs and CVNs

❑ Spectral tunable LED technology for research

- Vision： Colour matching function (CMF), Low vision
- Sensor: Design, characterisation (SSF)
- Display: Design, Display-primary
- Lighting: fidelity, preference
- Vision health: Low vision lighting and glasses
- Instrument： Multi-spectral imaging system

Thanks for your attention!

www.thouslite.com ***https://cel.zju.edu.cn***