The impact of the CIE research strategy on ICC applications

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COMMISSION INTERNATIONALE DE L'ÉCLAIRAGE
INTERNATIONAL COMMISSION ON ILLUMINATION
INTERNATIONALE BELEUCHTUNGSKOMMISSION

1. Vision and colour
2. Physical measurement of Light and radiation
3. Interior Environment and light design
4. Lighting and signaling for transport
5. Exterior and lighting applications
6. Photobioloy and photochemistry
8. Imaging technology

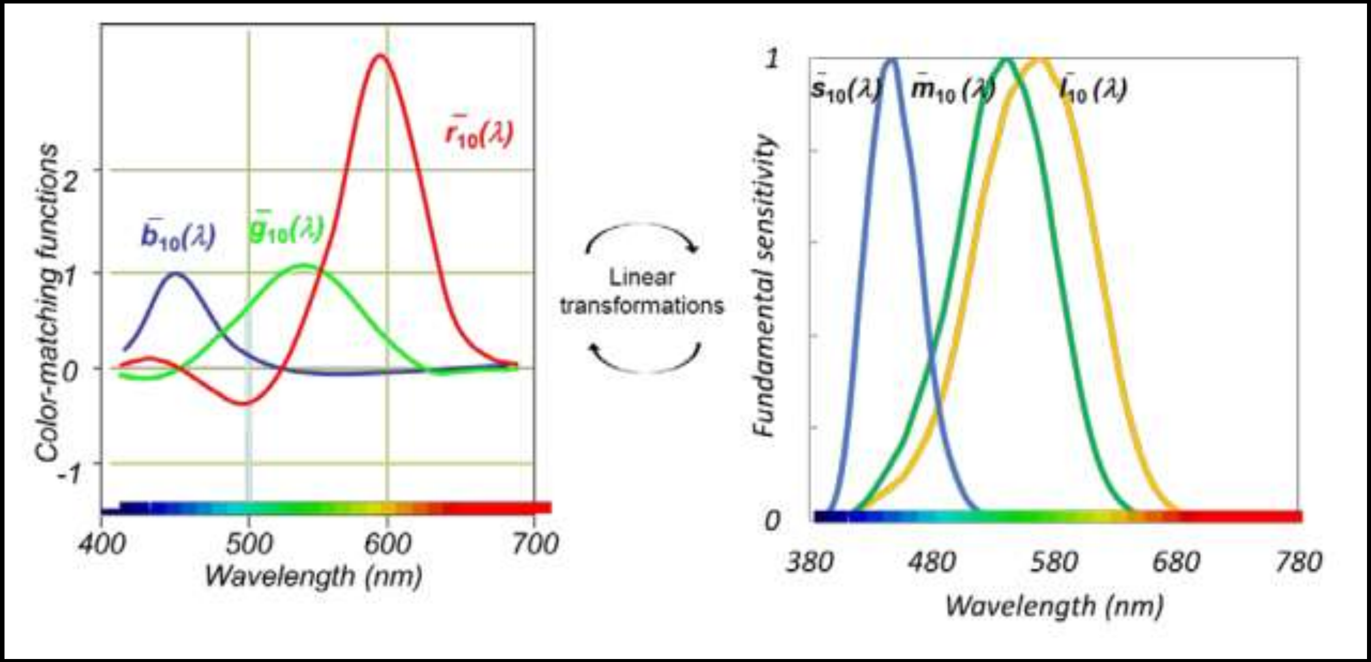
SCOPE

- CIE 2006 colorimetry
- LED spectral power distribution
- Colour rendering metric
- Whiteness

- LED daylight simulators
- UCS for lighting stimuli
- CAM16
- HDR-UCS

CIE 2006 Colorimetry
-Modelling Cone Fundamentals-

From Stiles-Burch 10º colour-matches

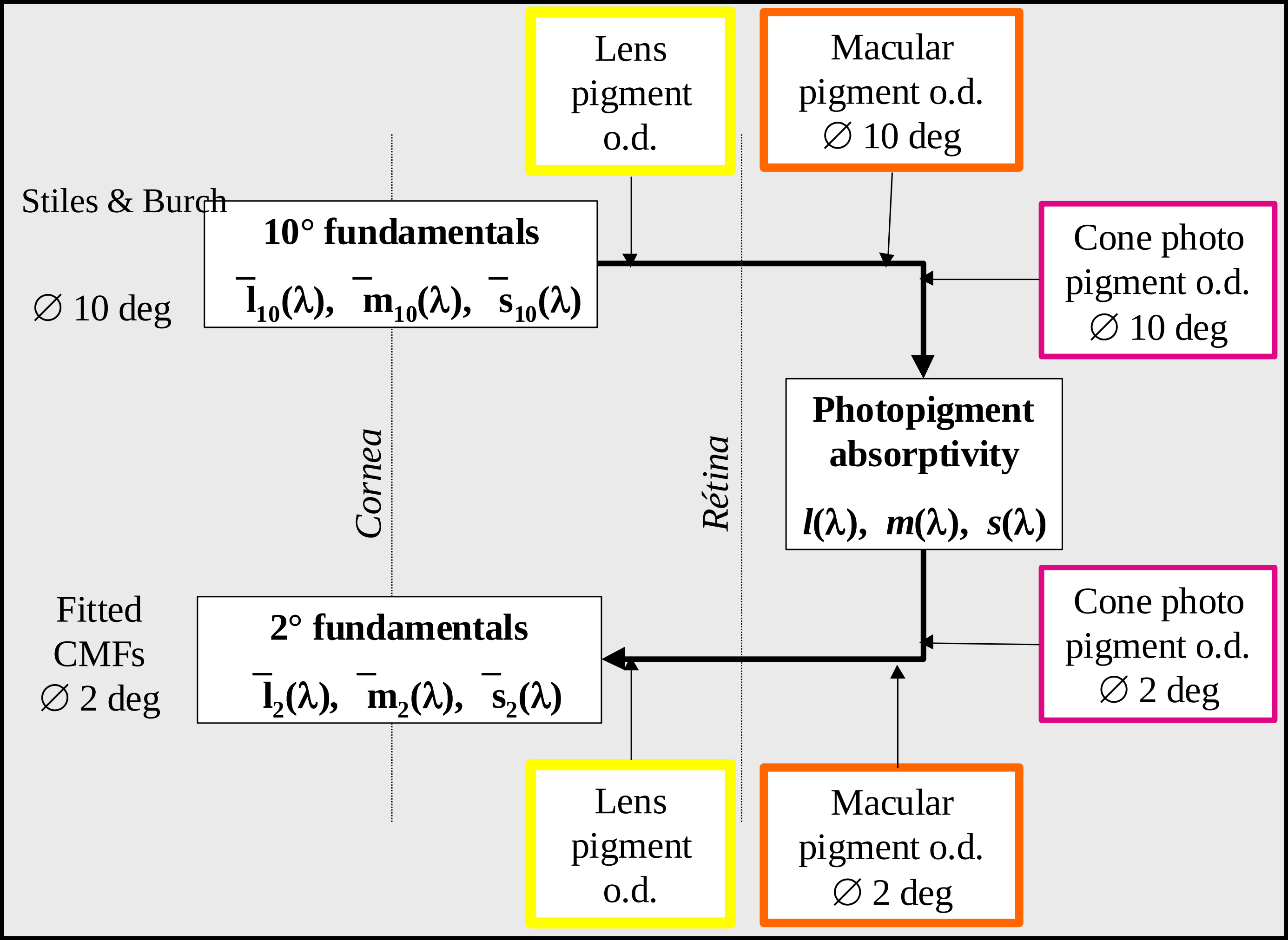


$$\bar{l}_{10}(\lambda) = l_R \cdot \bar{r}_{10}(\lambda) + l_G \cdot \bar{g}_{10}(\lambda) + l_B \cdot \bar{b}_{10}(\lambda)$$

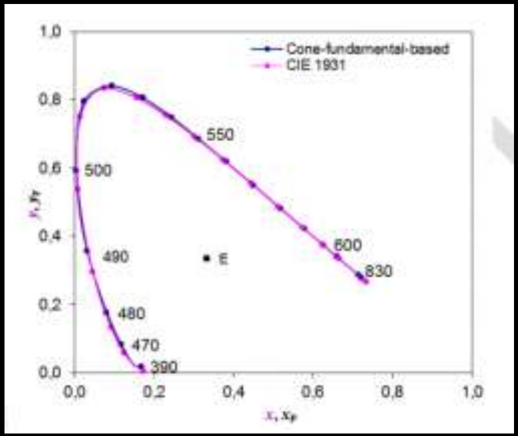
$$\bar{m}_{10}(\lambda) = m_R \cdot \bar{r}_{10}(\lambda) + m_G \cdot \bar{g}_{10}(\lambda) + m_B \cdot \bar{b}_{10}(\lambda)$$

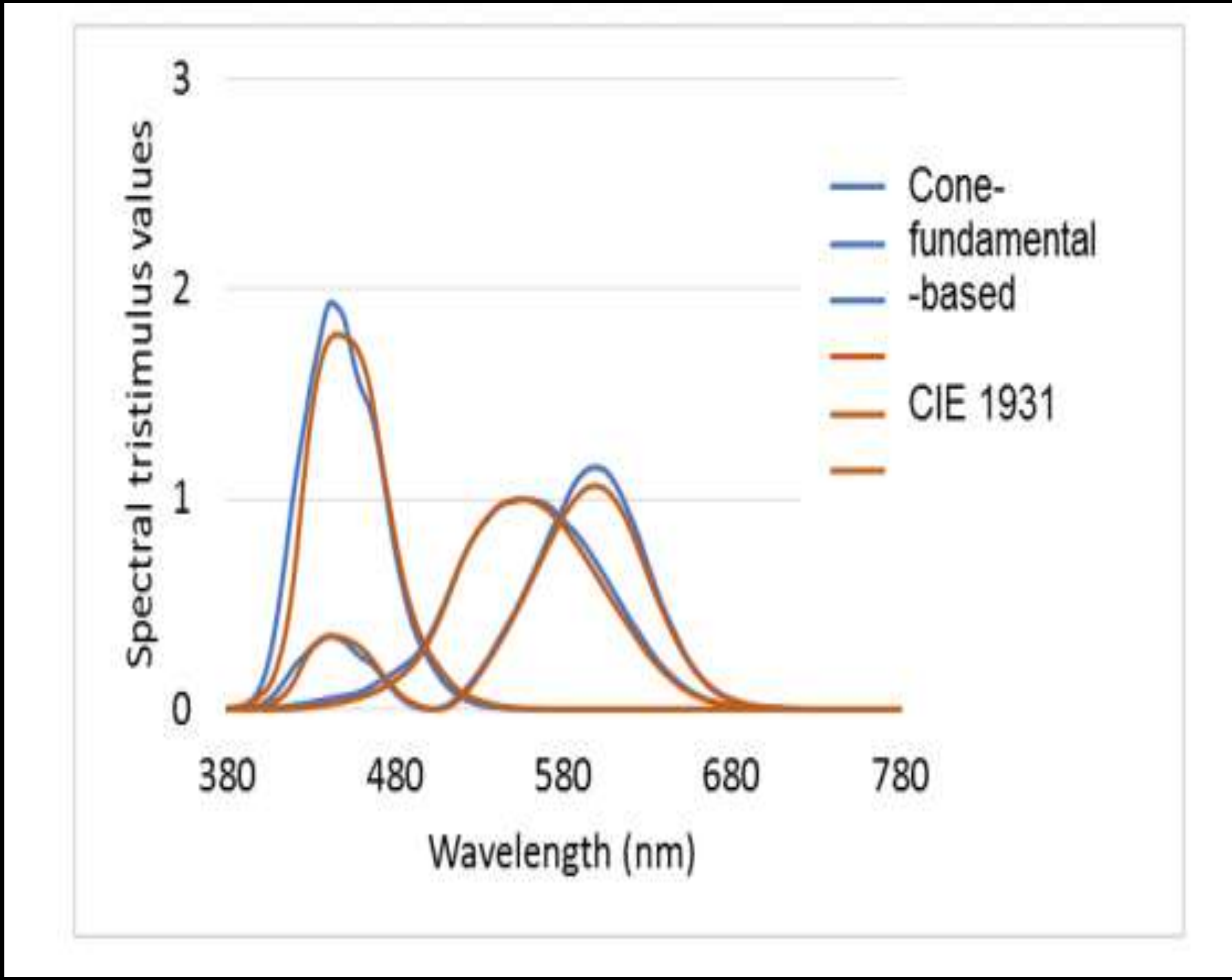
$$\bar{s}_{10}(\lambda) = s_R \cdot \bar{r}_{10}(\lambda) + s_G \cdot \bar{g}_{10}(\lambda) + s_B \cdot \bar{b}_{10}(\lambda)$$

Workflow of CIE 2006 colorimetry



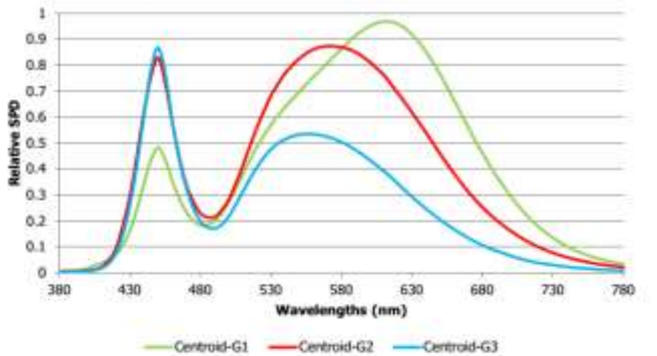
Comparing of cone-fundamental based spectral tristimulus values with CIE 1931 colorimetric observer



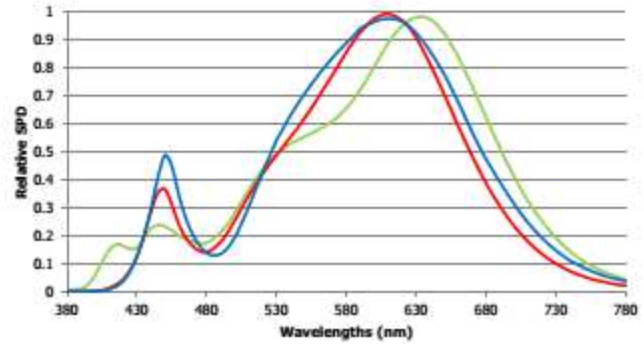


Typical Phosphor LED Spectra

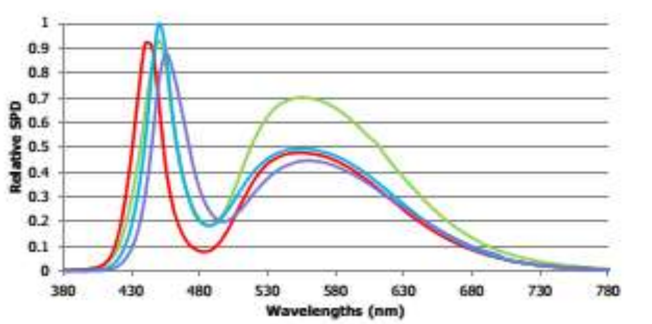
- 3 Groups (n=236)
  - [similarities 94% (AHC vs. K-means)]



- 3 Groups (n=59)
  - [similarities 94% (AHC vs. K-means)]



- 4 Groups (n=140)
  - [similarities 95% (AHC vs. K-means)]



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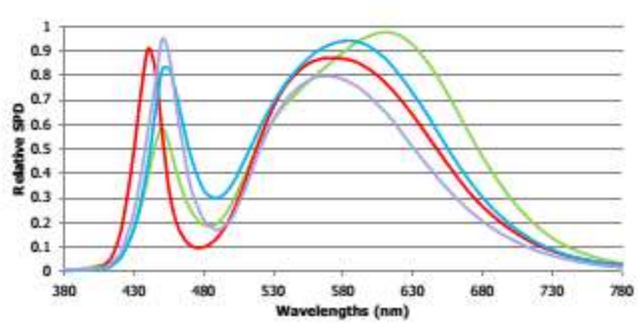
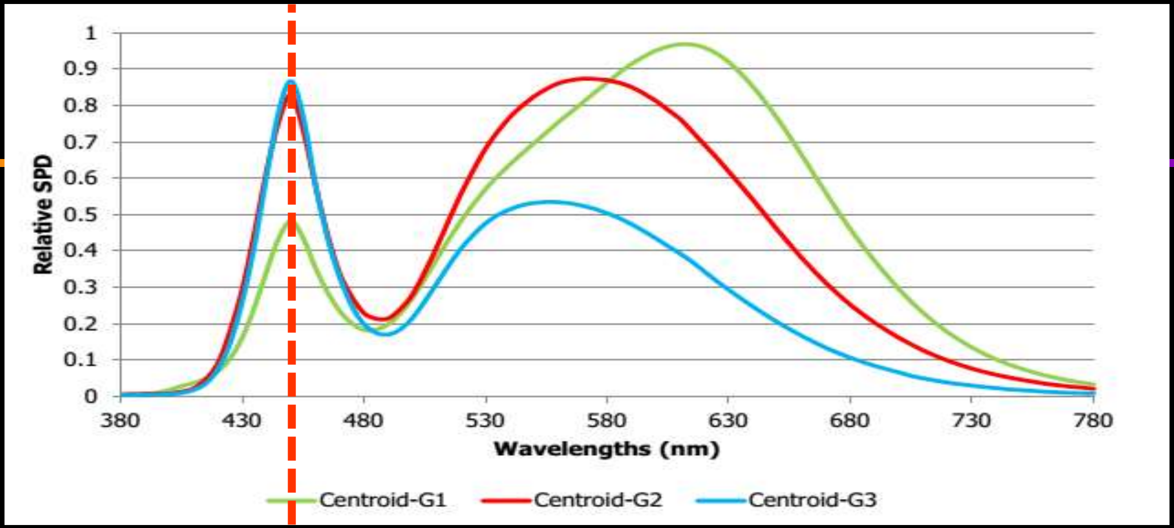
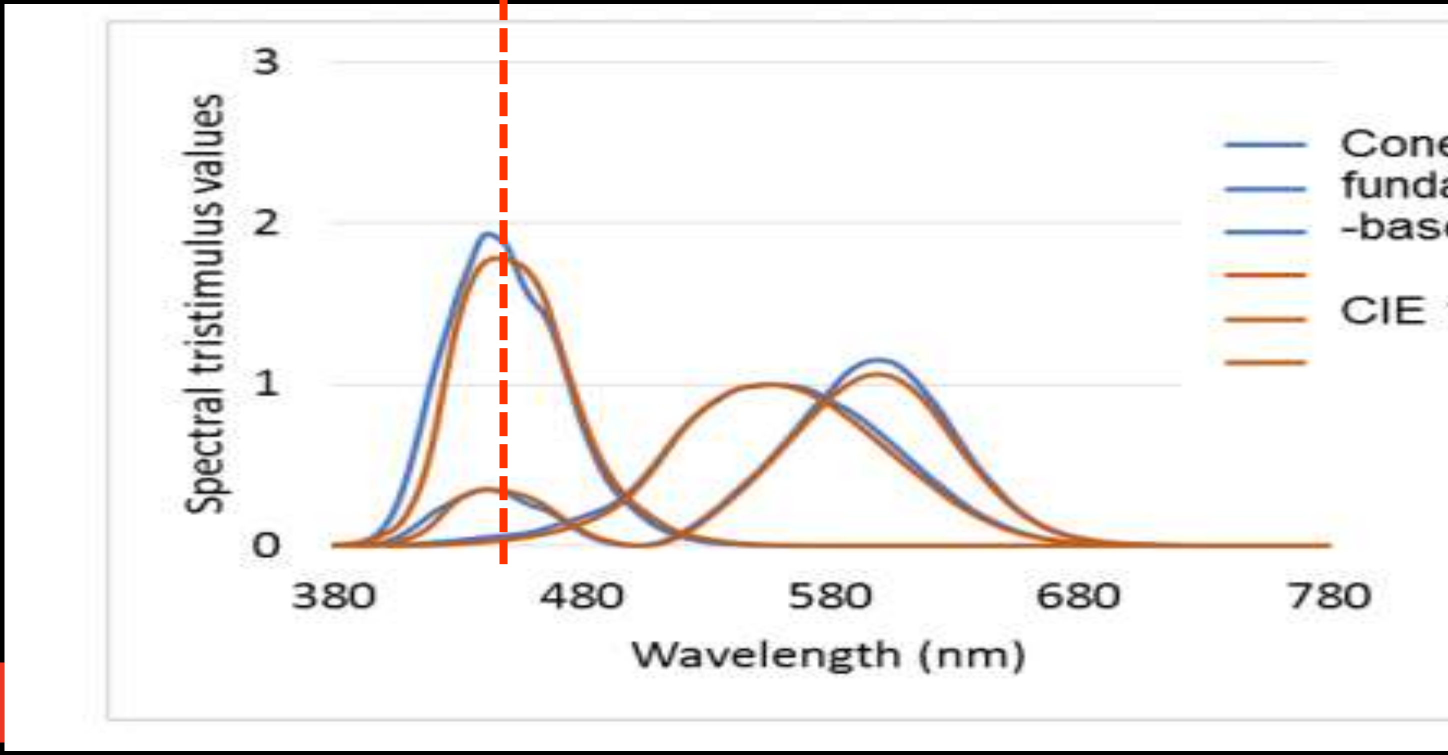


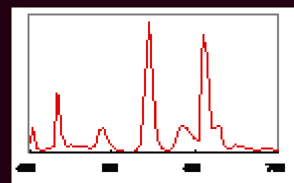
Comparing of 2° cone-fundamental based spectral tristimulus values with new LED SPDs



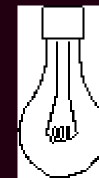


CIE-R_a

Test source

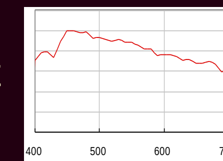


Reference illuminant



Planckian
(CCT<5000 K)

Standard Daylight
(CCT ≥ 5000 K)



Test Source (SPD) → **1. CCT** → 2. Ref. ill (SPD)

Test Source (SPD), 2. Ref. ill (SPD) → **3. Calculating XYZ**

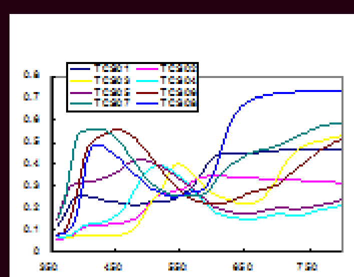
R%i → **3. Calculating XYZ**

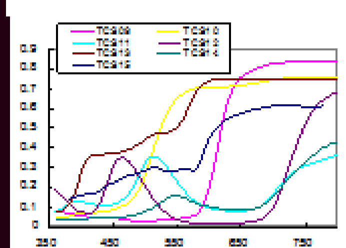
3. Calculating XYZ → (XYZ)-T, (XYZ)-R

(XYZ)-T → **4. Von Kries CAT** → (XYZ)-TR

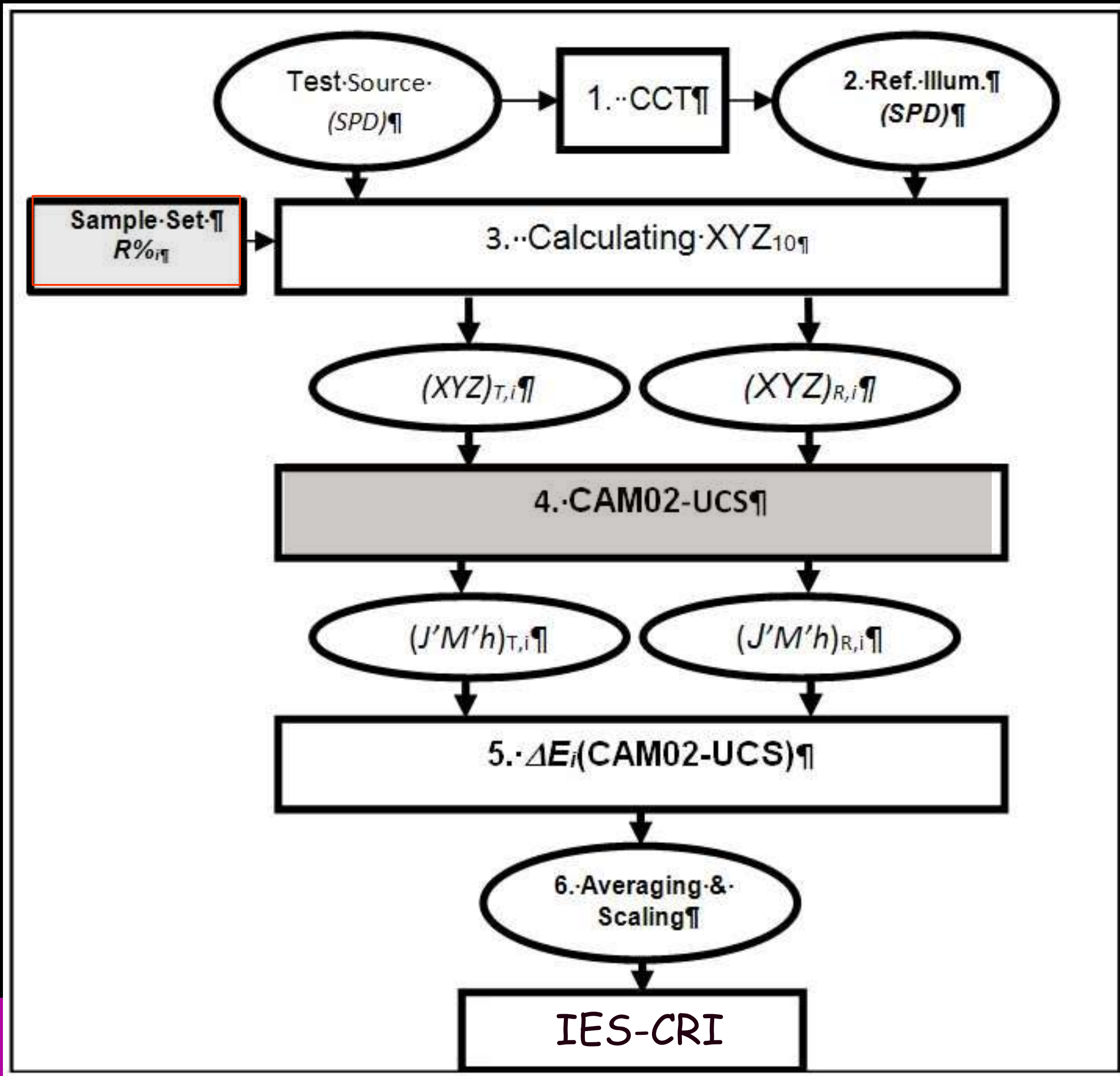
(XYZ)-TR, (XYZ)-R → **5. CIEU*V*W***

5. CIEU*V*W* → **$\text{CIE-}R_a = \Sigma(100 - 4.6\Delta E_i)/8$**

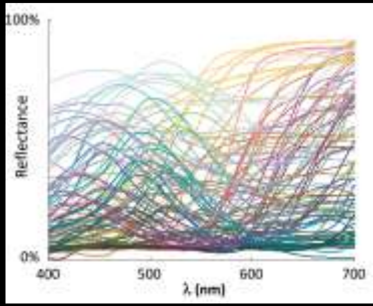


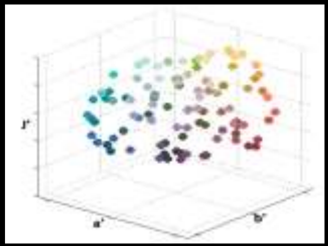


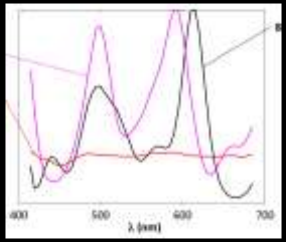
Recommended new colour fidelity metric: CRI2010 & IESNA-TM40



- Use new 99 test samples
- CAM02-UCS
- Calculate Ra

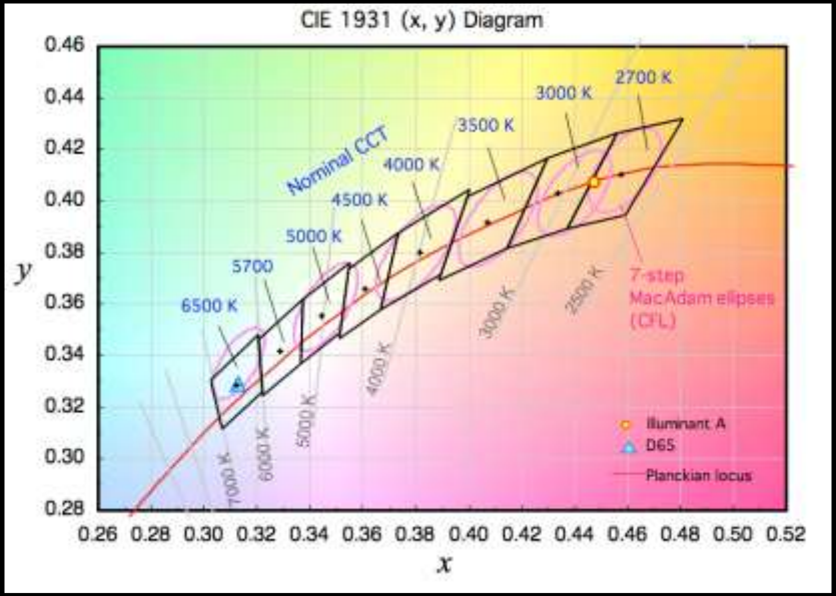


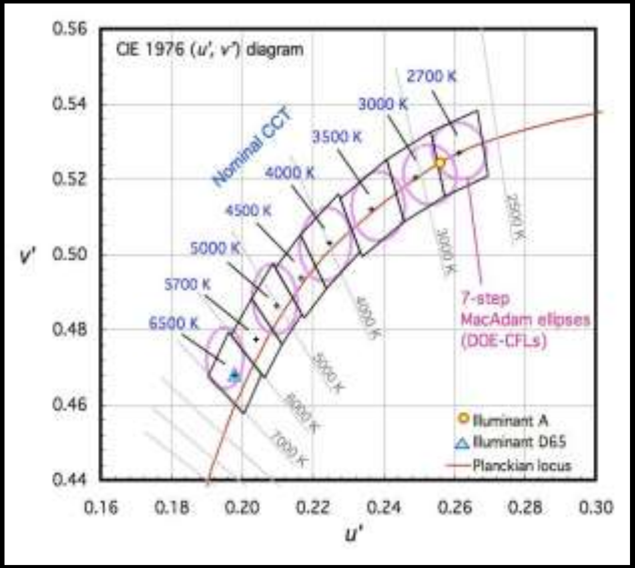


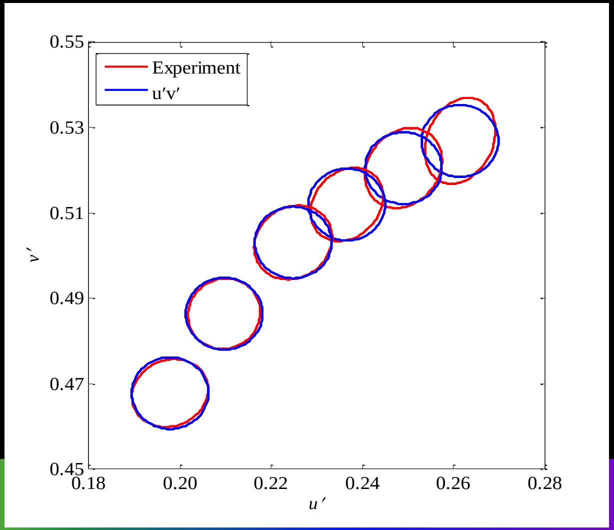


Whites

ANSI-NEMA_ANSLG 78.377-2008 Specifications for the chromaticity of SSL products

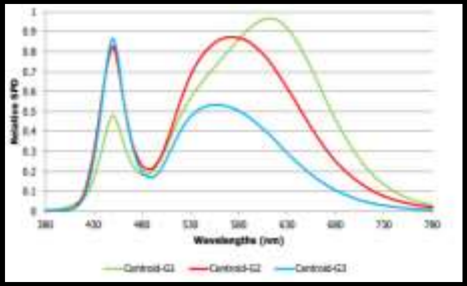


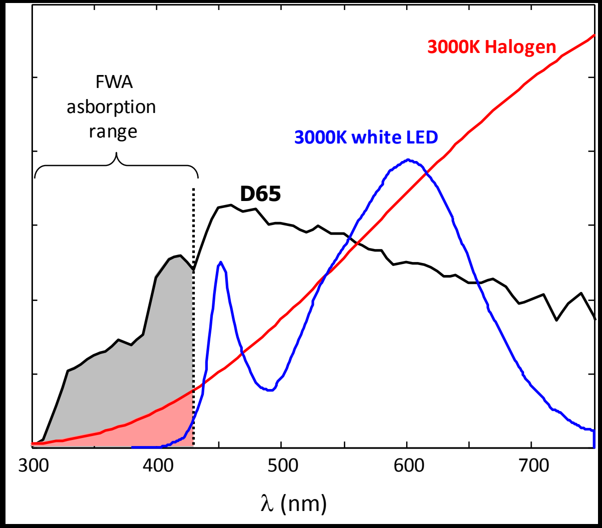




MR Luo, et al, Light. Res and Tech. 47(2015)360-369.

Whiteness




3000K Halogen
FWA
asborption
range
3000K white LED
D65
300
400
500
600
700
λ (nm)

Whiteness Index Formulation

- CIE Whiteness Index

$$W = Y + 800(x_n - x) + 1700(y_n - y)$$

$$T = 1000(x_n - x) - 650(y_n - y)$$

where

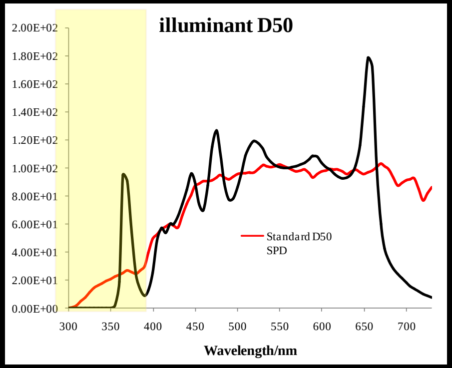
$$40 < W < (5Y - 280) \quad and$$

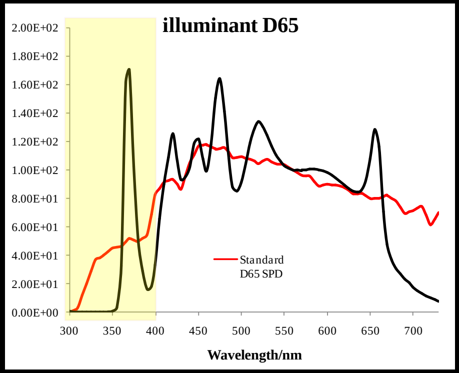
$$-3 < T < 3$$

1. Application to only D65 illuminant
2. Application to different illuminants by changing x_n, y_n
3. Optimisation of 800 and 1700 coefficients
4. Transformation via CAT02 to D65 from all illuminants

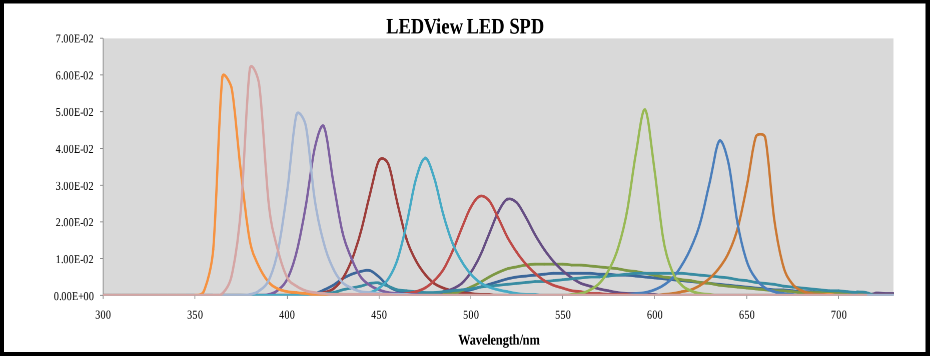
Whiteness perception

- Whiteness for object colours
- LED Daylight simulator

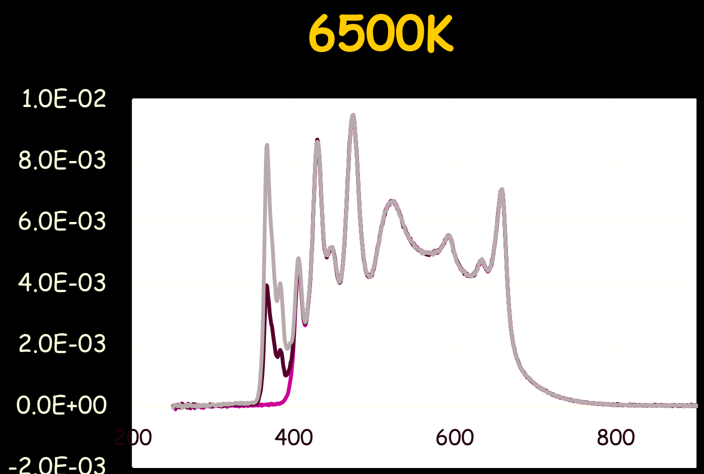


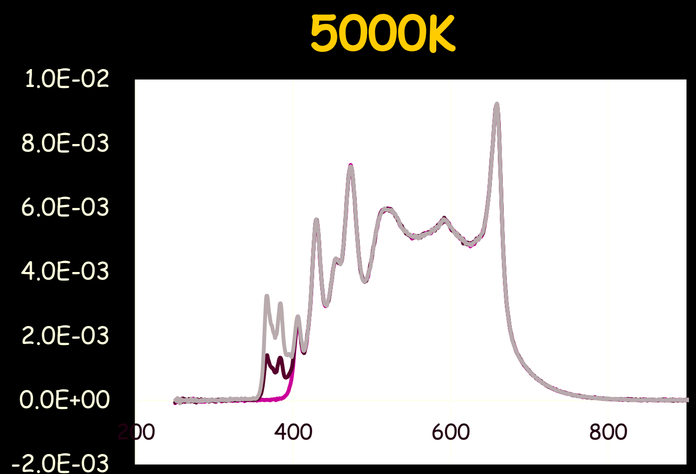


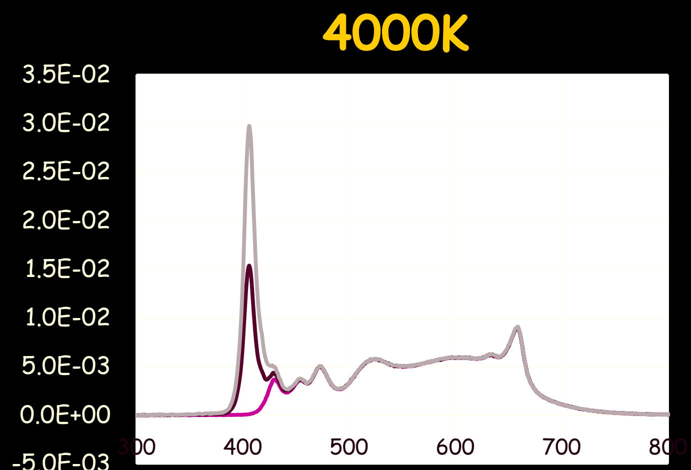
	D50	D65
CCT	5006 K	6488 K
CRI	99.37	99.28
MIvis	A (0.184)	A (0.219)
Miuv	B (0.333)	B (0.547)

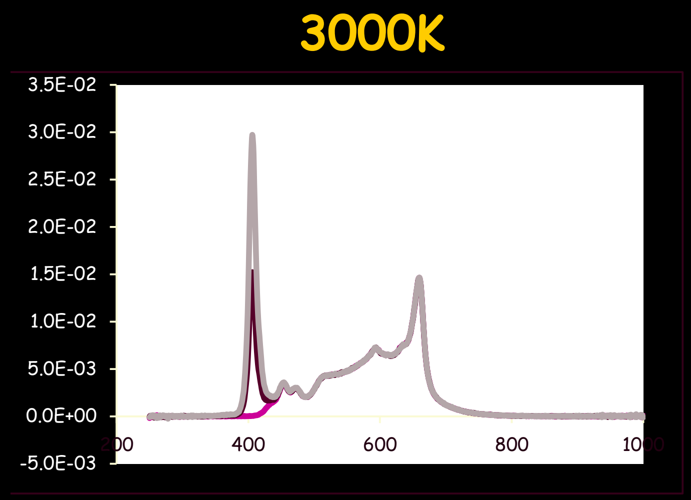


Whiteness Assessment (12 sources)

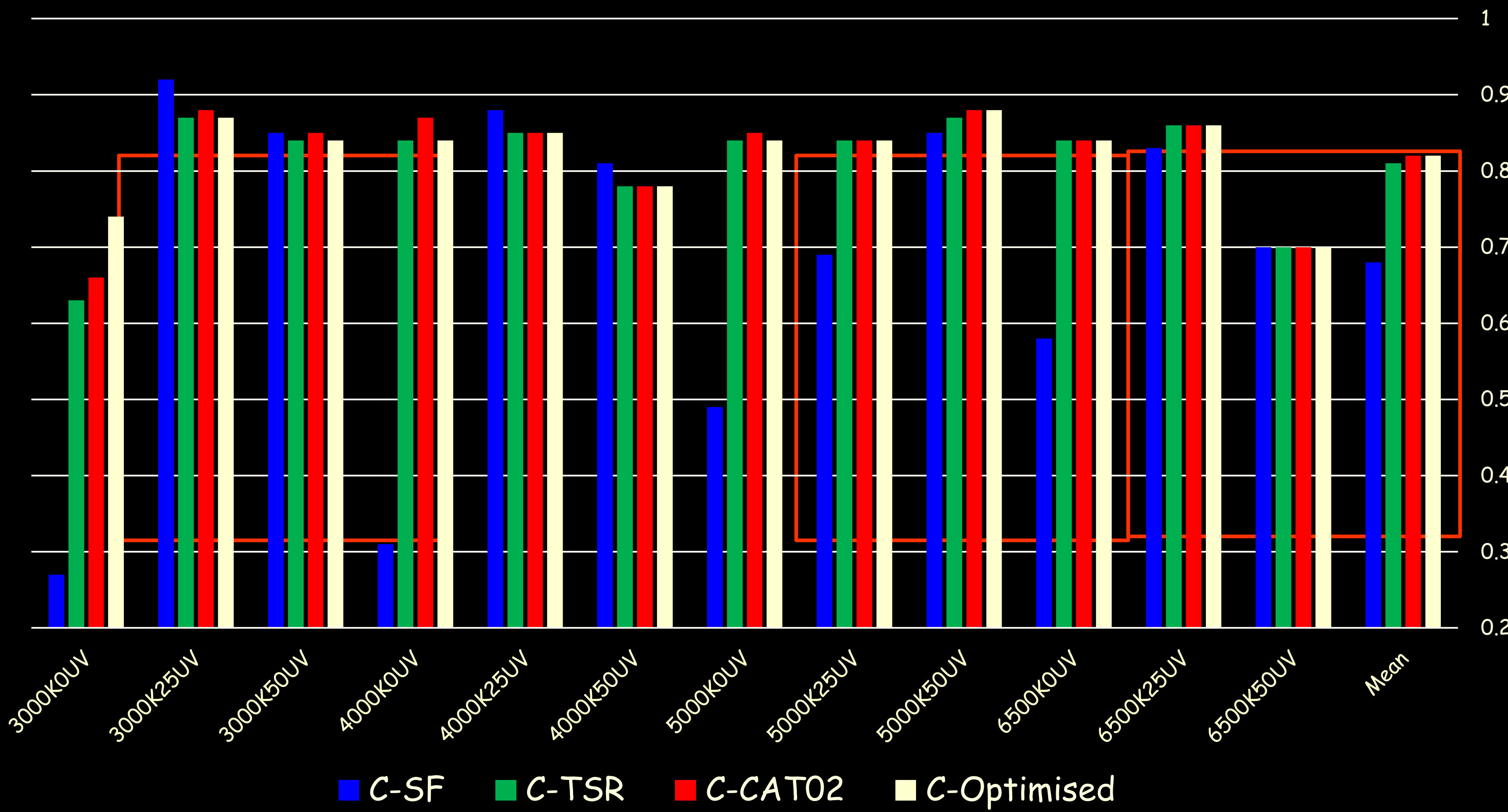






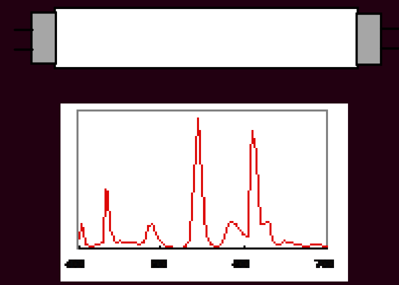


Testing various version of CIE Whiteness

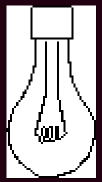


CIE-R_a

Test source



Reference illuminant



Planckian
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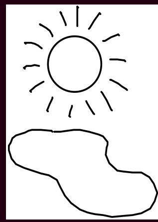
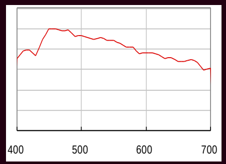


Standard Daylight
(CCT ≥ 5000 K)



Test Source (SPD) → **1. CCT** → 2. Ref. ill (SPD)

R%i → **3. Calculating XYZ**

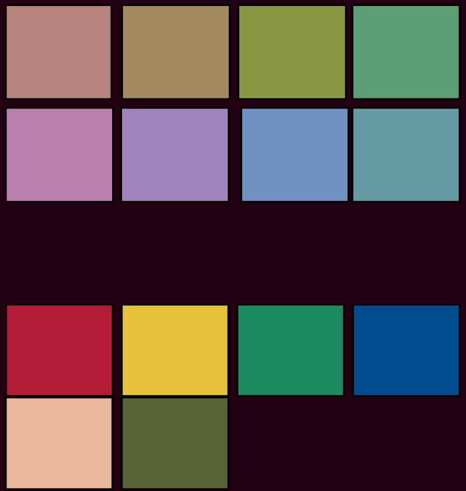
(XYZ)-T

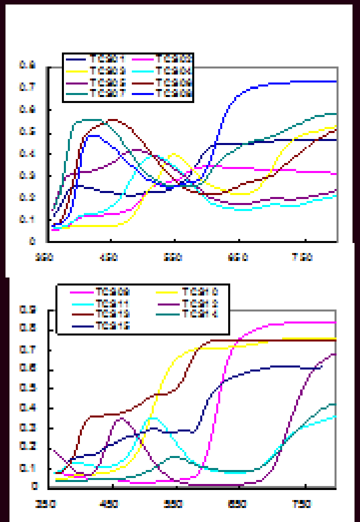
(XYZ)-R

4. Von Kries CAT

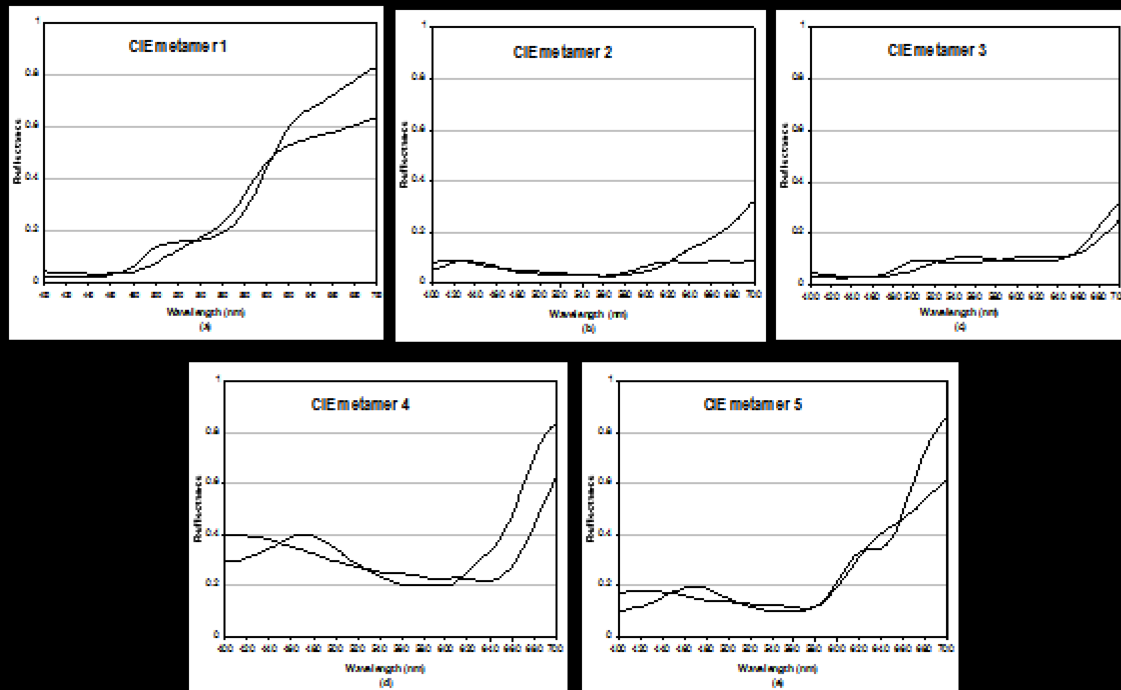
(XYZ)-TR → **5. CIEU*V*W***

CIE-R_a=Σ(100-4.6ΔEi)/8





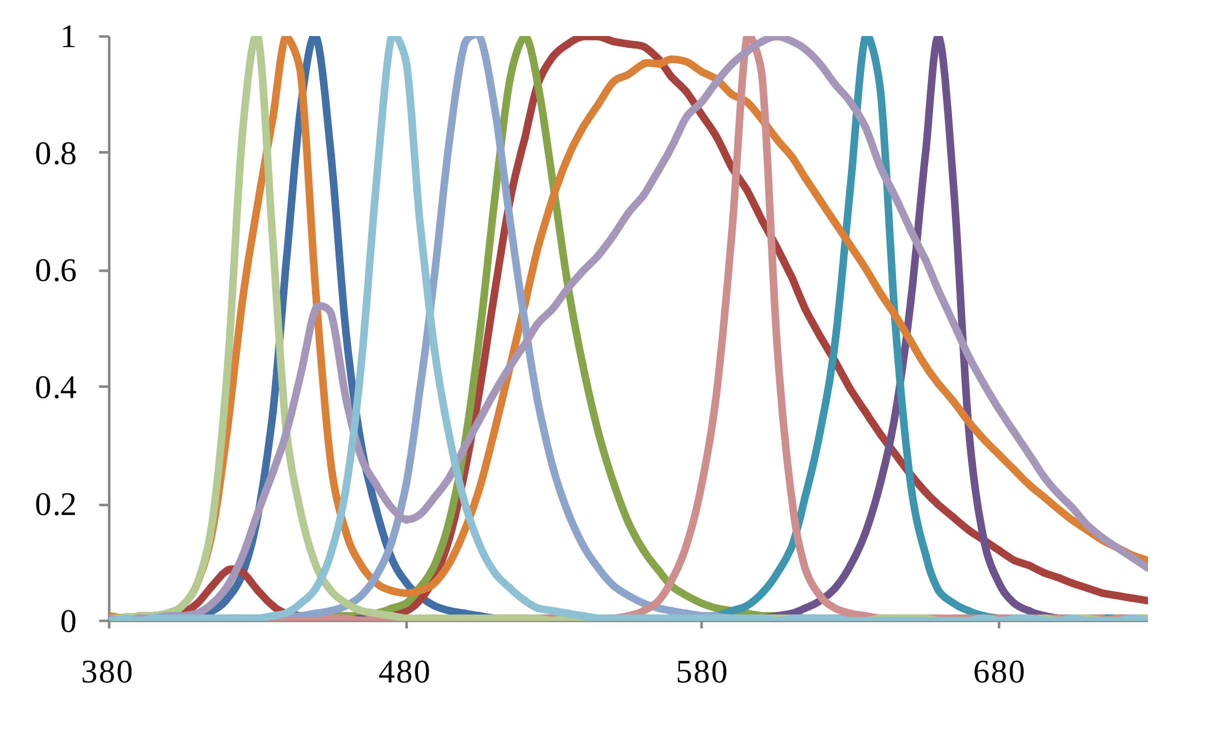
CIE Metamerism Index (CIE Pul. 51)



Colour Difference		CIE Metamerism Index
CIELAB	CIELUV	Category
<0.25	<0.32	A
0.25 to 0.5	0.32 to 0.65	B
0.5 to 1.0	0.65 to 1.3	C
1.0 to 2.0	1.3 to 2.6	D
>2.0	>2.6	E

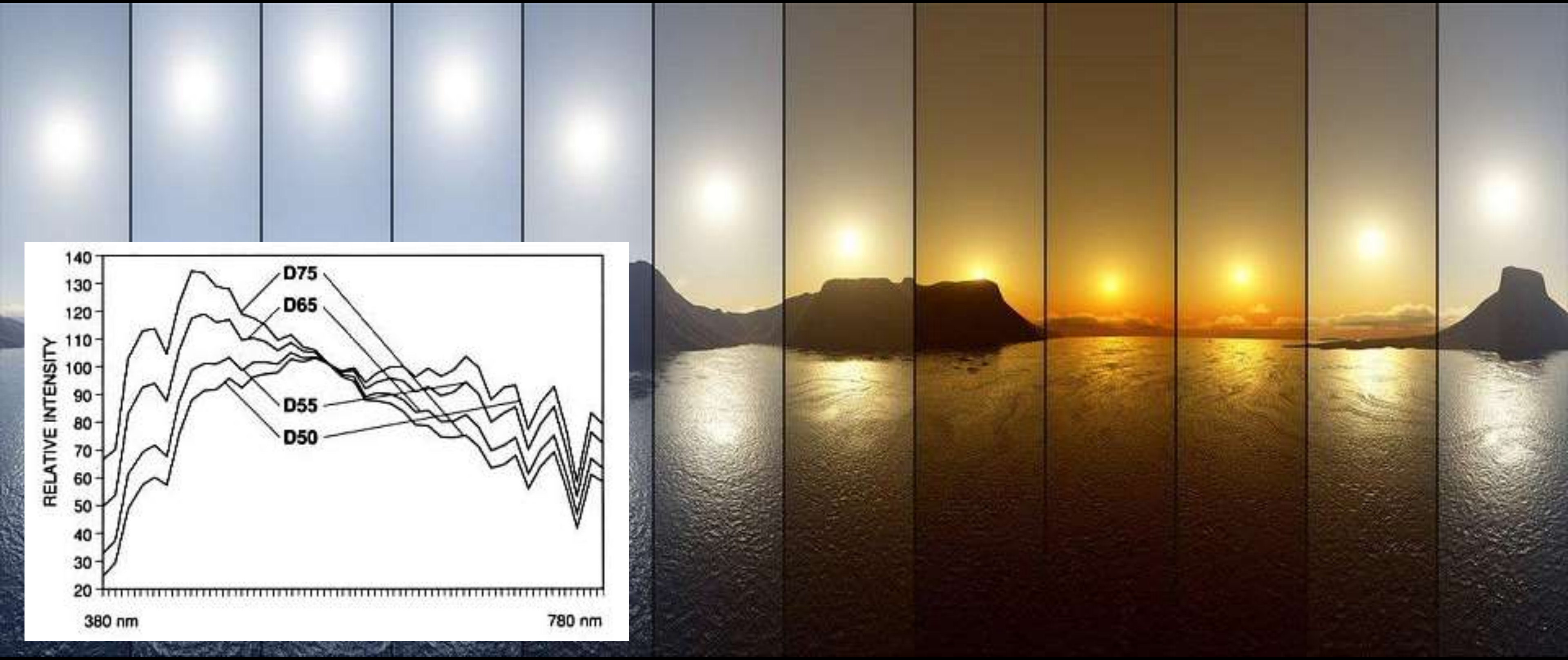
An LED Tuneable System LEDCube- system

- Multi-Channel (Colors+Whites), 400-700nm covering the visible range



LEDCube-Features

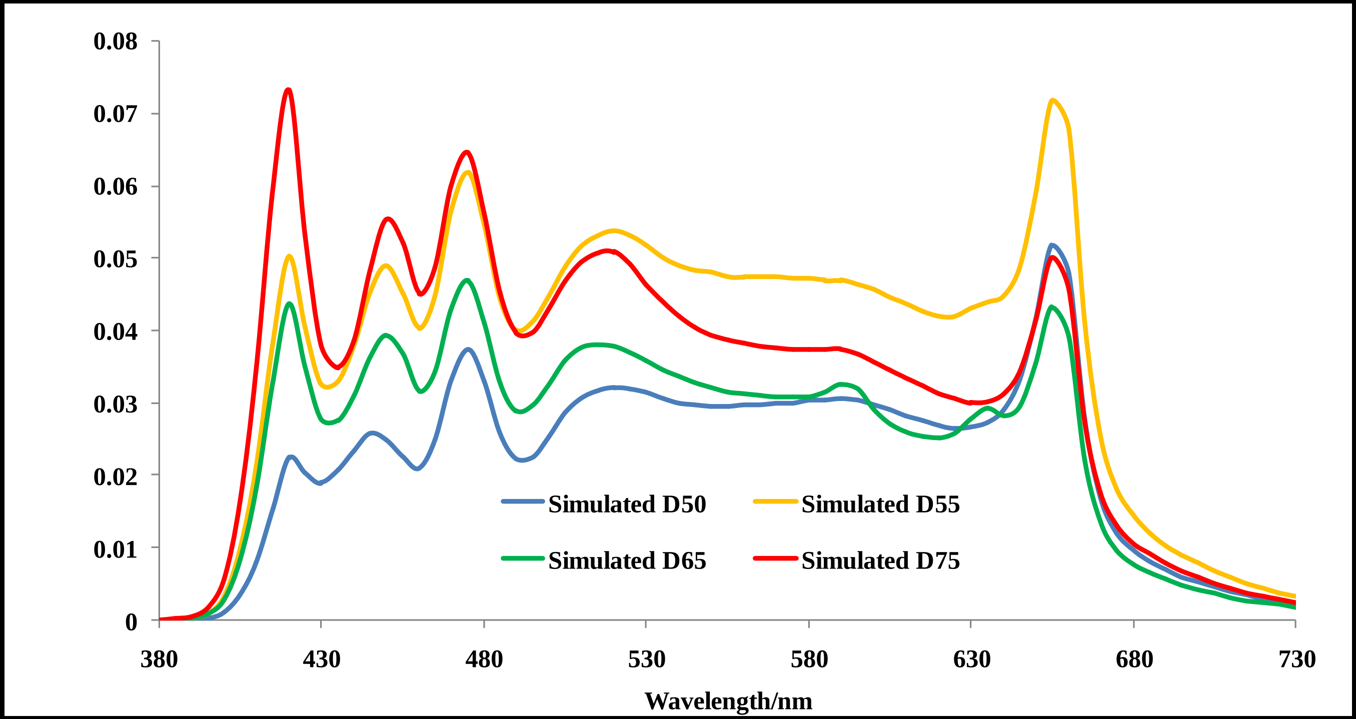
•High quality daylight illuminant, D50, D65, D75, etc ; CIE Ra[1]>99, MI[2]<0.25 (Grade A).



1. CIE 13.3-1995, Method of Measuring and Specifying Colour Rendering Properties of Light Sources
2. ISO 23603:2005, Standard method of assessing the spectral quality of daylight simulators for visual appraisal and measurement of colour

LEDCube-Features

- LEDCube Simulated Daylight Performance

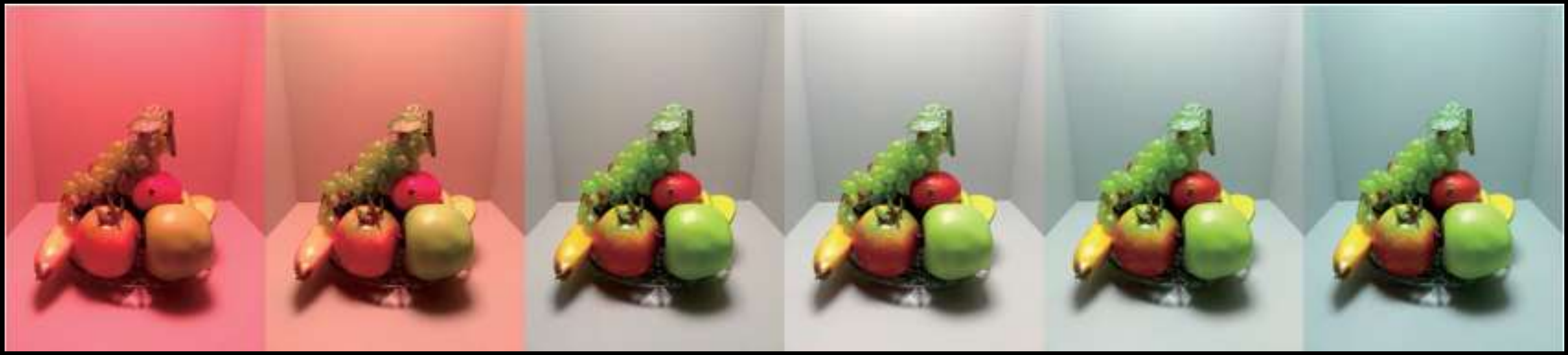


	CCT	CIE Ra	MIvis
D50	5002	99.0	0.2 Grade A
D55	5524	99.6	0.16 Grade A
D65	6496	99.5	0.18 Grade A
D75	7461	99.1	0.16 Grade A

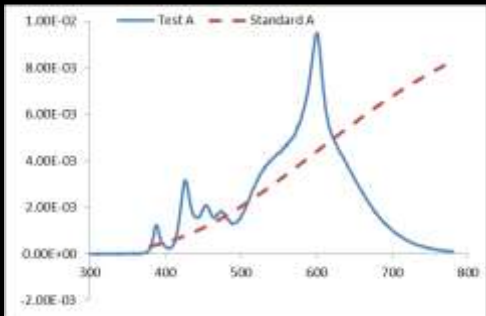
LEDCube-Features

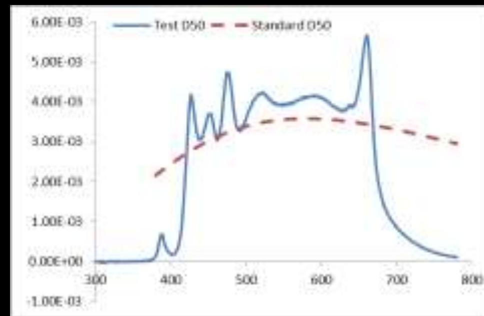
- **Blackbody simulator CCT with tunable CIE Ra 0-100 and Duv ±0.02 from 2000-6500K ±75K; 6500-10000K ±100K**

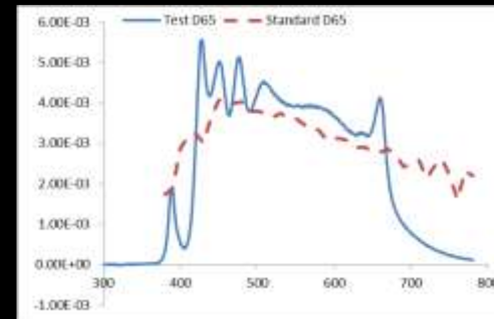
<-One LEDCube reproduce all CCT, save space, maintenance cost, Increase productive efficiency. Study the white balance, color appearance, whiteness assessment, skin color, pattern recognition under different CCT.

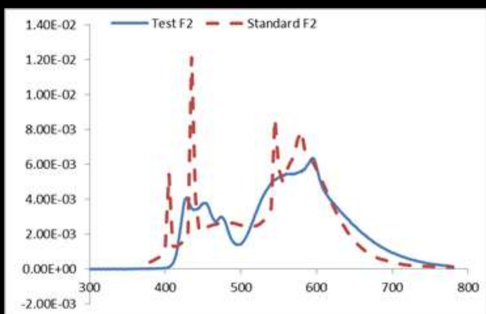


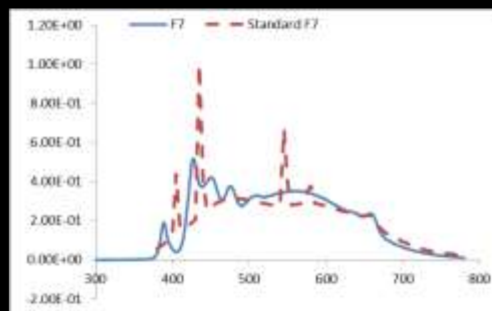
LED CIE illuminant simulators

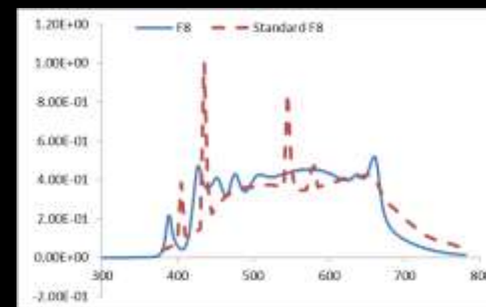


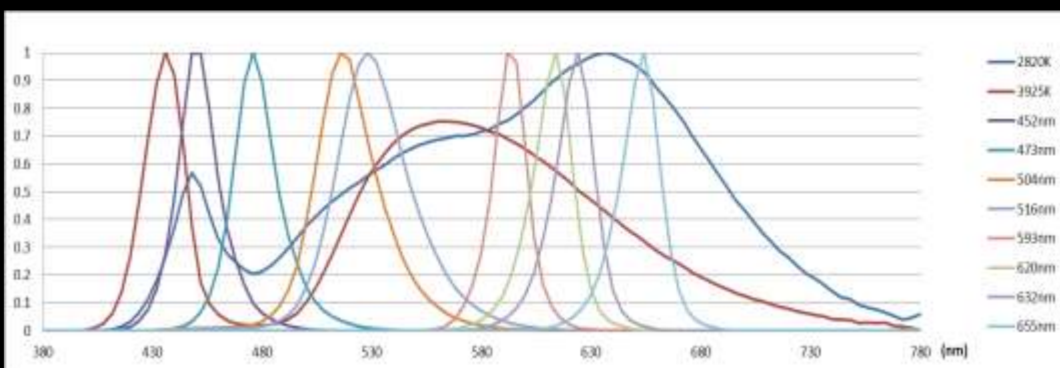


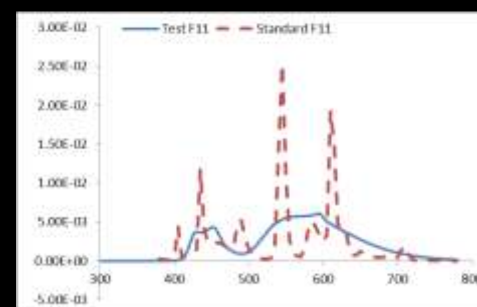












LEDCube-Features

- **Fast and accurate feedback (1 second) with external color sensor (Compensate for the aging and variable working environments)**

X-Rite i1 Pro2 ->Feedback

<-Record the light quality of LEDCube, dramatically increase the stability and lifetime of LEDCube, remote monitor the light from different sites

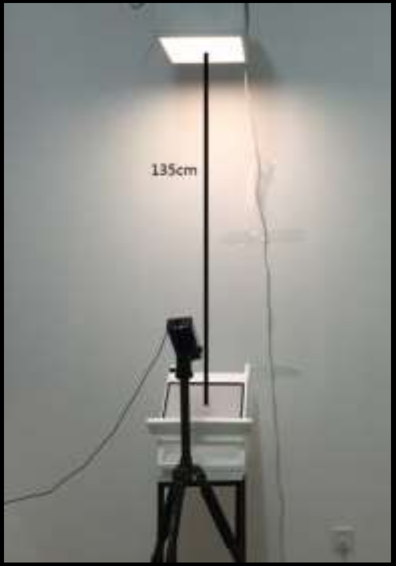
LEDCube-Performance

- Warm up time: 5 minutes
- Short-term stability

CCT(D65)< ±10K
CCT(D50)< ±5K
Luminance(D65,D50)< ±0.2%

- Long-term stability

CCT(D65)< ±25K
CCT(D50)< ±15K
Luminance(D65,D50)< ±1.0%



	Simulated D65	Simulated D50	Simulated A
Max illuminance / lx	874.1	1253	642.6
Max luminance / cd/m^2	20289	29171	12842

1700lm 2400lm

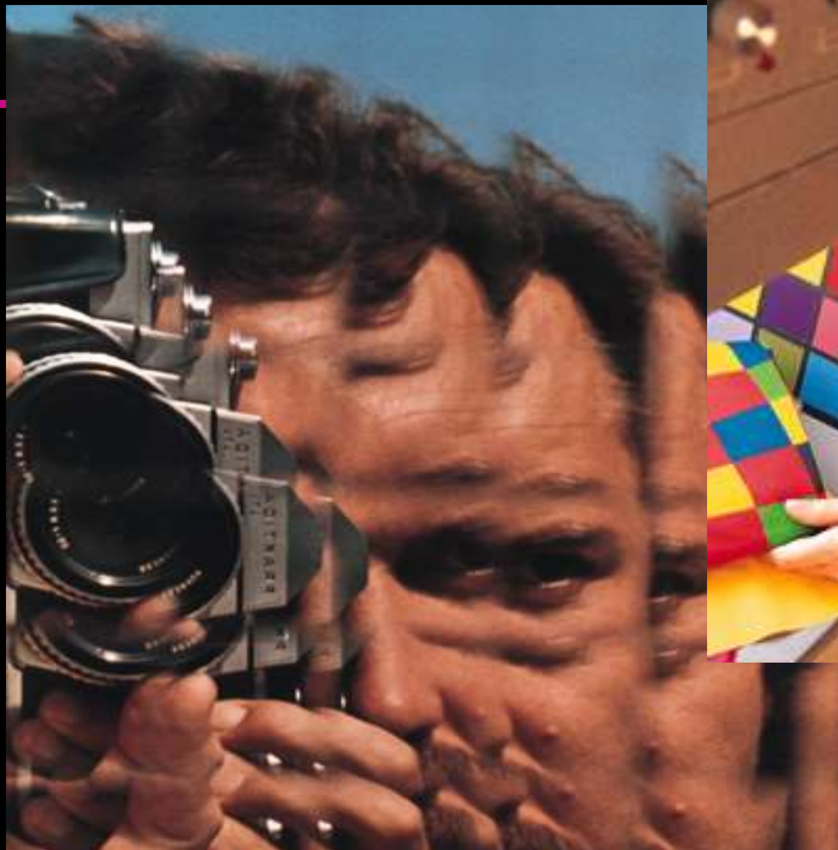
Uniform colour spaces

- UCS for lighting stimuli
  - CIELUV performed well , but MacAdam data did not
  - Aperture and object modes database are different.
- CIEAM02 revision
  - CAM16, CAT16, CAM16-UCS
- HDR-UCS
  - mICpCt, mICa,Cb
    - Large colour gamut and HDR conditions,
    - Simple formula and fast computation, and
    - Equal or better performance on the data of ellipses, hue constancy, and neutral convergence,

Conclusions

- CIE 2006 colorimetry
- LED spectral power distribution
- Colour rendering metric
- Whiteness

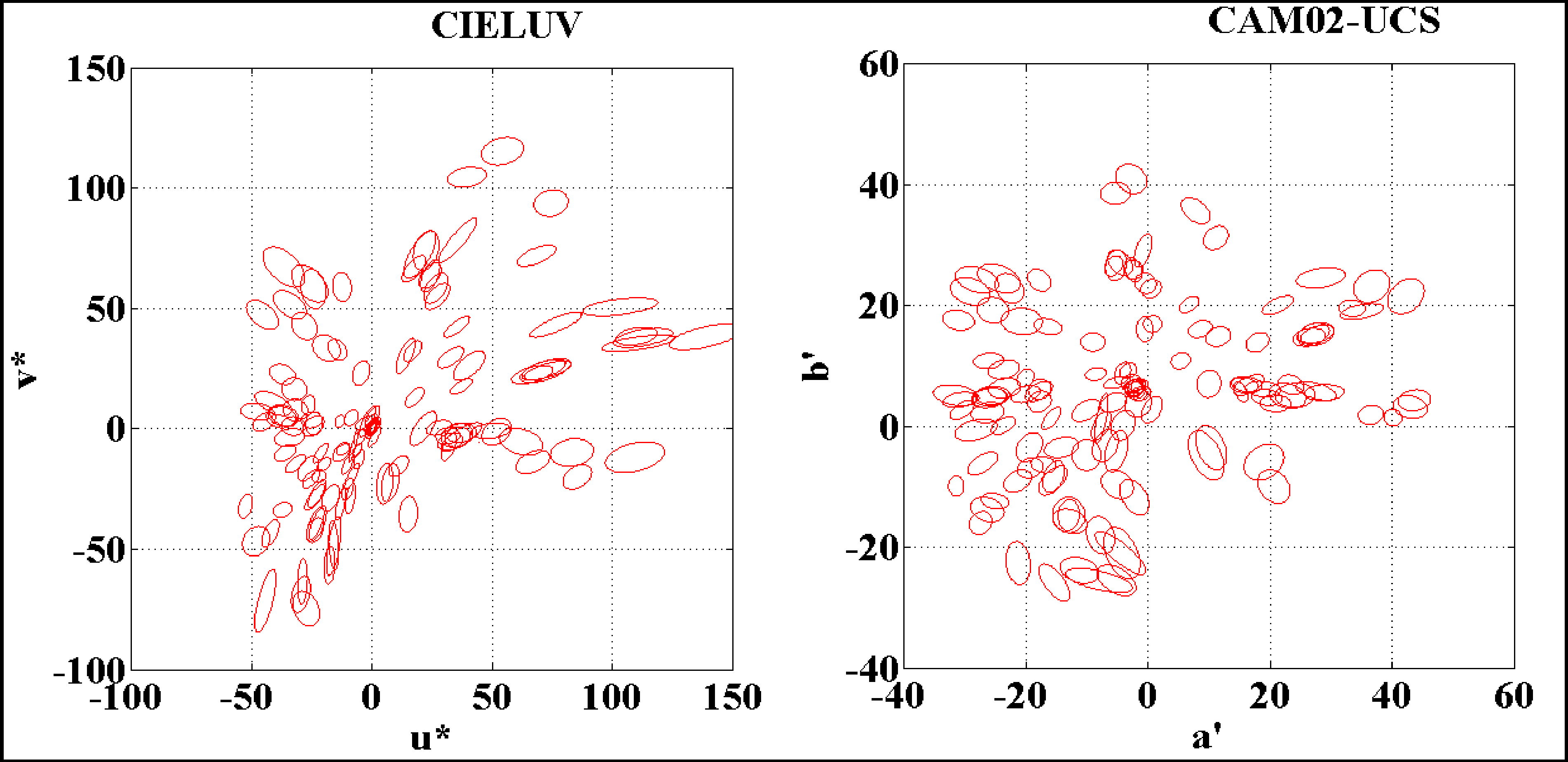
- LED daylight simulators
- UCS recommendations



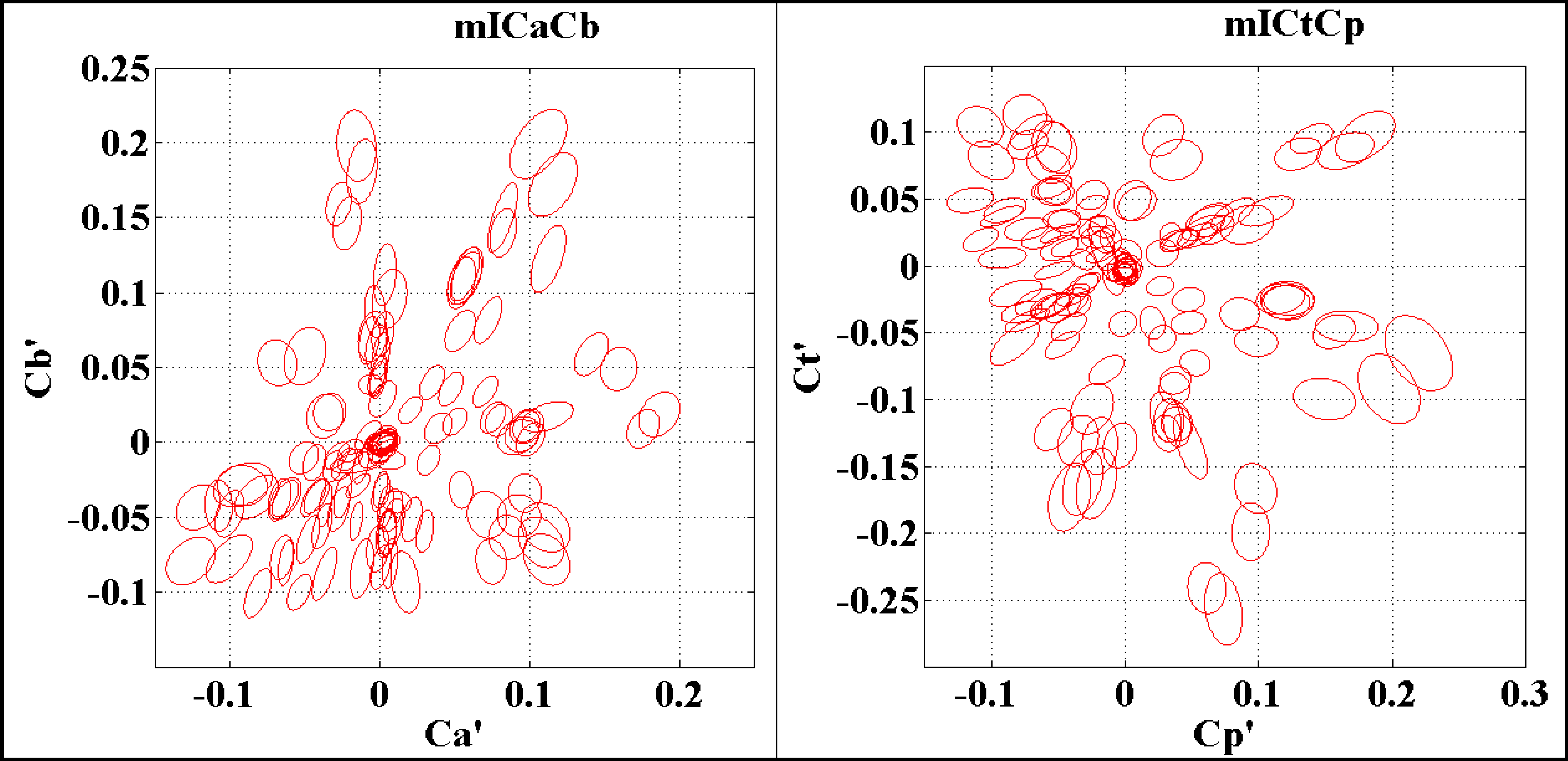
Thank for your attention!

m.r.luo@leeds.ac.uk

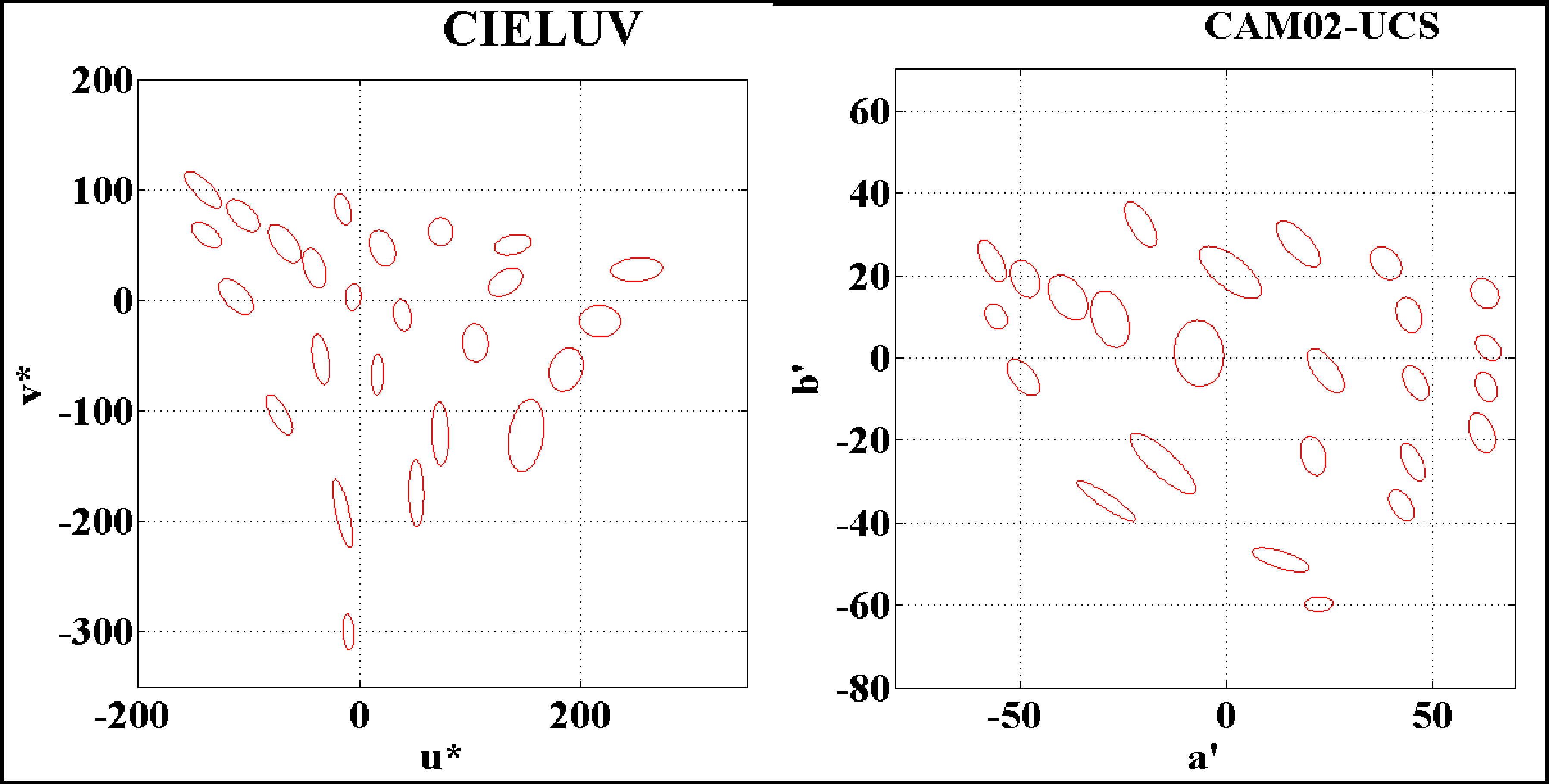
Object Ellipses Data



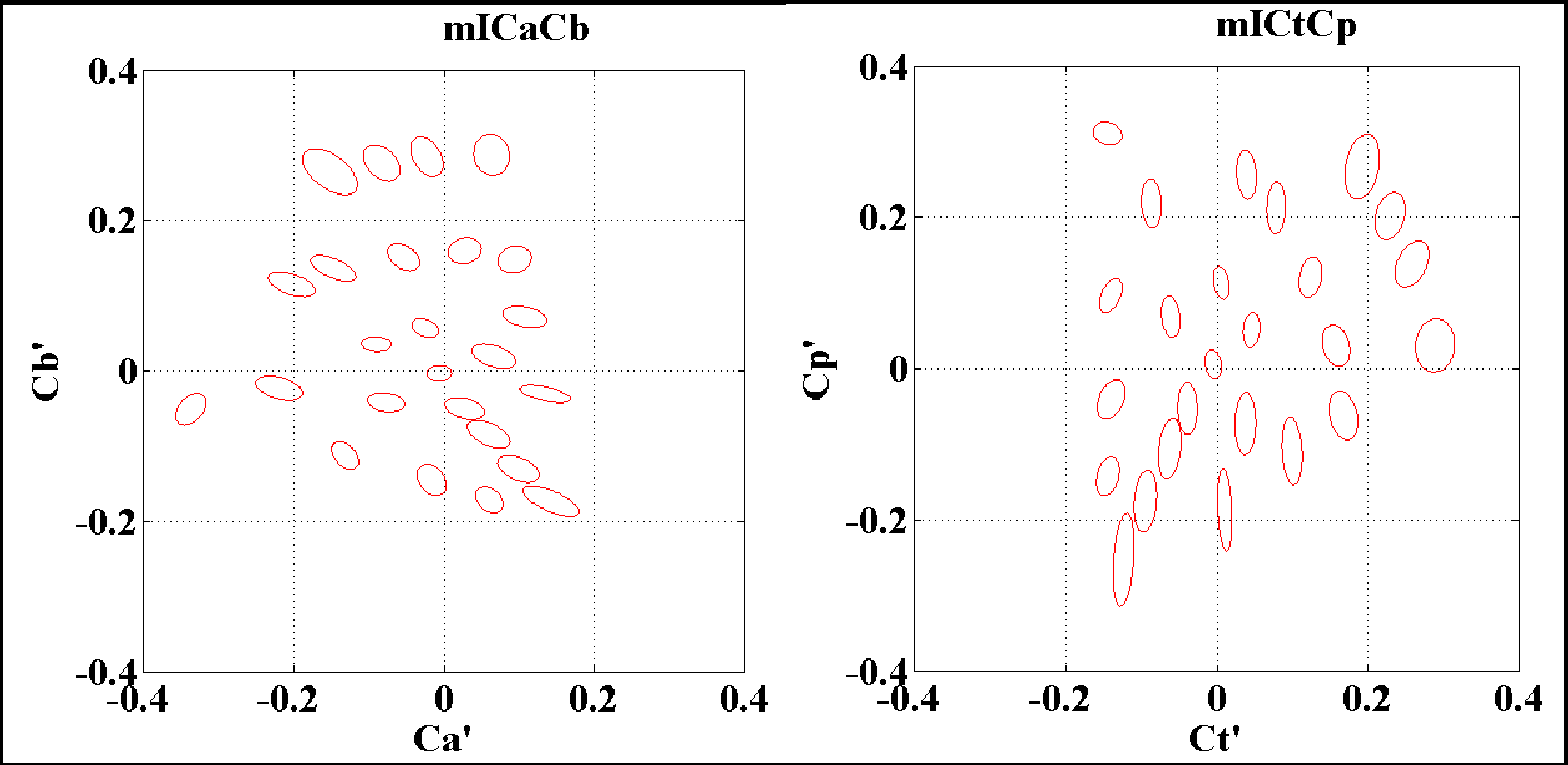
Object Ellipses Data



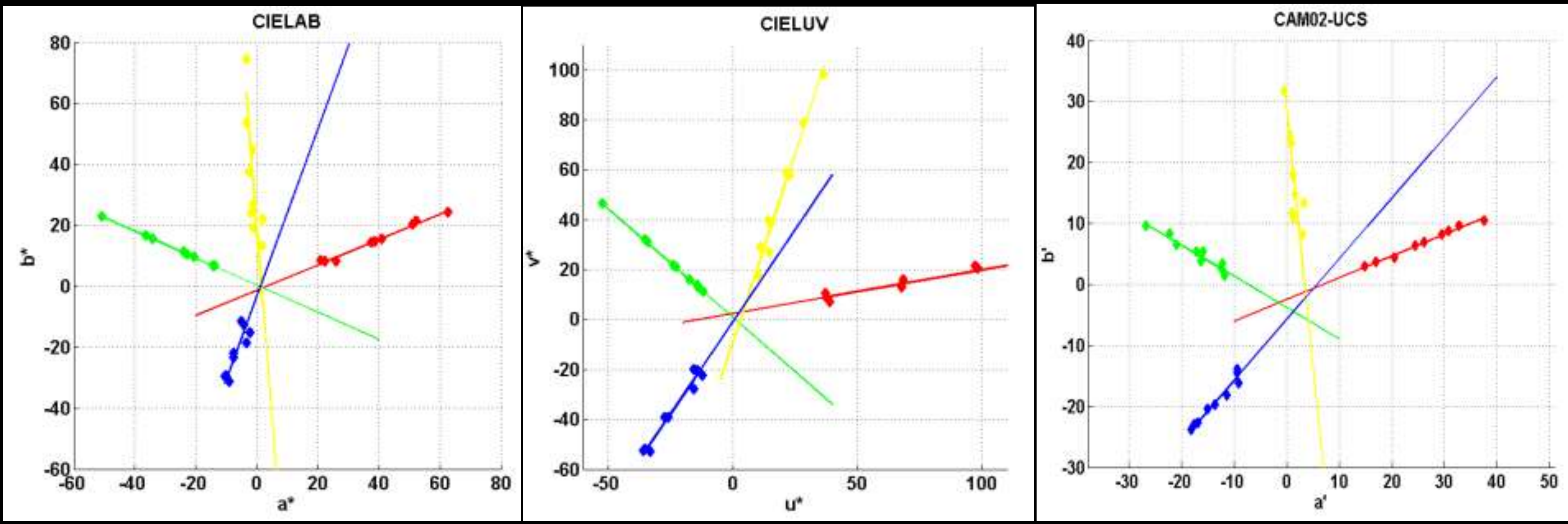
MacAdam Ellipses Data



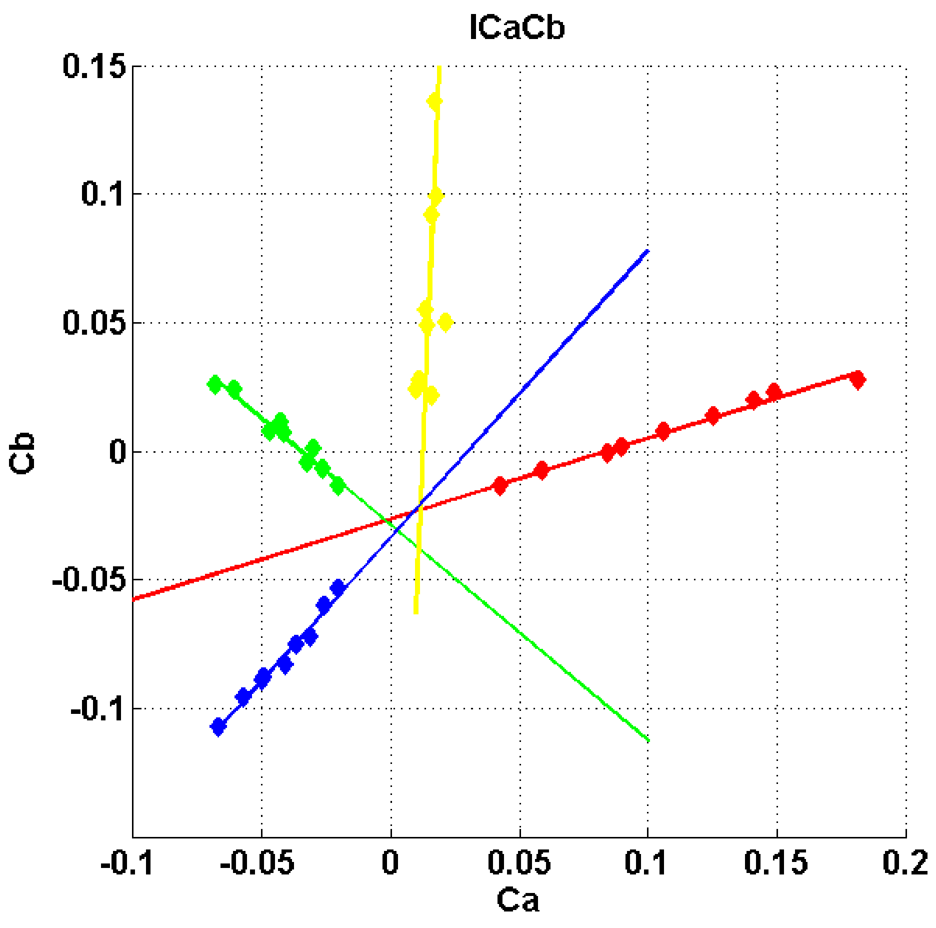
MacAdam Ellipses Data

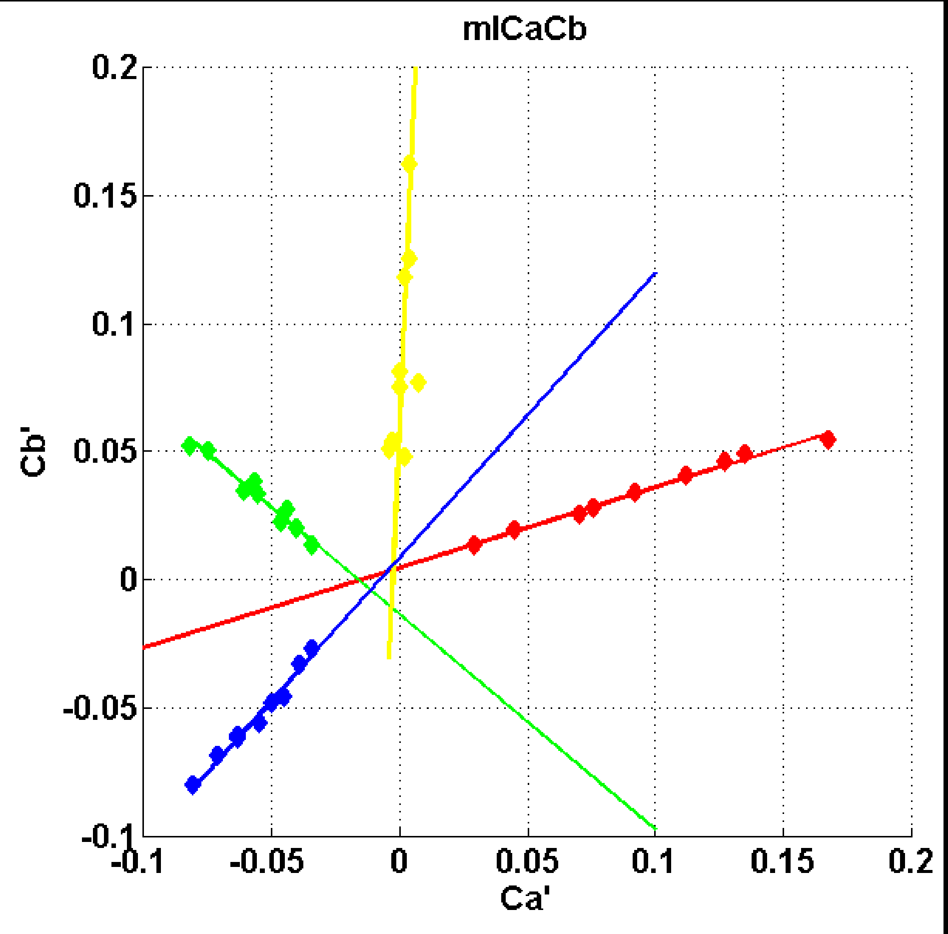


Liverpool Hue constancy data



Liverpool Hue constancy data





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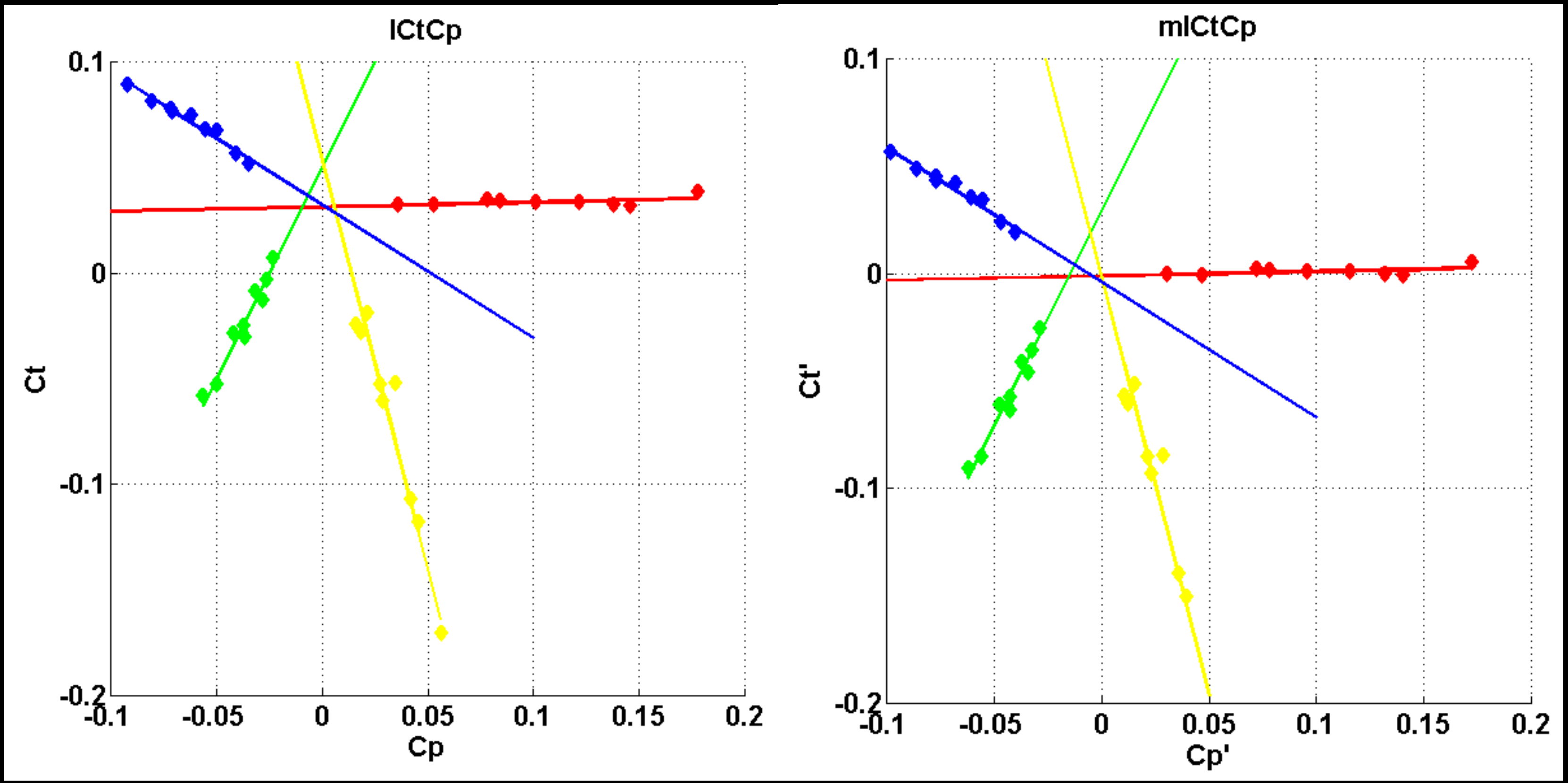
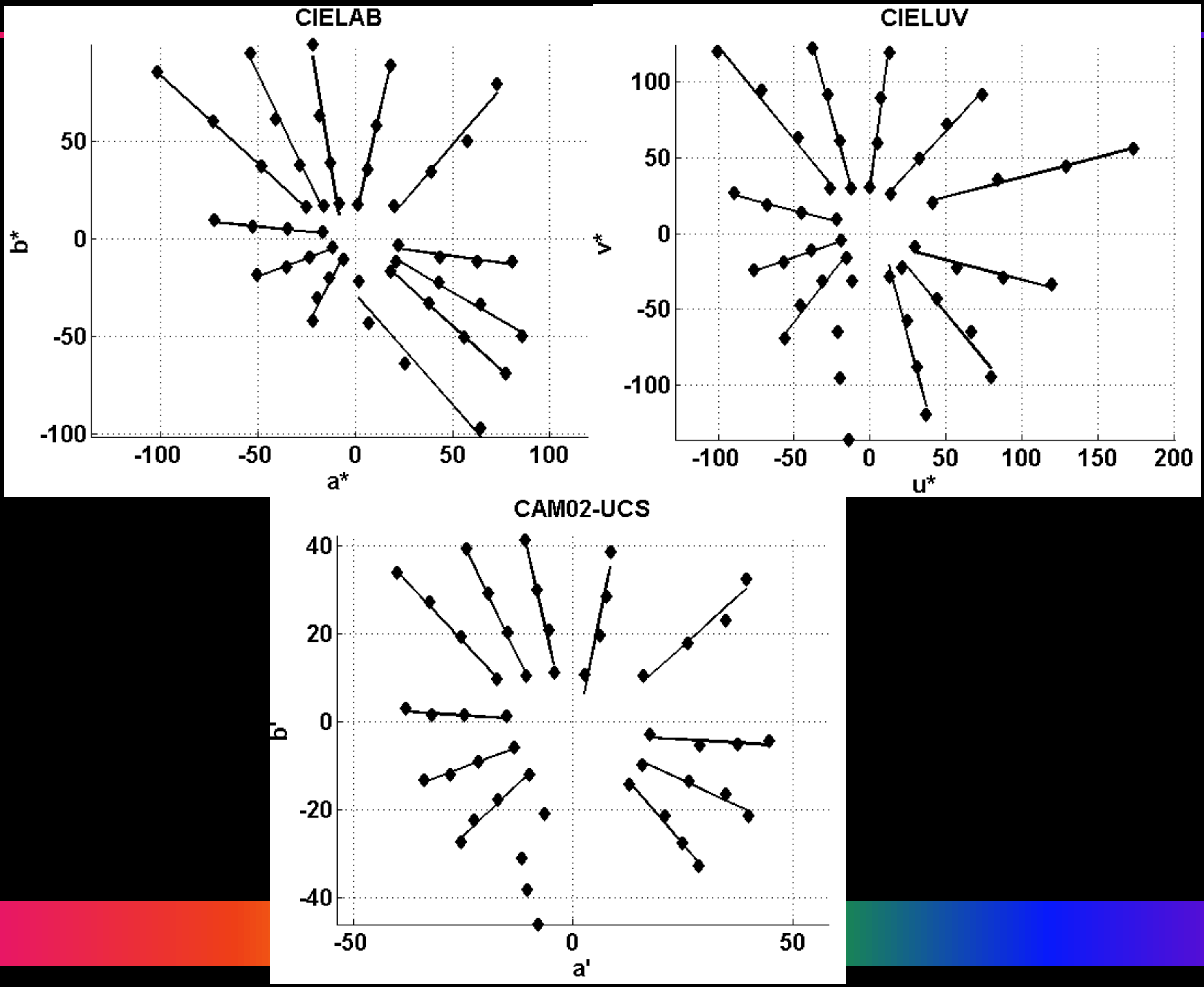


Hung and Berns data



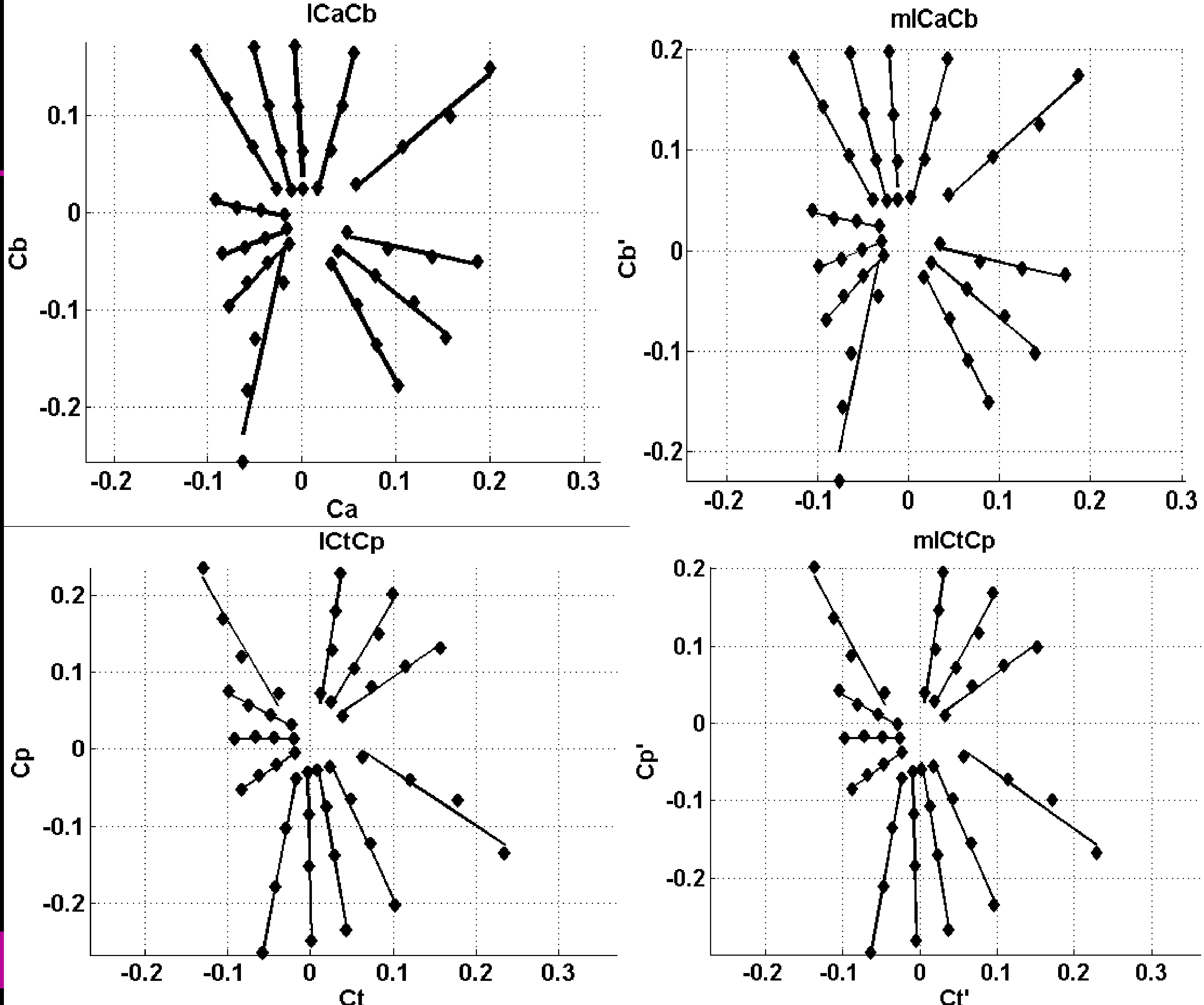

lCaCb
Ca
Cb
-0.2
-0.1
0
0.1
0.2
0.3
mlCaCb
Cb'
lCtCp
Ct
Cp
mlCtCp
Ct'
Cp'

Table 2. Results for hue linearity and hue error, luminance constancy, and neutral point error in terms of SD(h), correlation (CC_L) of Y with each luma-comp. , and ΔE^*_{ab}, respectively.

Spaces	Xiao-UH		H&B-CL		H&B-VL
	SD_h	ΔE^*_{ab}	SD_h	CC_L	SD_h
CIELAB	2.7	1.6	3.8	0.98	7.9
CIELUV	2.3	2.0	3.3	0.98	8.1
CAM02-UCS	3.9	5.5	2.9	0.95	7.0
ICaCb	9.9	11.9	4.7	0.96	6.6
mICaCb	2.9	1.7	5.9	0.96	7.6
ICtCp	11.1	12.6	5.2	0.96	6.7
mICtCp	2.6	1.2	5.2	0.96	7.3

Table 1. Results for local and global uniformity of test color spaces in terms of STRESS.

Color Spaces	BFD & RIT-DuPont			MacAdam-PNG		
	Loc.	Glob.	Avg.	Loc.	Glob.	Avg.
CIELAB	38	61	49	53	47	50
CIELUV	43	53	48	40	41	40
CAM02-UCS	31	39	35	39	47	43
ICaCb	35	62	48	33	37	35
mICaCb	29	47	38	28	32	31
ICtCp	40	68	54	42	38	40
mICtCp	28	53	40	36	37	37