CIE USNC Annual Meeting
Lake George, NY, October 12, 2018

Vision Experiment on CIE 2015 Cone-Fundamental-based 10° Color Matching Functions for Lighting Applications

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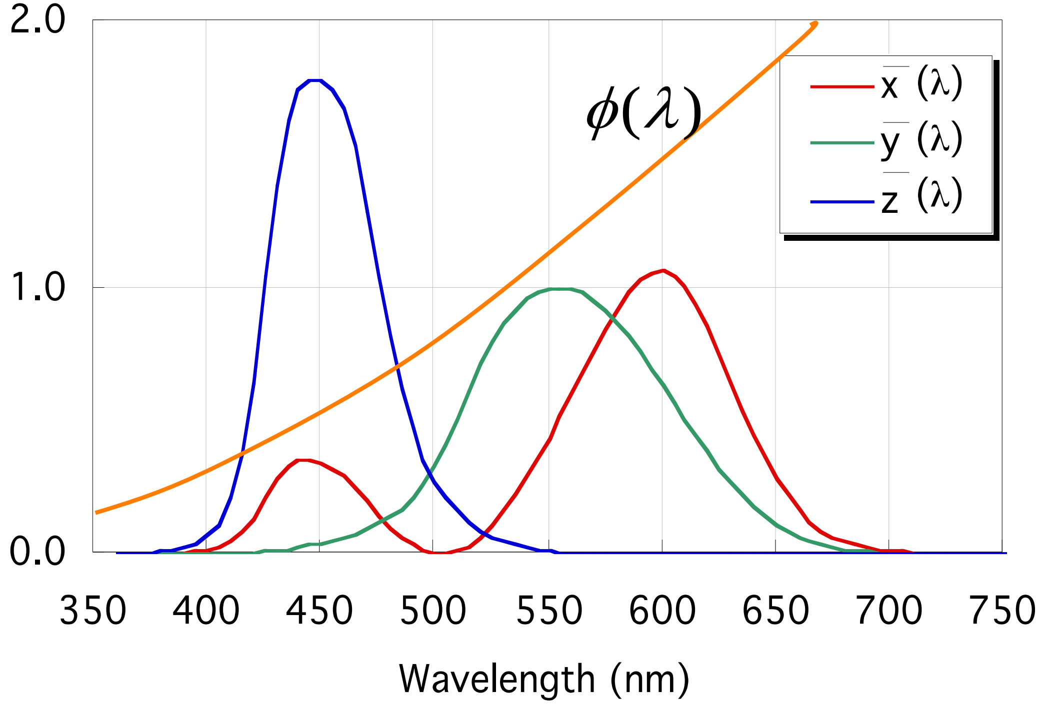
CIE 1931 Color Matching Functions

CIE 1931 Colorimetry System - The basis for all color quantities



Tristimulus Values

$$X = k\int_{\lambda} \phi(\lambda)\bar{x}(\lambda)\mathrm{d}\lambda$$

$$Y = k\int_{\lambda} \phi(\lambda)\bar{y}(\lambda)\mathrm{d}\lambda$$

$$Z = k\int_{\lambda} \phi(\lambda)\bar{z}(\lambda)\mathrm{d}\lambda$$

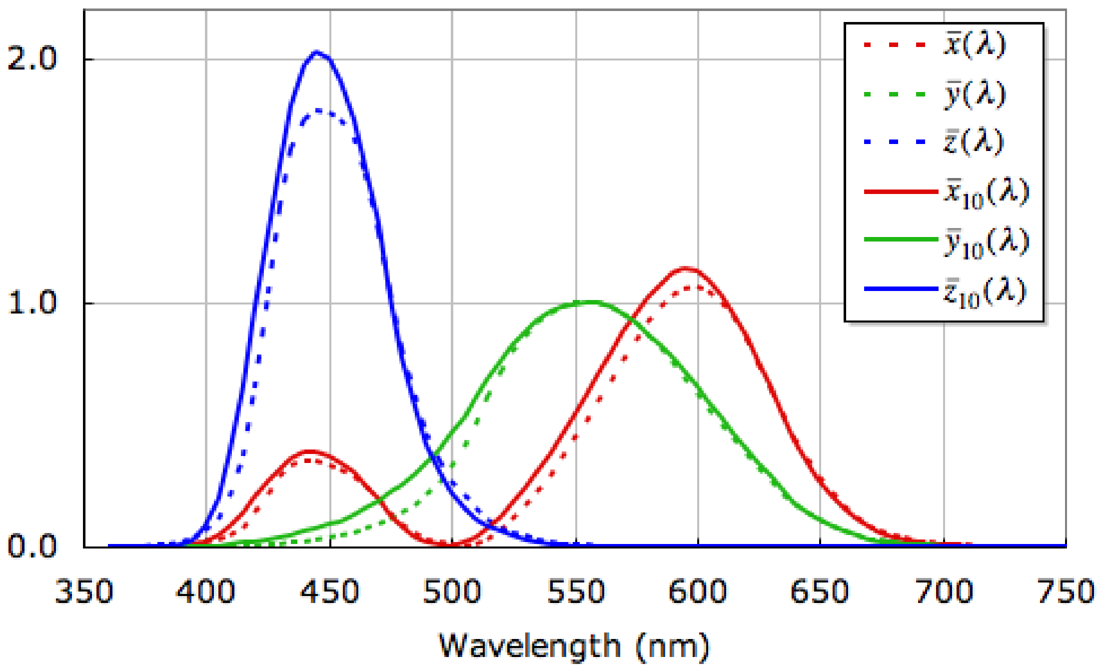
Chromaticity x, y, u', v'

CCT, Duv

ISO 11664-1:2007(E)/CIE S 014-1/E:2007: Joint ISO/CIE Standard: Colorimetry — Part 1: CIE Standard Colorimetric Observers

CIE 1964 10° color matching functions

CIE 1964 Colorimetry System:
often used for object color specifications
(seldom used in lighting applications,
except in CIE 224)



Tristimulus Values

$$X_{10} = k\int_{\lambda} \phi(\lambda)\bar{x}_{10}(\lambda)\mathrm{d}\lambda$$

$$Y_{10} = k\int_{\lambda} \phi(\lambda)\bar{y}_{10}(\lambda)\mathrm{d}\lambda$$

$$Z_{10} = k\int_{\lambda} \phi(\lambda)\bar{z}_{10}(\lambda)\mathrm{d}\lambda$$

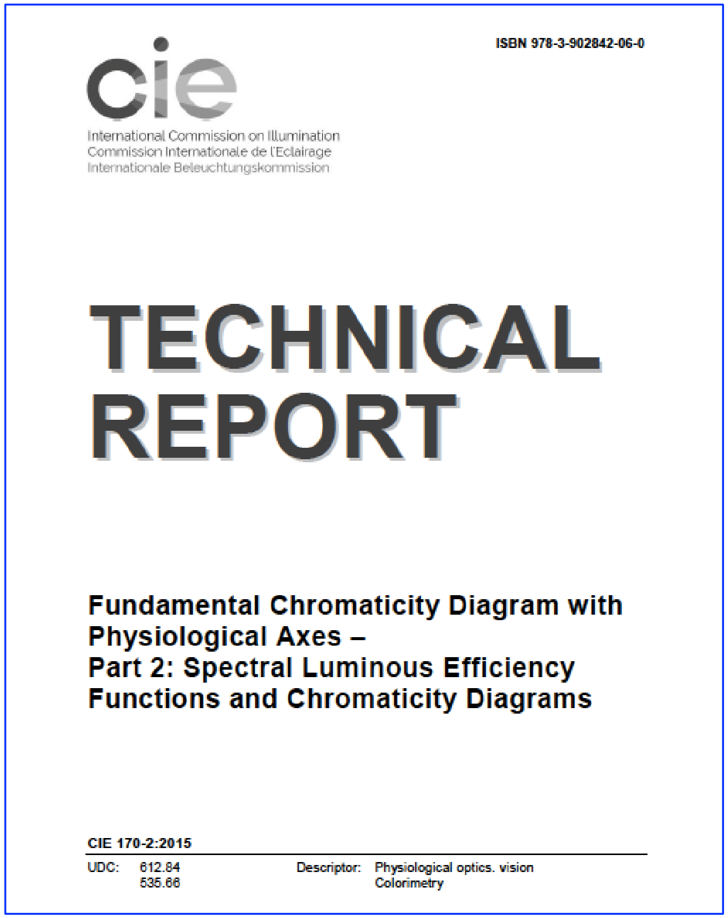
Chromaticity x_{10}, y_{10}, u_{10}', v_{10}'

(CCT, Duv are defined only with CIE 1931 CMF)

ISO 11664-1:2007(E)/CIE S 014-1/E:2007: Joint ISO/CIE Standard: Colorimetry — Part 1: CIE Standard Colorimetric Observers

CIE 2015 Cone-Fundamental-Based CMFs (CIE 170-2:2015)

Improvements from recent physiological studies on human vision



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International Commission on Illumination
Commission Internationale de l'Eclairage
Internationale Beleuchtungskommission

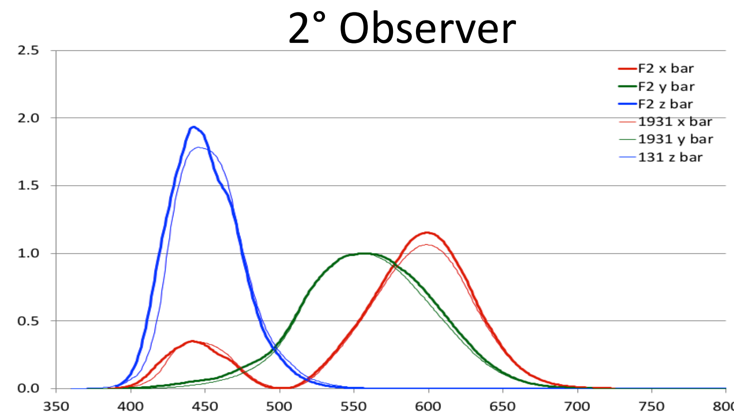
TECHNICAL REPORT

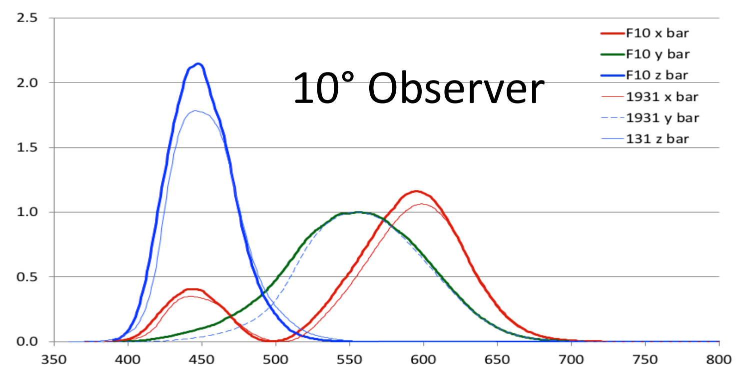
Fundamental Chromaticity Diagram with Physiological Axes – Part 2: Spectral Luminous Efficiency Functions and Chromaticity Diagrams

CIE 170-2:2015

UDC: 612.84
535.66

Descriptor: Physiological optics. vision
Colorimetry





CIE Research Strategy (2016)

International Commission on Illumination
Commission Internationale de l'Eclairage
Internationale Beleuchtungskommission

ABOUT THE CIE | DIVISIONS AND TECHNICAL WORK | PUBLICATIONS | RESEARCH STRATEGY | NEWS AND E

RESEARCH STRATEGY

Light and lighting technologies are essential to modern daily life, touching on its every aspect. These technologies require well-founded knowledge, both fundamental and applied, to ensure that they can be used with confidence in their safety and quality. CIE publications provide that confidence. They are based on the strongest available scientific evidence and follow a rigorous review and ballot process. To develop consensus-based documents fit for the future requires that scientists engage now in building the knowledge base that will support them.

Top Priority Topics

- Recommendations for Healthful Lighting and Non-Visual Effects of Light
- Colour Quality of Light Sources Related to Perception and Preference
- Integrated Glare Metric for Various Lighting Applications
- New Calibration Sources and Illuminants for Photometry, Colorimetry, and Radiometry
- Adaptive, Intelligent and Dynamic Lighting
- Application of New CIE 2006 Colorimetry
- Visual Appearance: Perception, Measurement and Metrics
- Support for Tailored Lighting Recommendations
- Metrology for Advanced Photometric and Radiometric Devices
- Reproduction and Measurement of 3D Objects

6 Application of CIE 2015 Cone-Fundamental-Based CIE Colorimetry

6.1 Description of research

Since colorimetry was established in 1931, considerable improvements in the metrology of the colour stimulus and immense advances in the knowledge of colour vision have been made. Based on the modern knowledge of the human colour visual system CIE published a set of new colour-matching functions that takes into consideration the age of the observer and the field size of the stimulus, and provides a method to derive the associated chromaticity diagram (see CIE 170-2:2015).

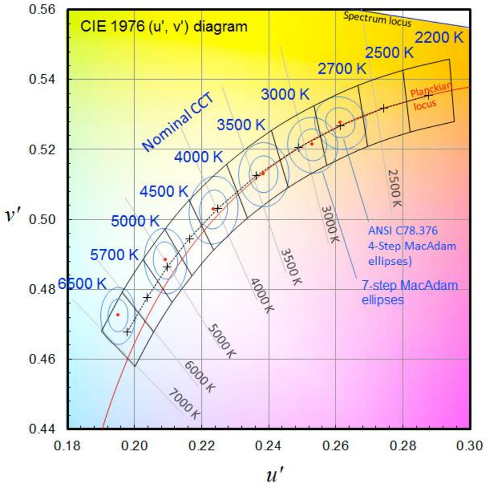
The objective of this research is to conduct field trials that compare the results of the use of the CIE 1931 (2°), CIE 1964 (10°) and CIE 2015 cone-fundamental-based colour-matching functions, especially when applied to LED lighting and in imaging applications. Also the method to be used to calculate the CIE 2015 cone-fundamental-based colour-matching functions needs to be standardized.

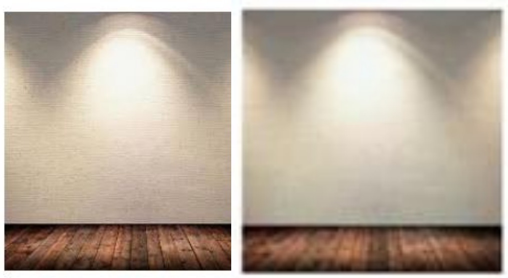
6.2 Key research questions

- How accurate are cone-fundamental-based colorimetry results compared with those of 1931 and 1964 in predicting typical colorimetry applications such as colour difference, colour appearance, whiteness, colour rendering, etc.?
- Can the cone-fundamental-based colorimetry be used to quantify the age metamerism effect and the size metamerism effect? There is an urgent need to quantify observer metamerism. Evidence suggests that the earlier CIE method underestimates these effects.

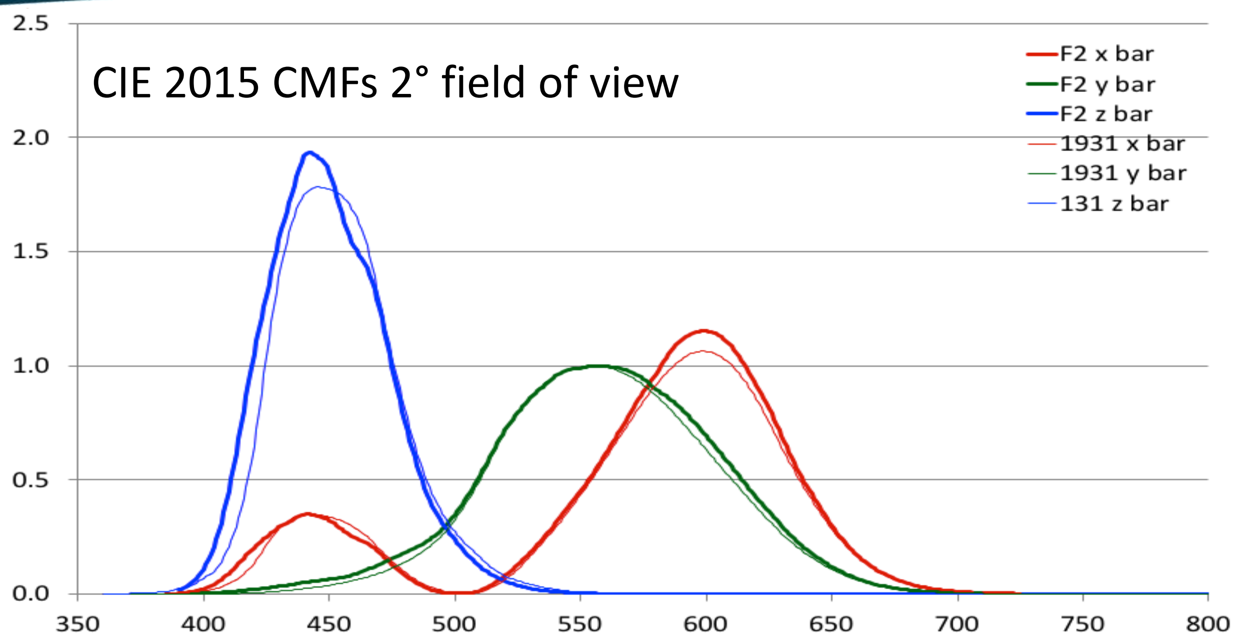
In Lighting Applications

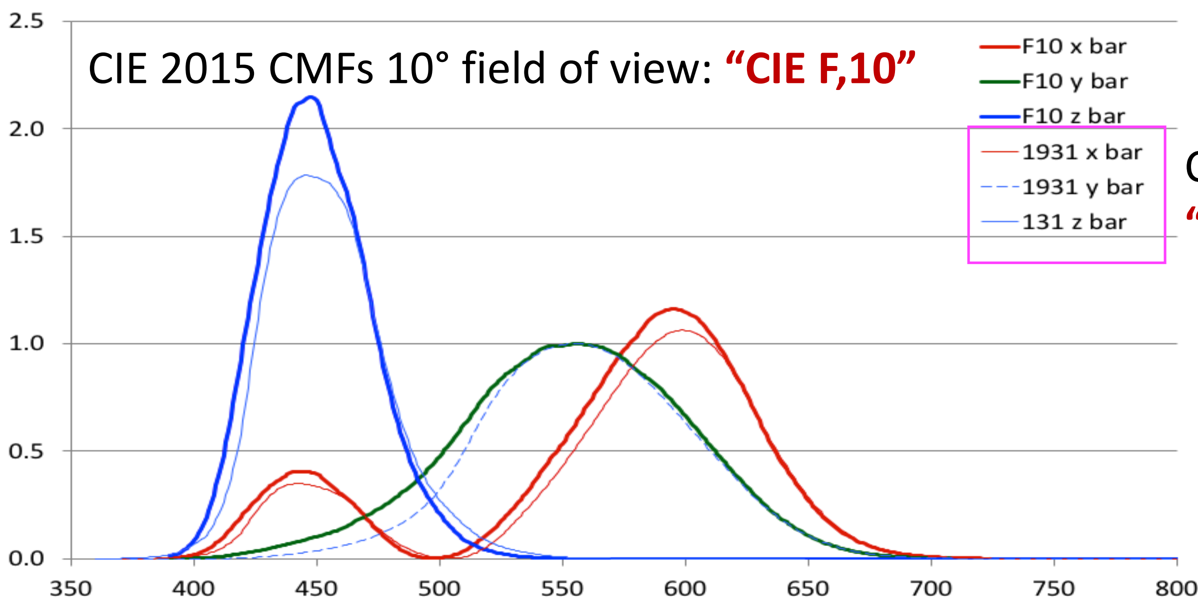
- CIE 1931 colorimetry system (2°) is used for all lighting products specifications.
- Chromaticity specifications of solid state lighting products (ANSI C78.377) all based on CIE 1931.
- People experience, in some cases, that color of light sources (different SPDs) appear slightly different though the chromaticity is matched exactly the same.
- Lighting scenes are generally observed in a field of view greater than 10°.





Comparison of new 10° CMFs vs. CIE 1931 CMFs.





CIE 1931 CMFs:
“CIE 1931”

Color quantities based on CIE F,10

Tristimulus Values

$$X_{\mathrm{F,10}} = k\int \varphi(\lambda)\,\bar{x}_{\mathrm{F,10}}(\lambda)\,\mathrm{d}\lambda$$

$$Y_{\mathrm{F,10}} = k\int \varphi(\lambda)\,\bar{y}_{\mathrm{F,10}}(\lambda)\,\mathrm{d}\lambda$$

$$Z_{\mathrm{F,10}} = k\int \varphi(\lambda)\,\bar{z}_{\mathrm{F,10}}(\lambda)\,\mathrm{d}\lambda$$

Chromaticity coordinates

$$x_{\mathrm{F,10}} = \frac{X_{\mathrm{F,10}}}{X_{\mathrm{F,10}} + Y_{\mathrm{F,10}} + Z_{\mathrm{F,10}}}$$

$$y_{\mathrm{F,10}} = \frac{Y_{\mathrm{F,10}}}{X_{\mathrm{F,10}} + Y_{\mathrm{F,10}} + Z_{\mathrm{F,10}}}$$

Chromaticity coordinates

$$u_{\mathrm{F,10}} = \frac{4X_{\mathrm{F,10}}}{X_{\mathrm{F,10}} + 15Y_{\mathrm{F,10}} + 3Z_{\mathrm{F,10}}}$$

$$v_{\mathrm{F,10}} = \frac{6Y_{\mathrm{F,10}}}{X_{\mathrm{F,10}} + 15Y_{\mathrm{F,10}} + 3Z_{\mathrm{F,10}}}$$

$$u'_{\mathrm{F,10}} = u_{\mathrm{F,10}}$$

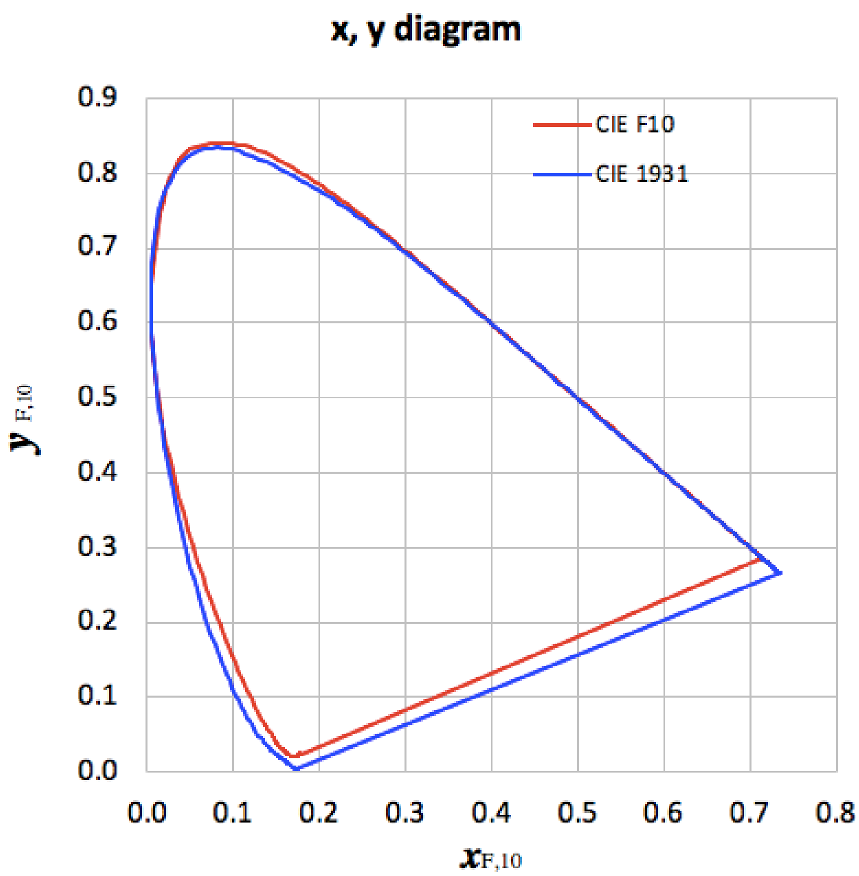
$$v'_{\mathrm{F,10}} = 1.5 \cdot v_{\mathrm{F,10}}$$

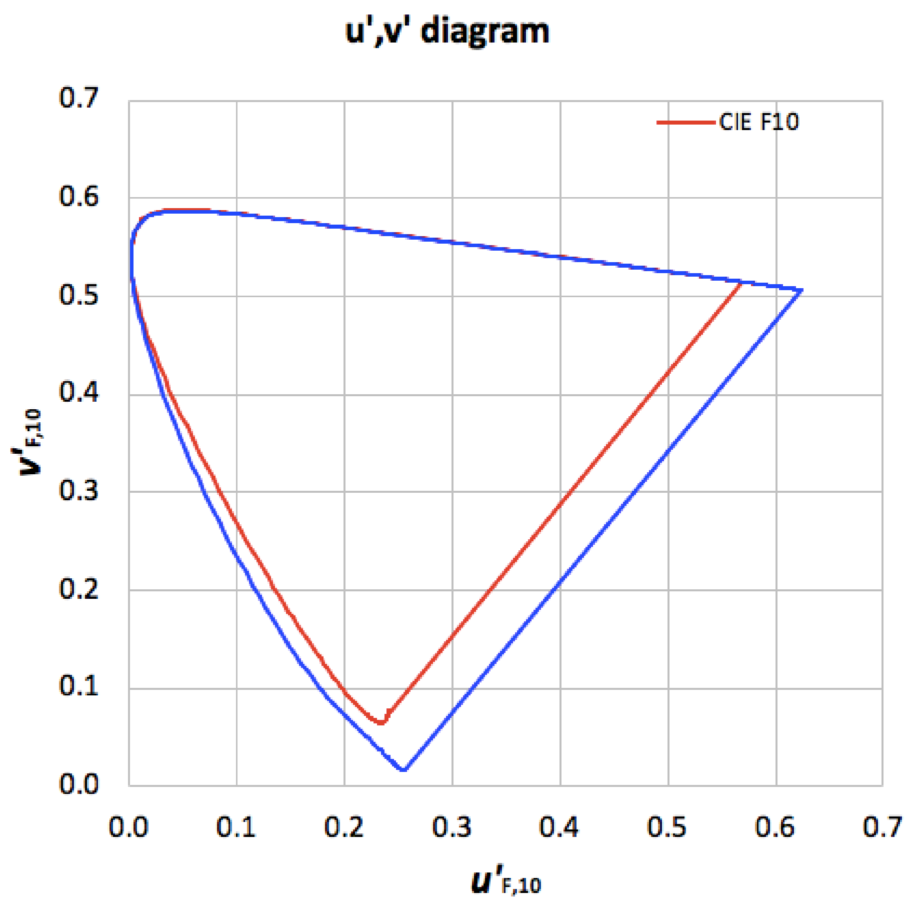
Correlated Color Temperature and Duv

$T_{\mathrm{cp,F10}}$ and $D_{\mathrm{uv,F10}}$

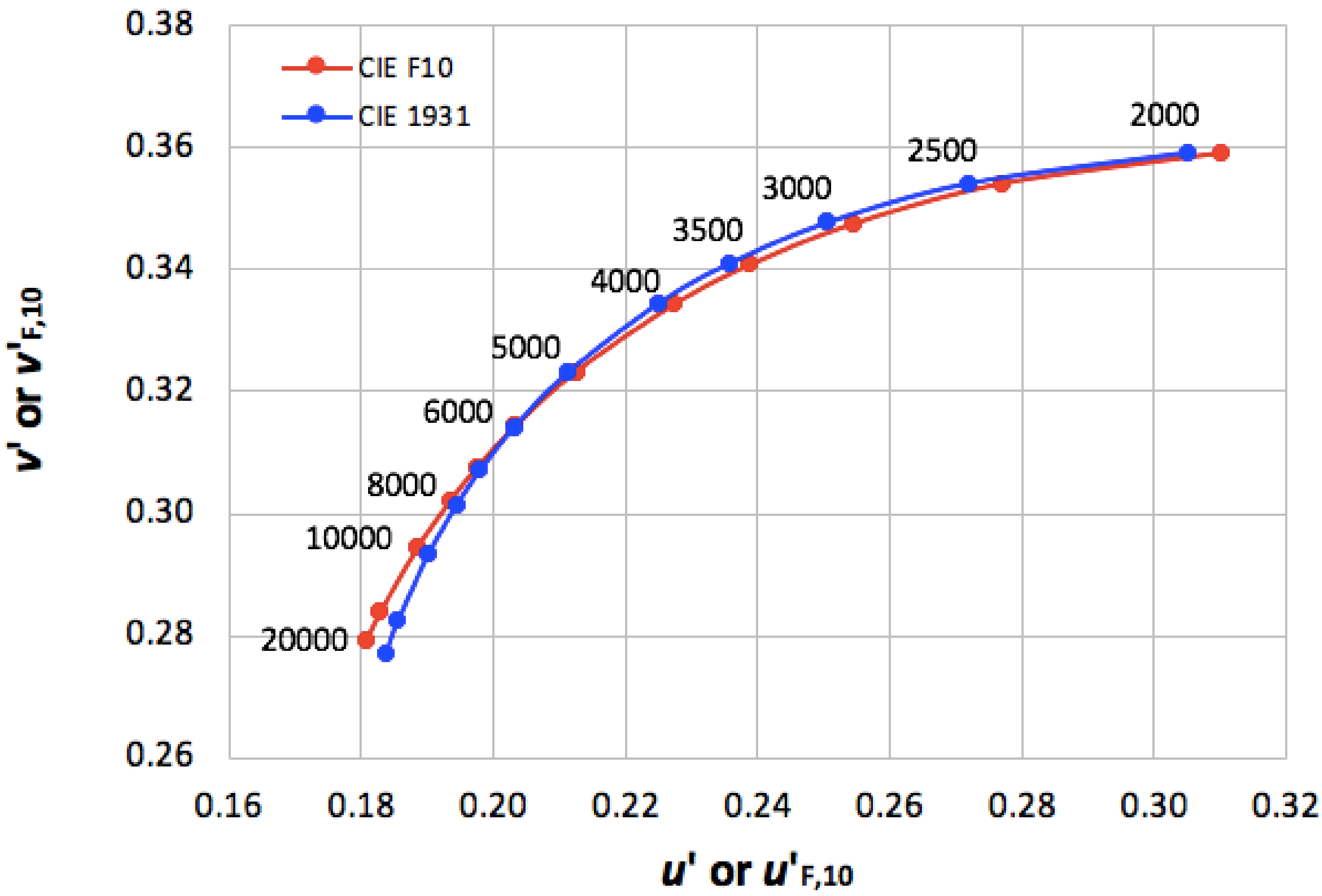
defined on the ($u_{\mathrm{F,10}}$, $v_{\mathrm{F,10}}$) coordinates.

Chromaticity Diagrams

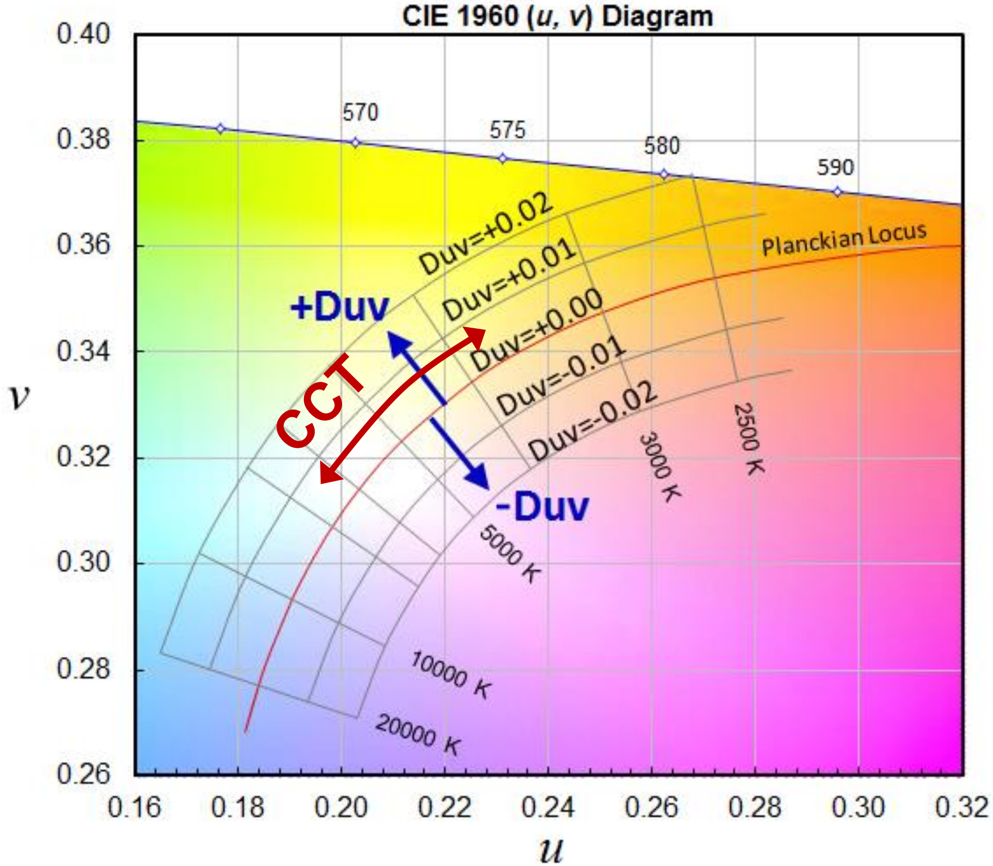




Planckian Locus on (u', v') diagram



CCT & Duv

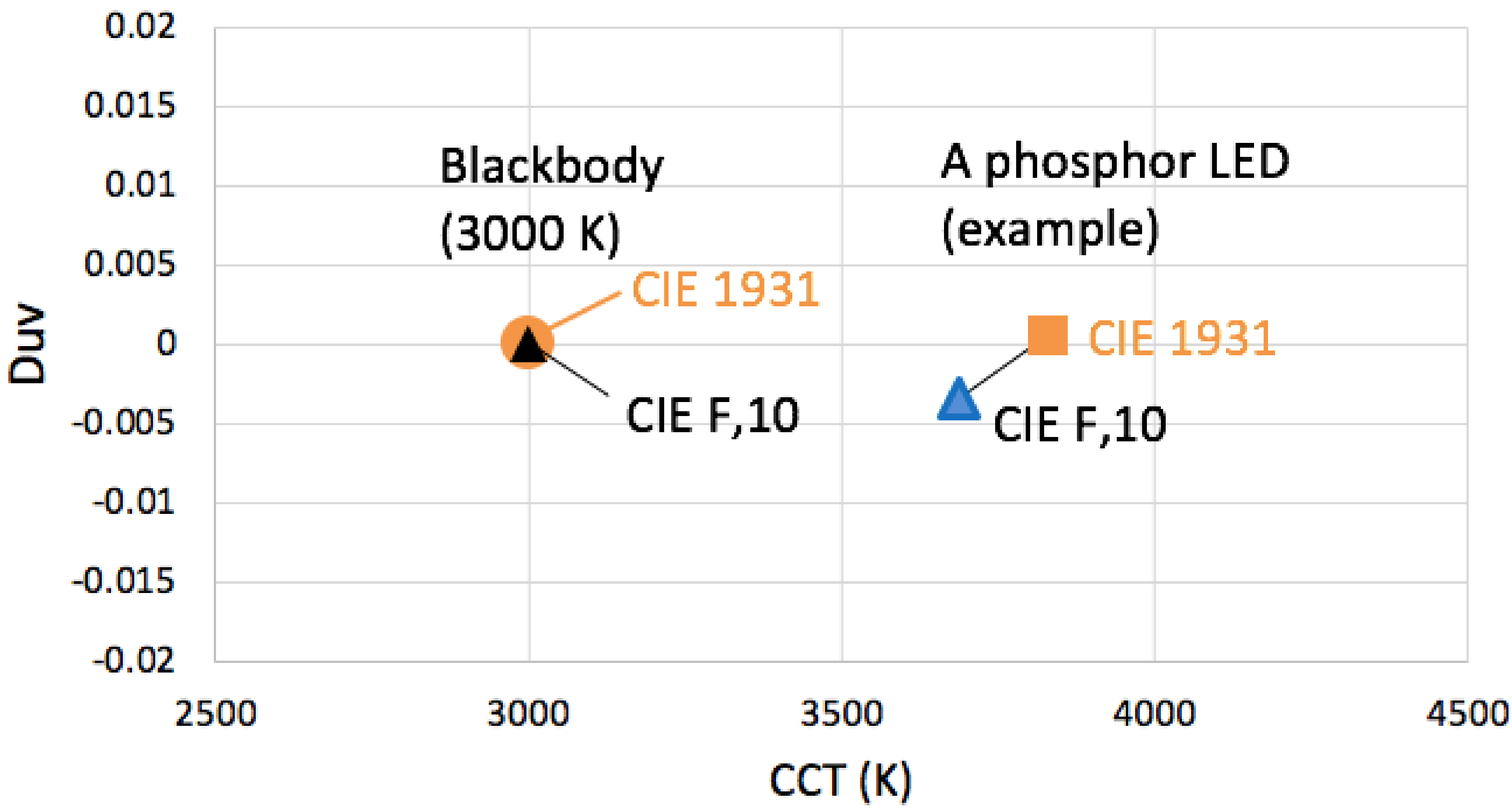


CCT: The temperature of blackbody whose chromaticity coordinate is closest to that of a given light source in 1960 (u,v) diagram.

Duv: Closest distance from the light source's chromaticity coordinate to Planckian locus on 1960 (u,v) diagram, with ± sign for above and below the Planckian locus.

CCT and Duv can be re-defined with CIE F,10 (symbol: $T_{cp,\mathrm{F},10}$ and $D_{\mathrm{uv,F},10}$) on the CIE 2015 $(u_{\mathrm{F},10}, v_{\mathrm{F},10})$ diagram.

Changes of CCT and Duv

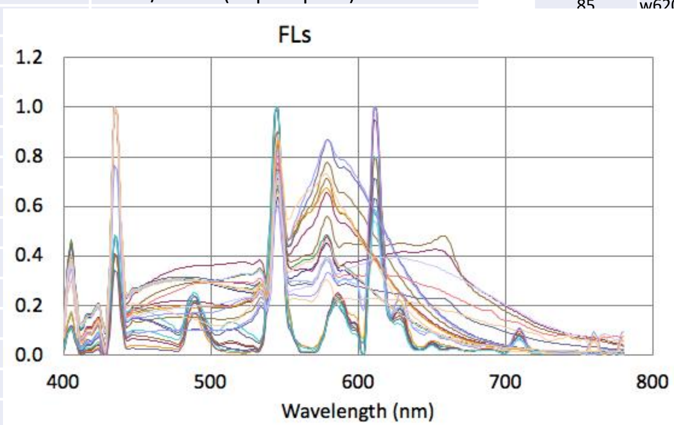


CCT and Duv of a blackbody do not change by definition.
CCT and Duv of a real light source will change with CMFs.

120 Light sources in CQS 9.0 spreadsheet

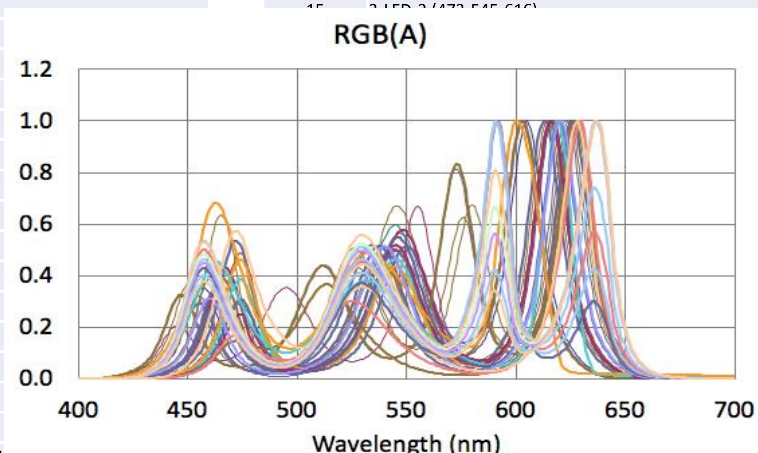
FL (33)

INDEX #	Name
4	Cool White FL
5	Daylight FL
6	Tri-phosphor FL
34	CIE F1
35	CIE F2*
36	CIE F3
37	CIE F4
38	CIE F5
39	CIE F6
40	CIE F7*
41	CIE F8
42	CIE F9
43	CIE F10
44	CIE F11*
45	CIE F12
49	F32T8/TL830 (Triphosphor)
50	F32T8/TL835 (Triphosphor)
77	Triphosphor model. Duv= +0.006
78	Triphosphor model. Duv= +0.01



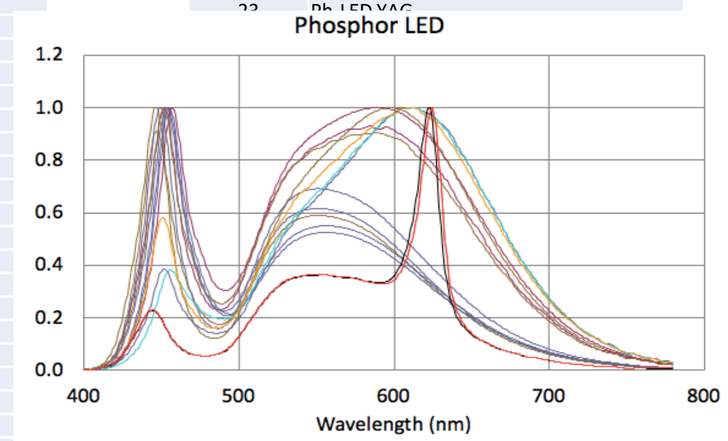
RGB(A) (47)

INDEX #	Name
14	3-LED-1 (457-540-605)
85	w620
	model (Ra=80) good color -464/546/620
	model (Ra=67) enhanced -460/540/620
	al RGB product (3000 K)
	al RGB product (5000 K)
	ak 3012 K, Ra 70 desat 4
	ak 3020 K, Ra 75, desat 3
	ak 3022 K, Ra 83, desat 2
	ak 3000 K, Ra 89, desat 1
	ak 3000 K, Ra 95, neutral
	ak 3000 K, Ra 89, Satu 1
	ak 3010 K, Ra 83, Satu 2
	ak 3000 K, Ra 75, Satu 3
	ak 3030 K, Ra 70, Satu 4
	ak 4050 K, Ra 70, desat 4
	ak 4045 K, Ra 76, desat 3
	ak 4030 K, Ra 83, desat 2
	peak 4020 K, Ra 89, desat 1
107	4 peak 4070 K, Ra 94, norma
108	4 peak 4045 K, Ra 89, Satu 1
109	4 peak 4060 K, Ra 83, Satu 2
110	4 peak 4080 K, Ra 76, Satu 3
111	4 peak 4090 K, Ra 70, Satu 4



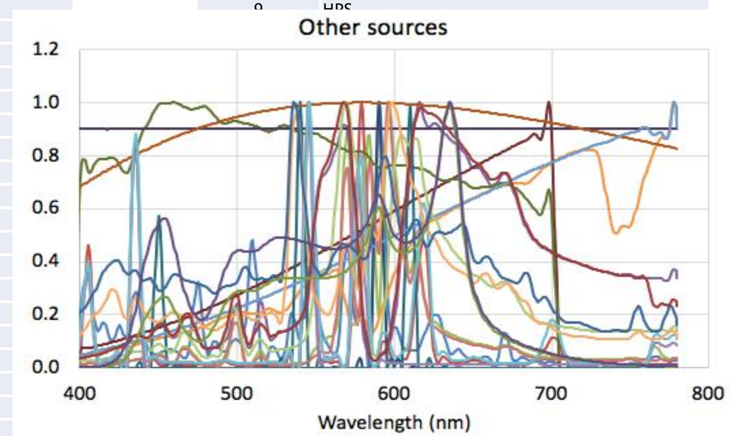
Phosphor LED (16)

INDEX #	Name



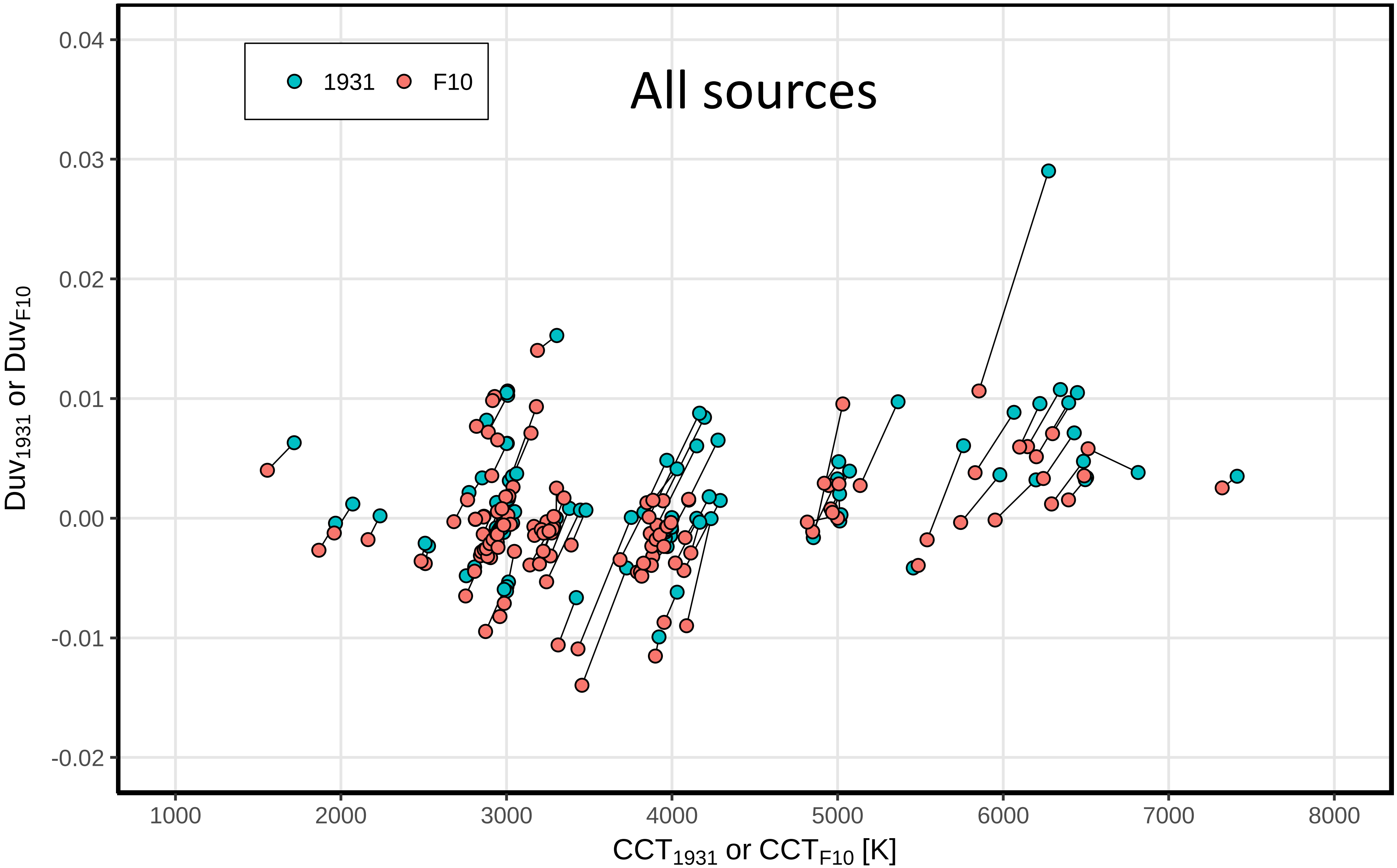
Other types (22)

7	Metal Halide
8	Mercury
102	Broad 4030 K, Ra 98, x ref (LED)



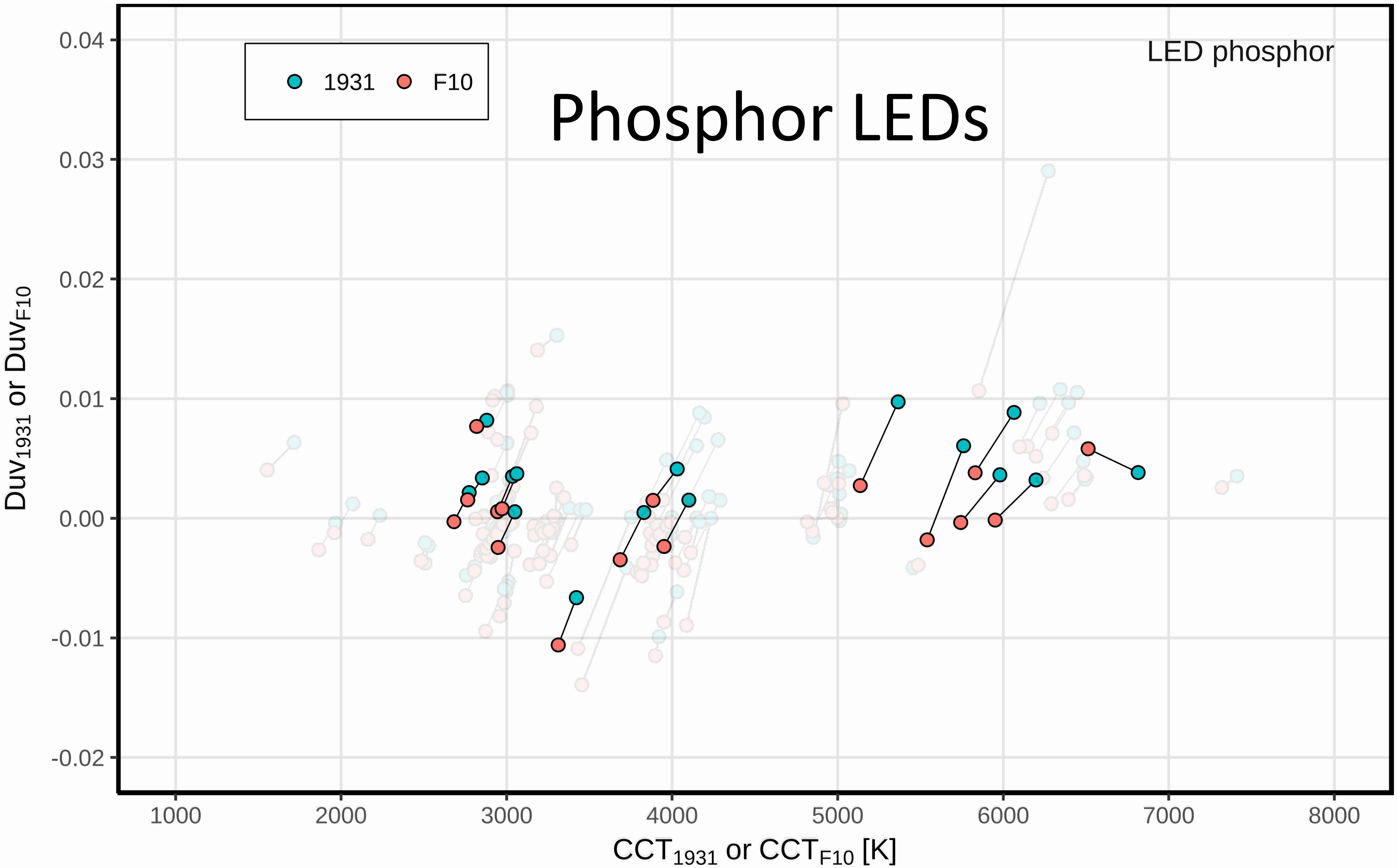
NIST

(CCT, Duv) plots

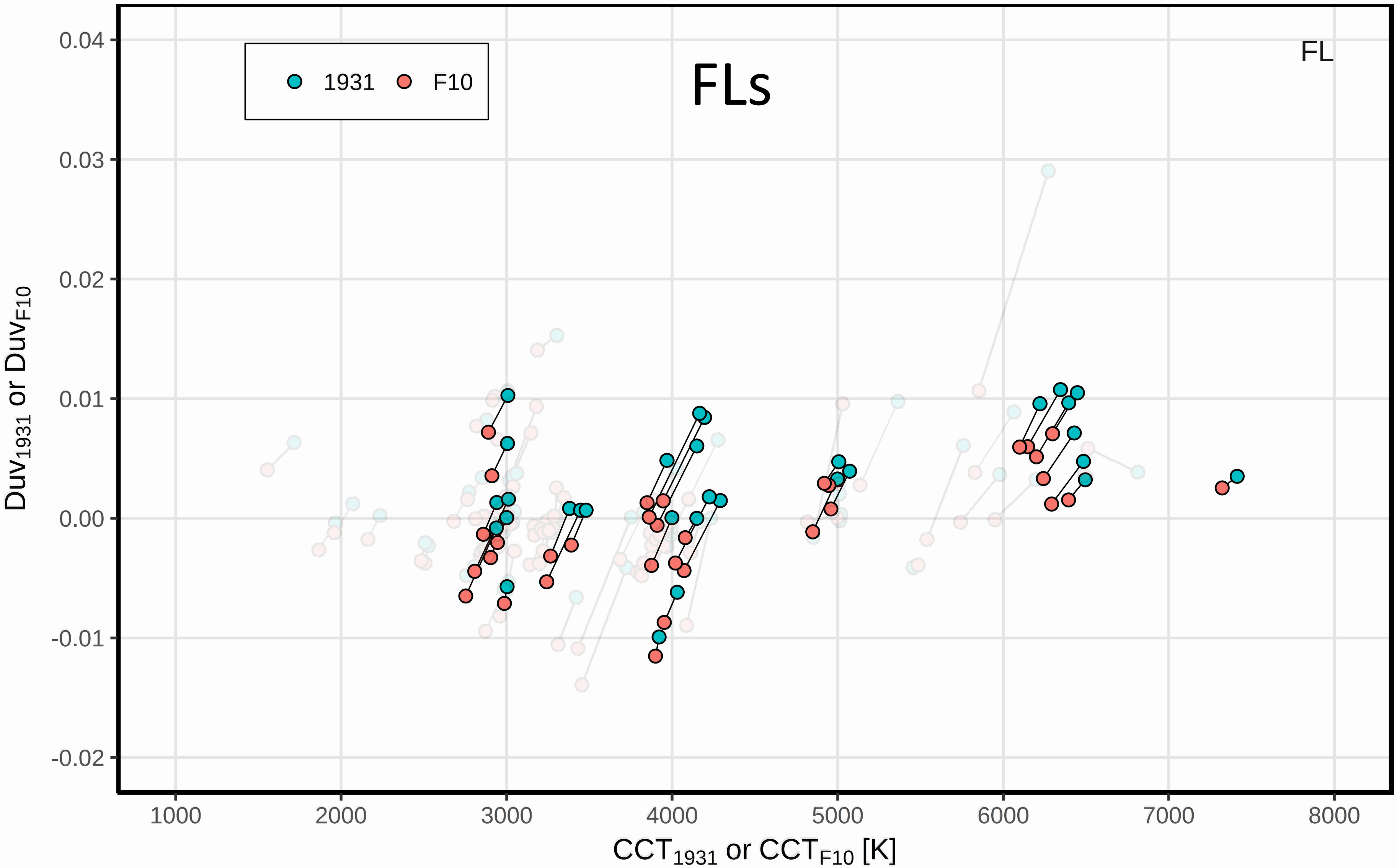


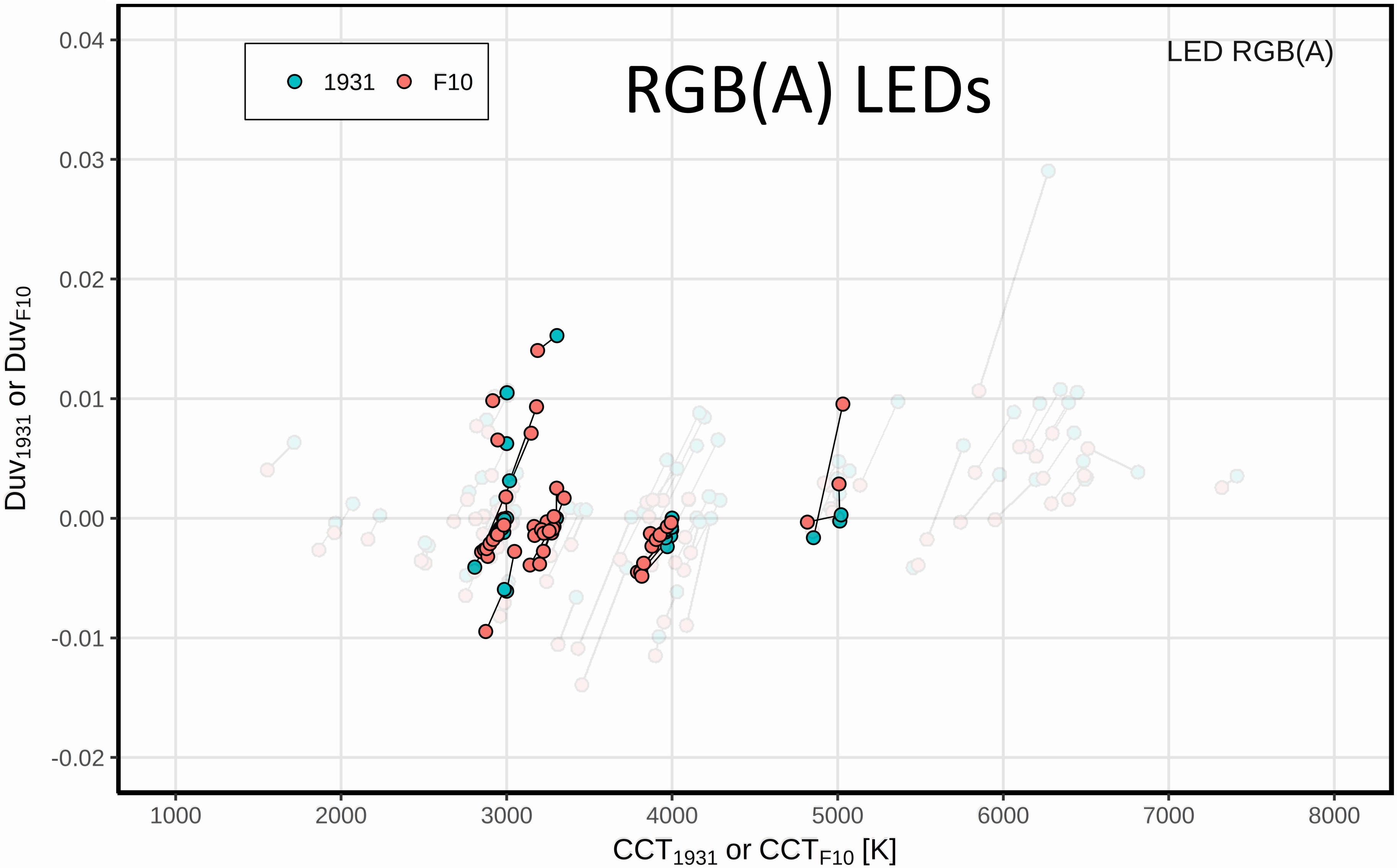
NIST

(CCT, Duv) plots

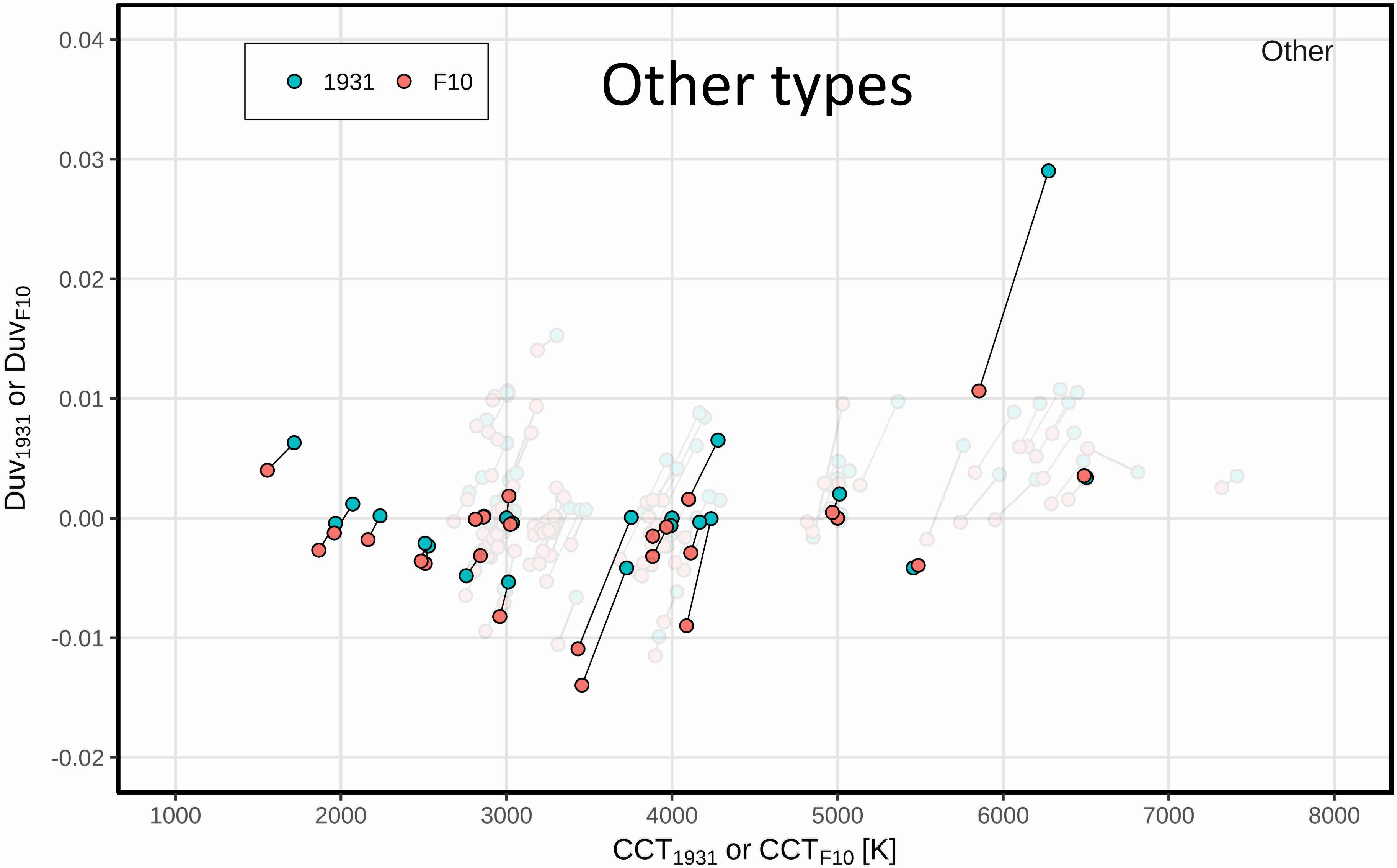


NIST


FLs
FL
1931
F10
0.04
0.03
0.02
0.01
0.00
-0.01
-0.02
1000
2000
3000
4000
5000
6000
7000
8000
Duv_{1931} or Duv_{F10}
CCT_{1931} or CCT_{F10} [K]

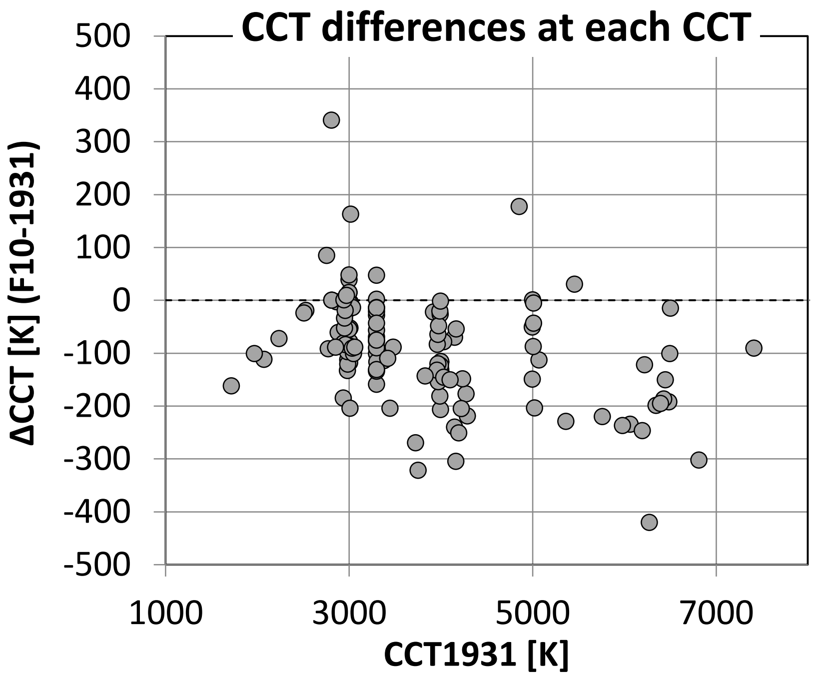

RGB(A) LEDs
LED RGB(A)
1931
F10
0.04
0.03
0.02
0.01
0.00
-0.01
-0.02
Duv1931 or DuvF10
1000
2000
3000
4000
5000
6000
7000
8000
CCT1931 or CCTF10 [K]

Other types

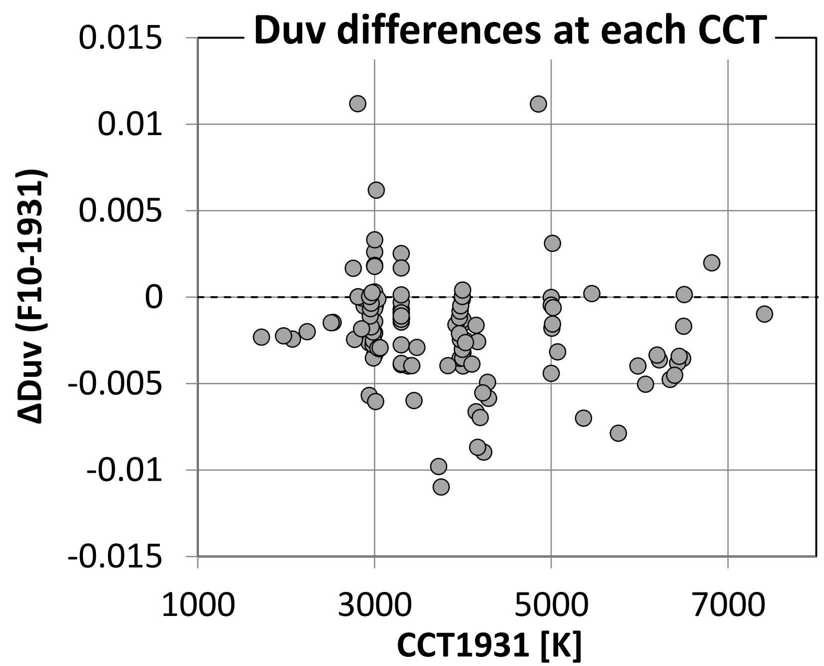


1931
F10
Other
0.04
0.03
0.02
0.01
0.00
-0.01
-0.02
Duv1931 or DuvF10
1000
2000
3000
4000
5000
6000
7000
8000
CCT1931 or CCTF10 [K]

All sources



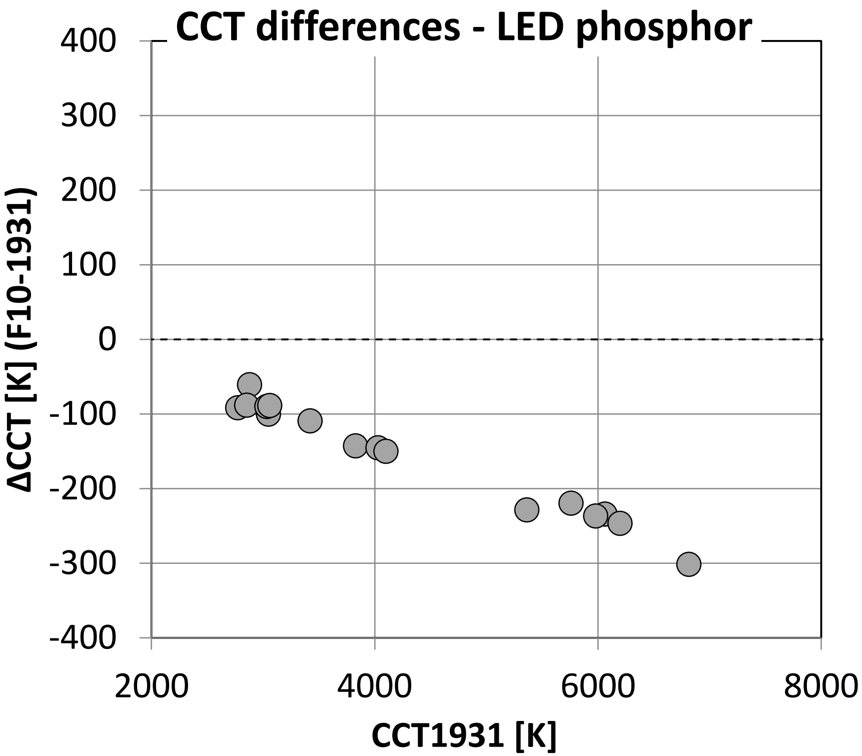
CCT differences at each CCT
500
400
300
200
100
0
-100
-200
-300
-400
-500
ΔCCT [K] (F10-1931)
1000
3000
5000
7000
CCT1931 [K]

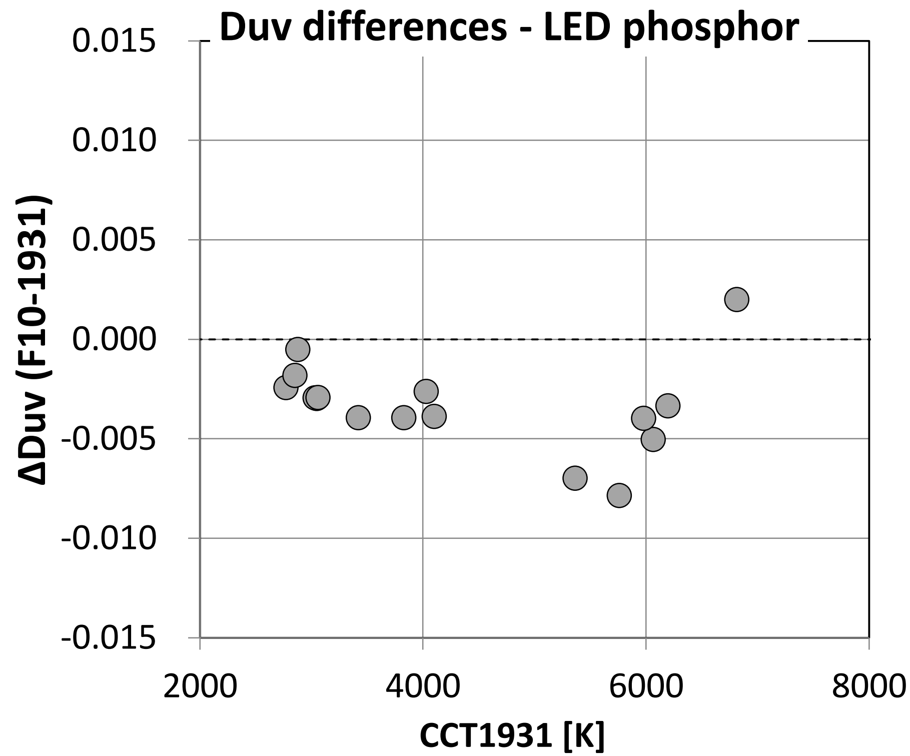


Duv differences at each CCT
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
ΔDuv (F10-1931)
1000
3000
5000
7000
CCT1931 [K]

<Breakdowns>

Phosphor LED





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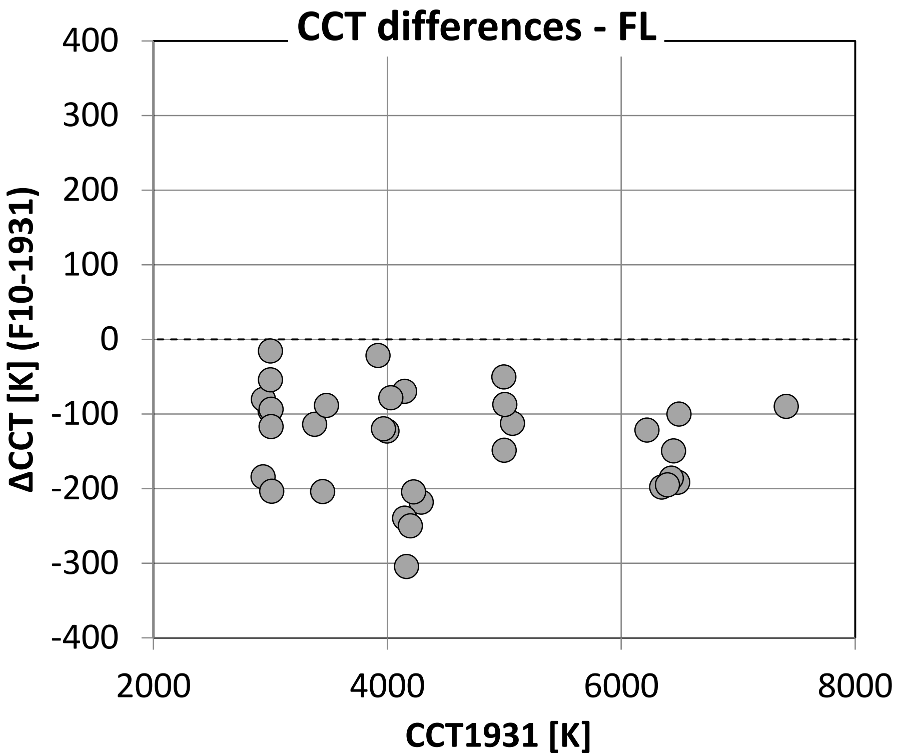
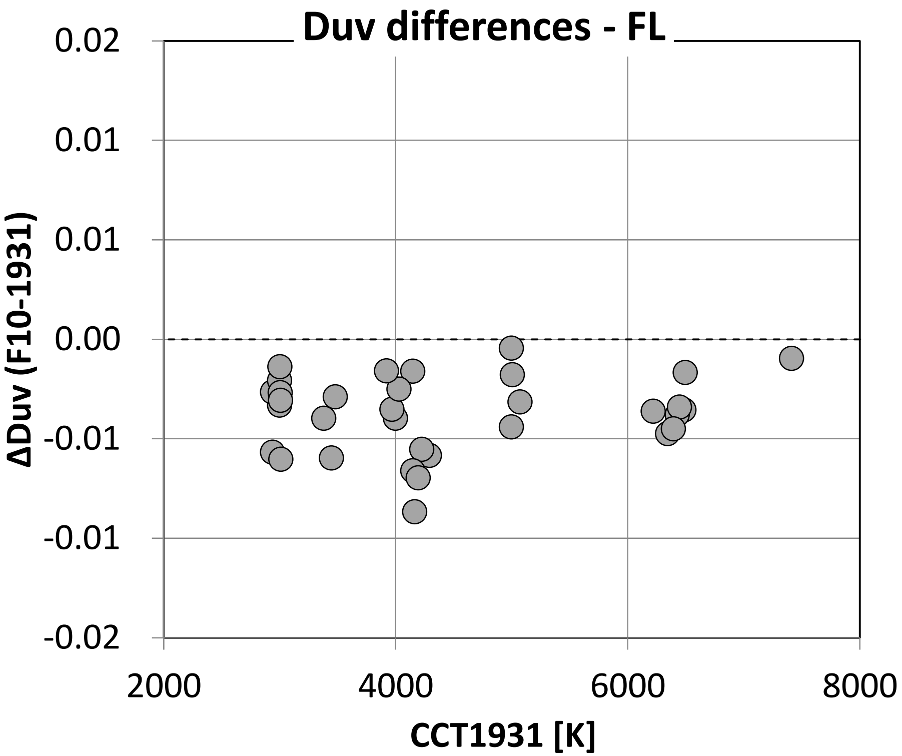
FLs

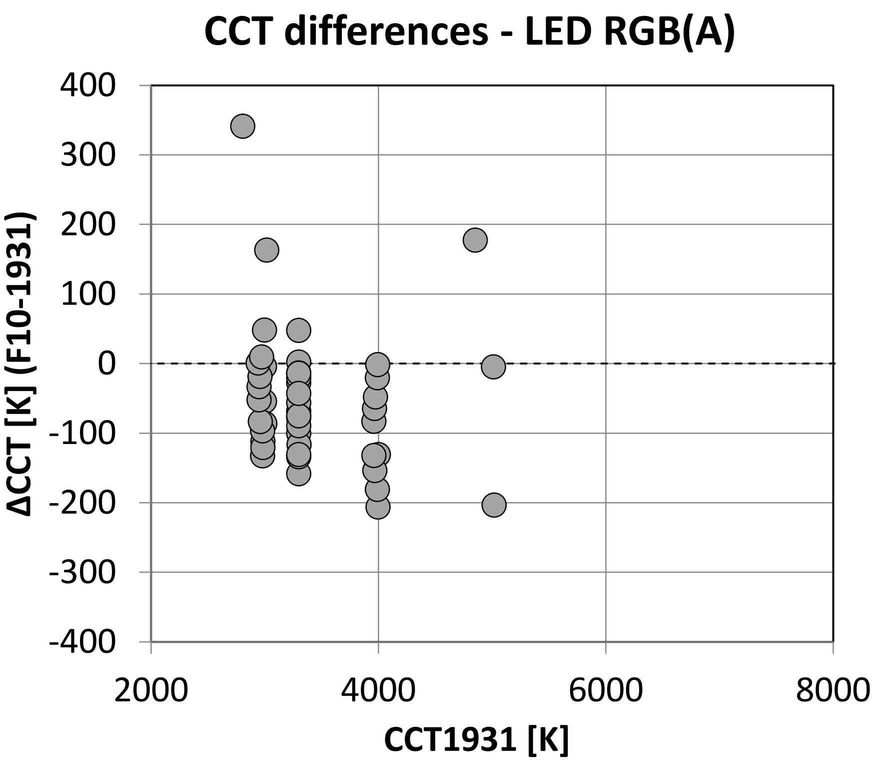


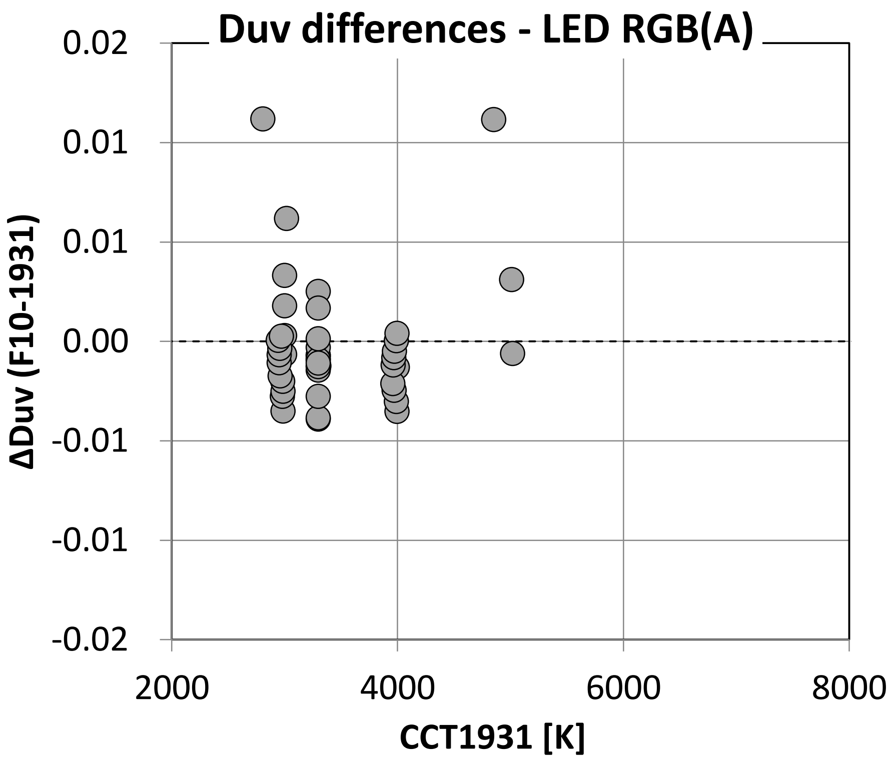


NIST

<Breakdowns>

RGB(A) LED





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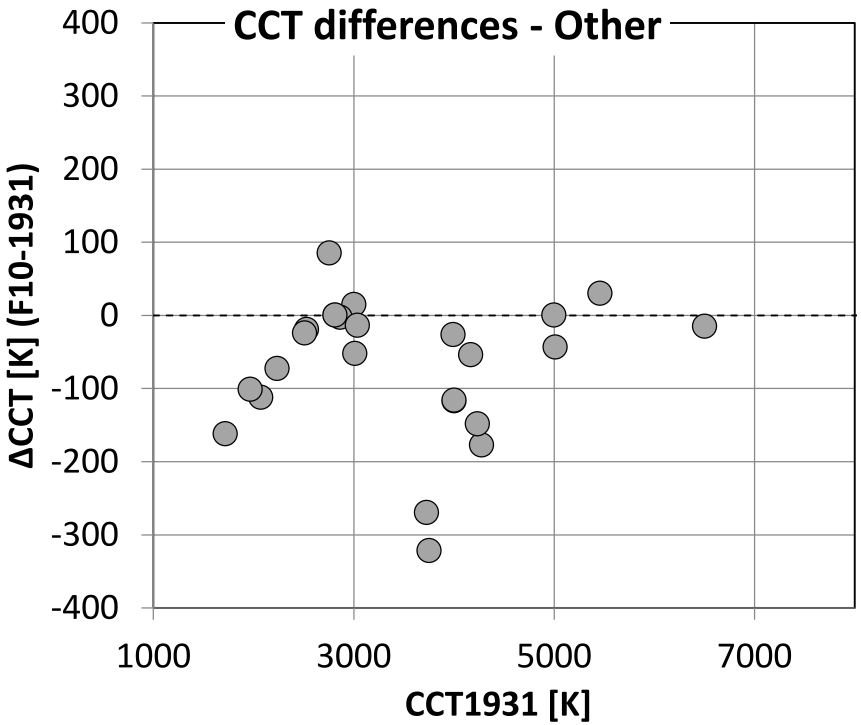
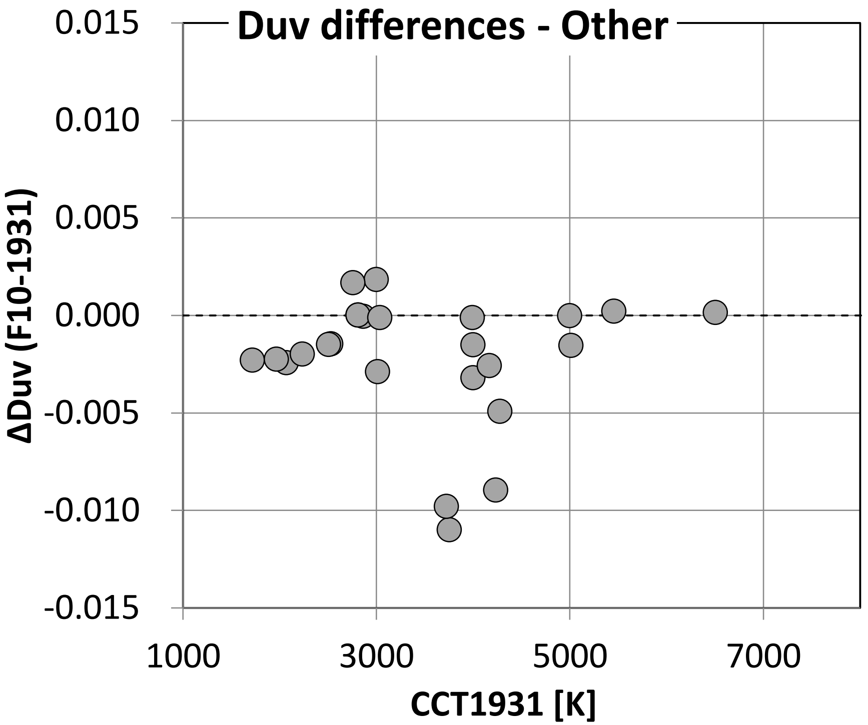
Other types





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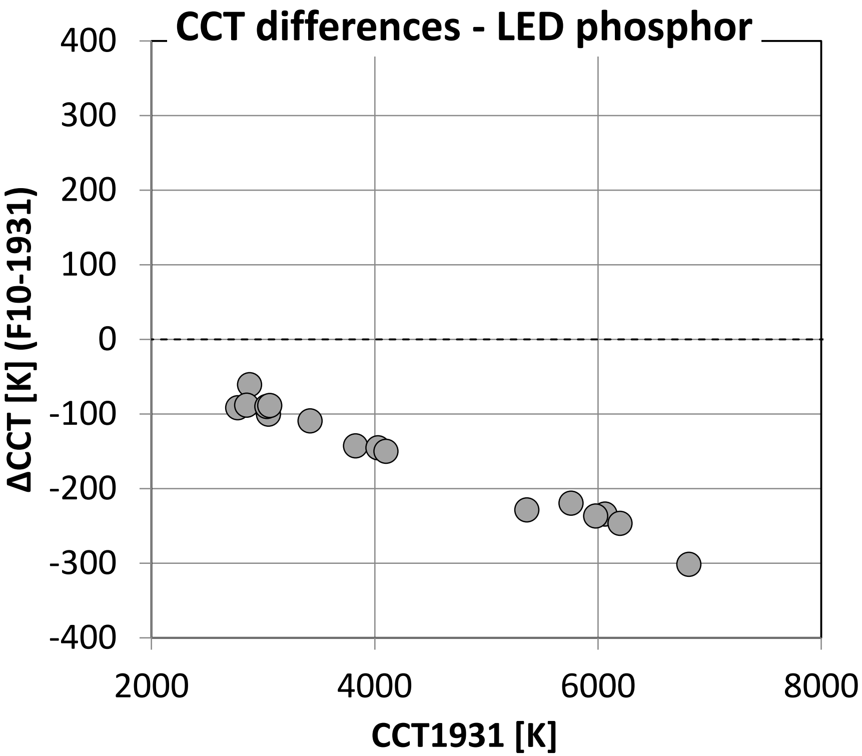
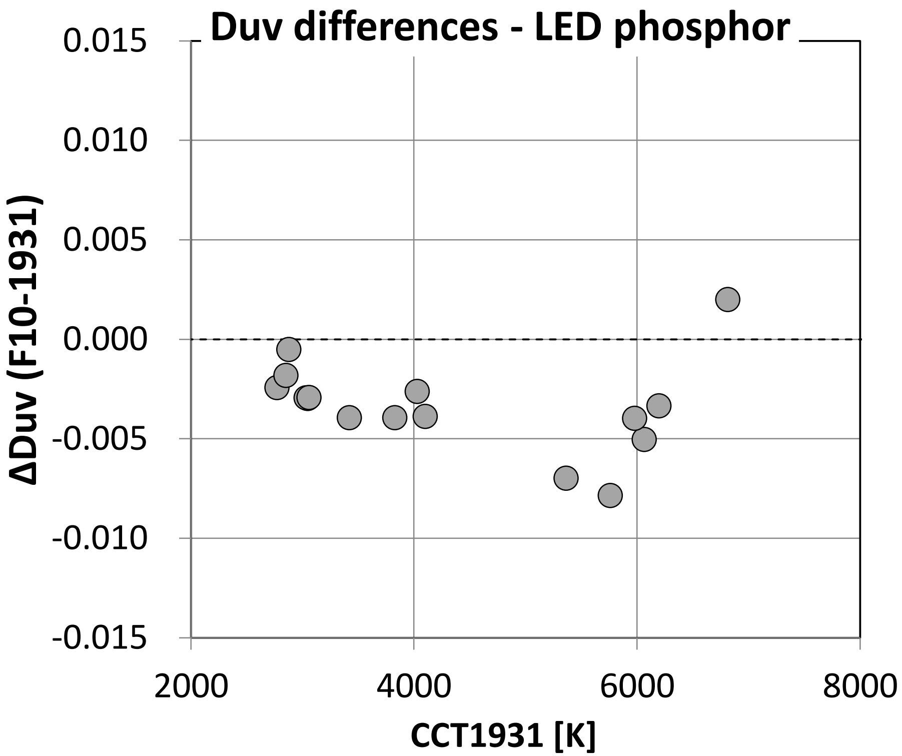
Phosphor LED





2018 Vision Experiment on CIE 1931 vs. CIE F,10

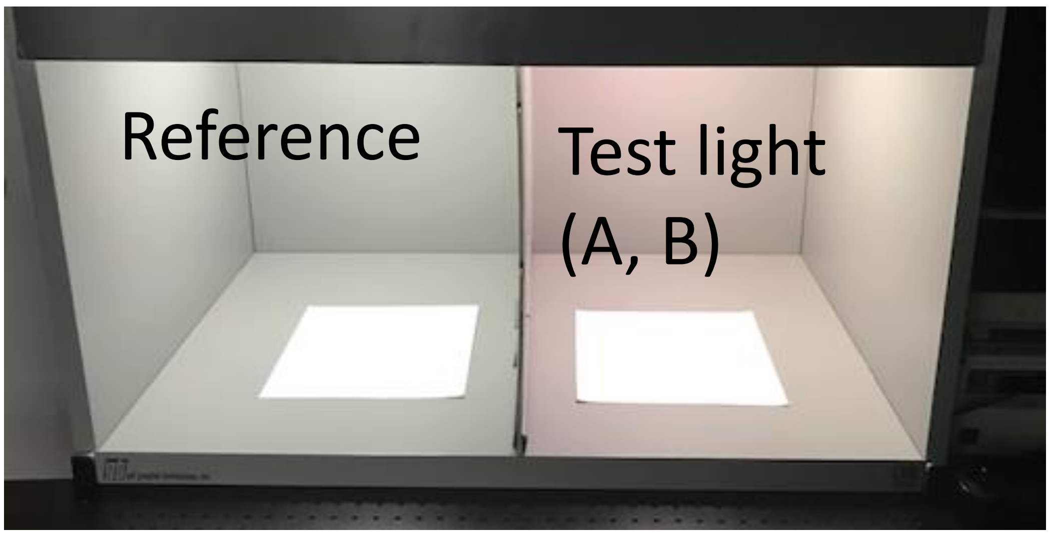
Subjects

- 22 subjects, 9 males, 13 females
- Age 18 to 63 (average 34)
- 16 white, 4 Asian, 2 dark skin

Method

<Left side>
Reference light (close to Planckian) at 3000 K and 5000 K, Duv=0.

16-ch Spectrally-Tunable Double-Booth at NIST

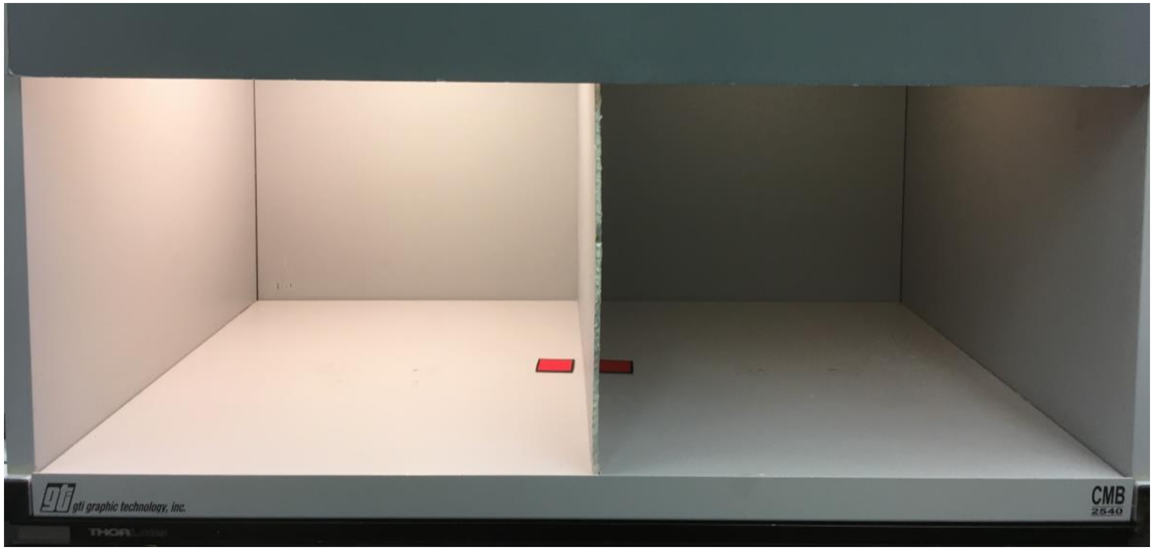


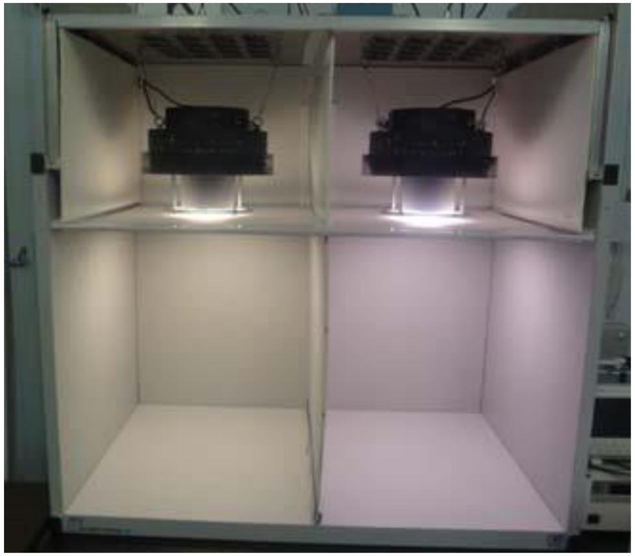
<Right side>
Test lights of 6 different SPDs presented as a pair of light (A and B).

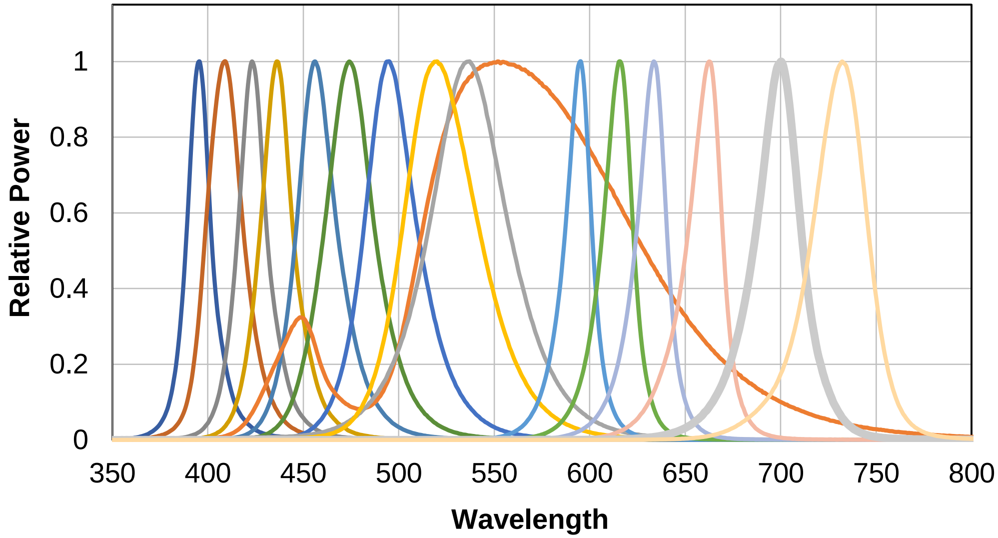
- A: CCT & Duv matched under CIE 1931
- B: CCT & Duv matched under CIE F,10
- Illuminance 250 lx.

Each subject compared the colors of white sheets for pair of test light (A or B), and answered which light appeared closer color to the Reference, or ”difficult”.

Spectrally-Tunable Double-Booth

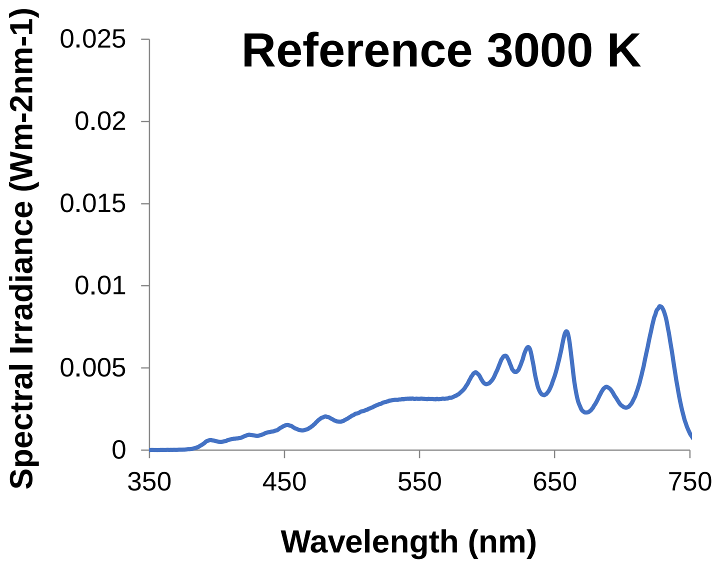


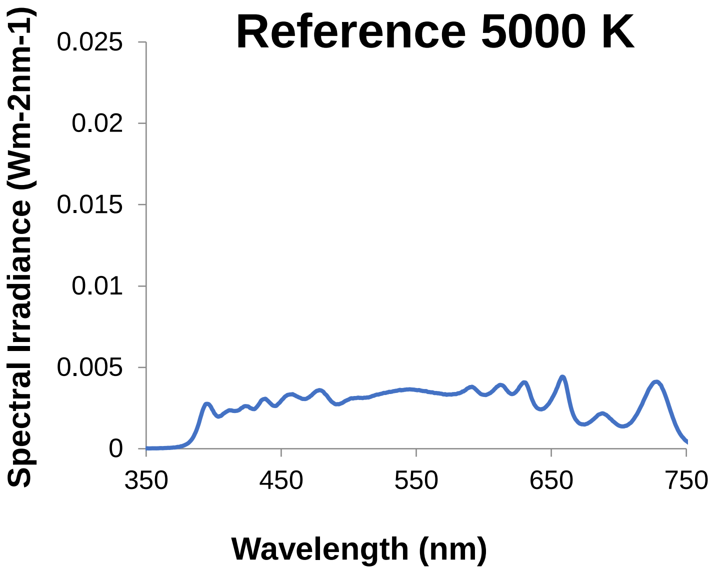


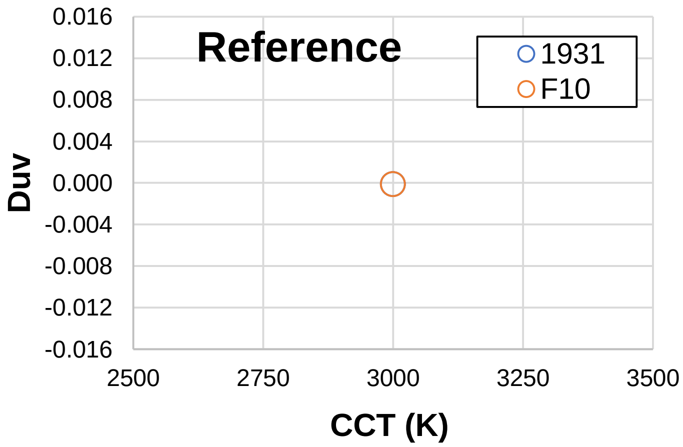


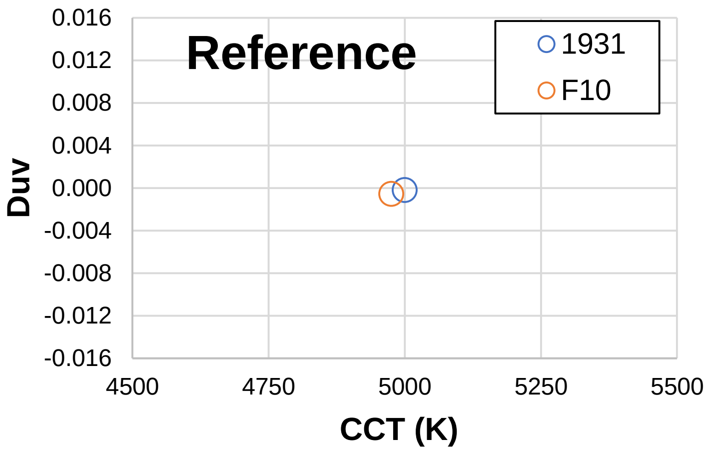
NIST

Reference Light

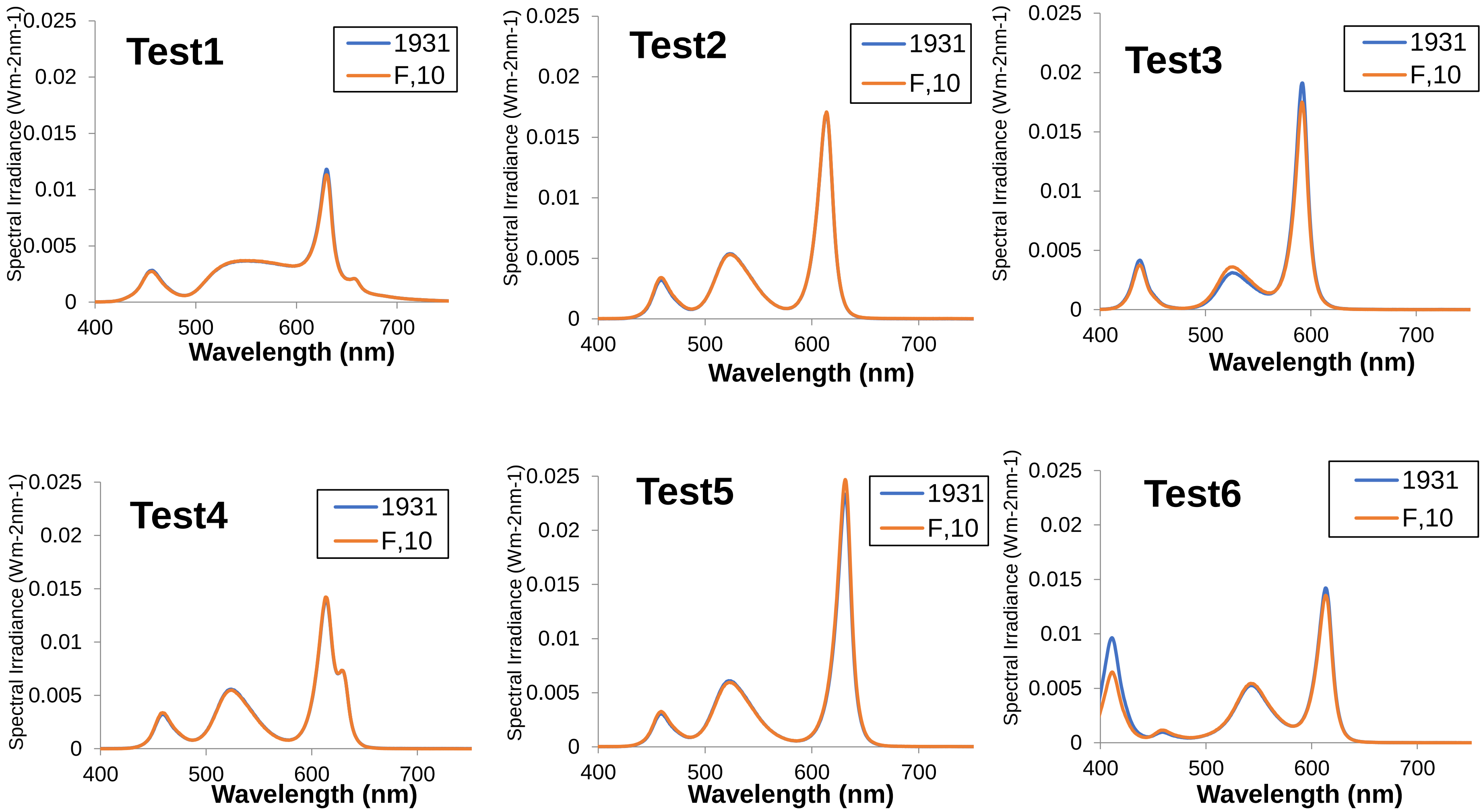




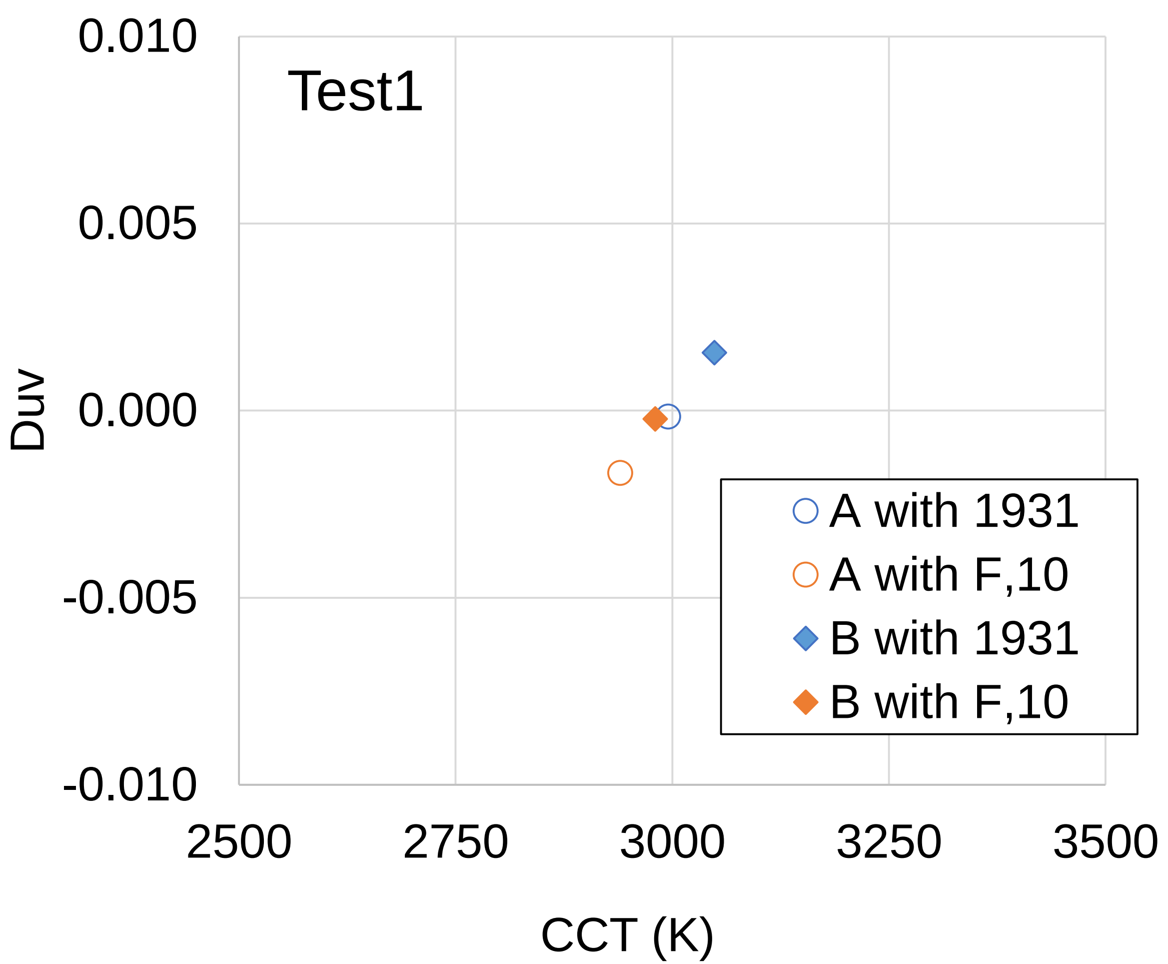




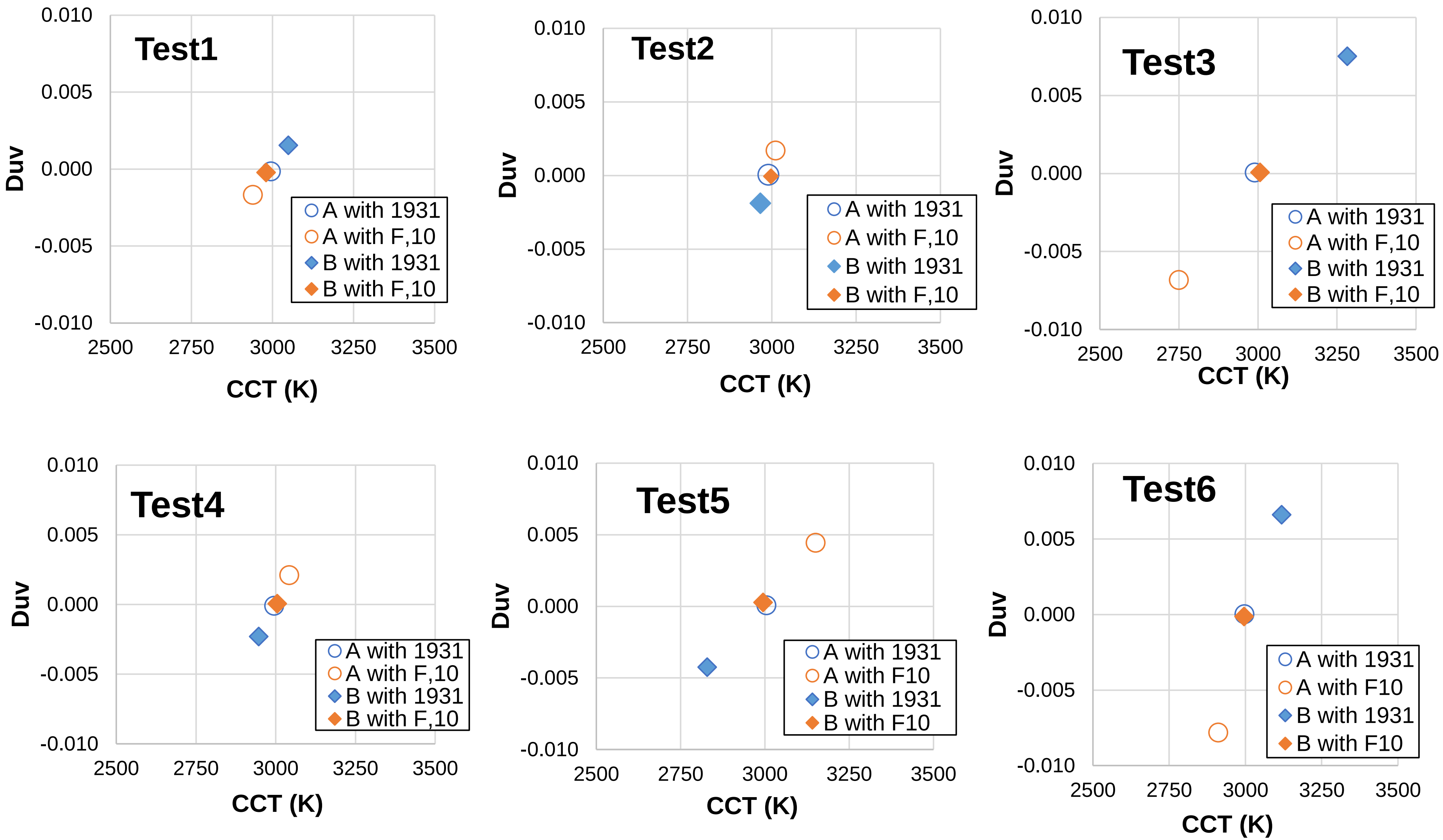
Test Lights SPD (3000 K)



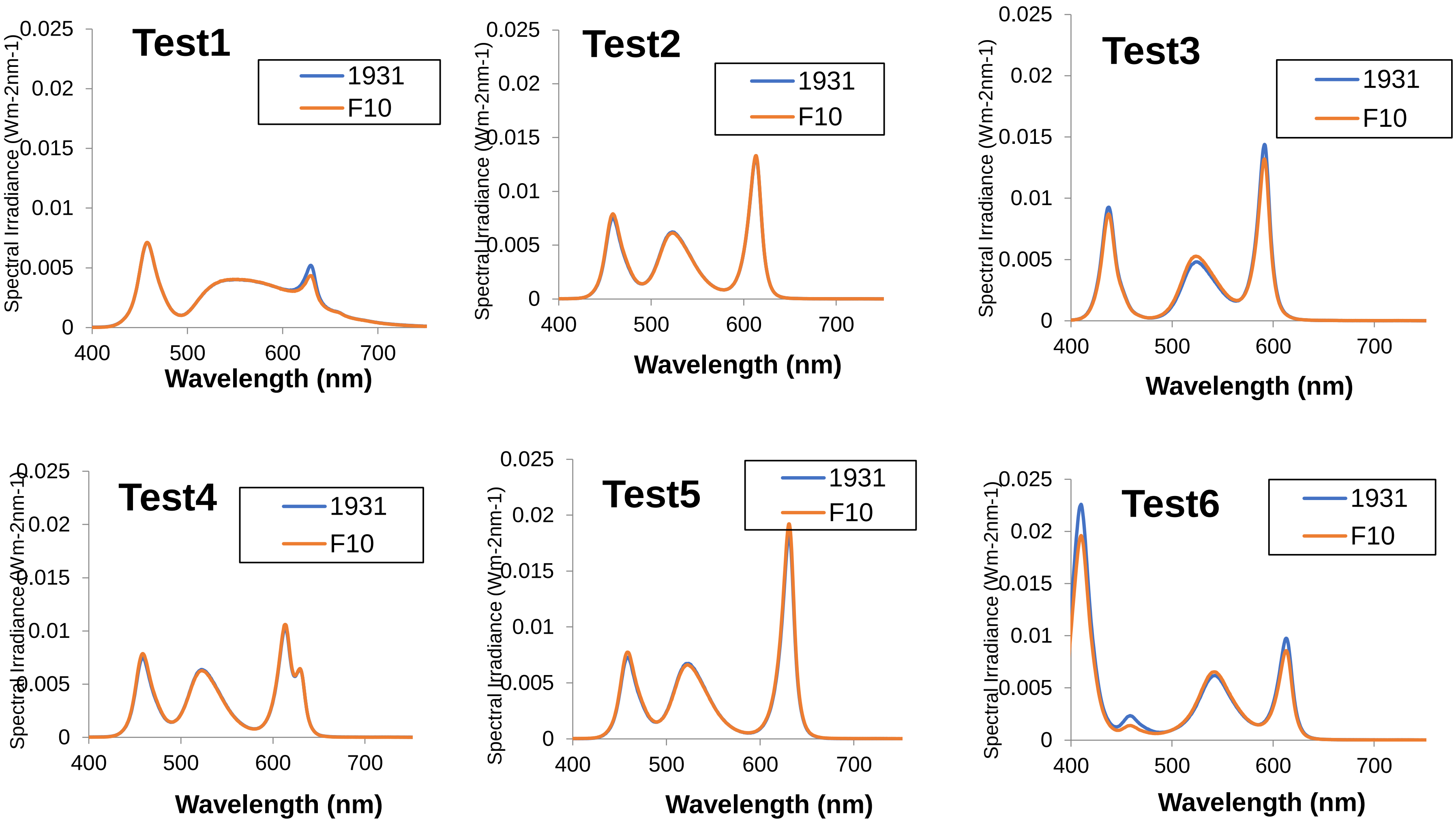
CCT & Duv plot (Test 1)



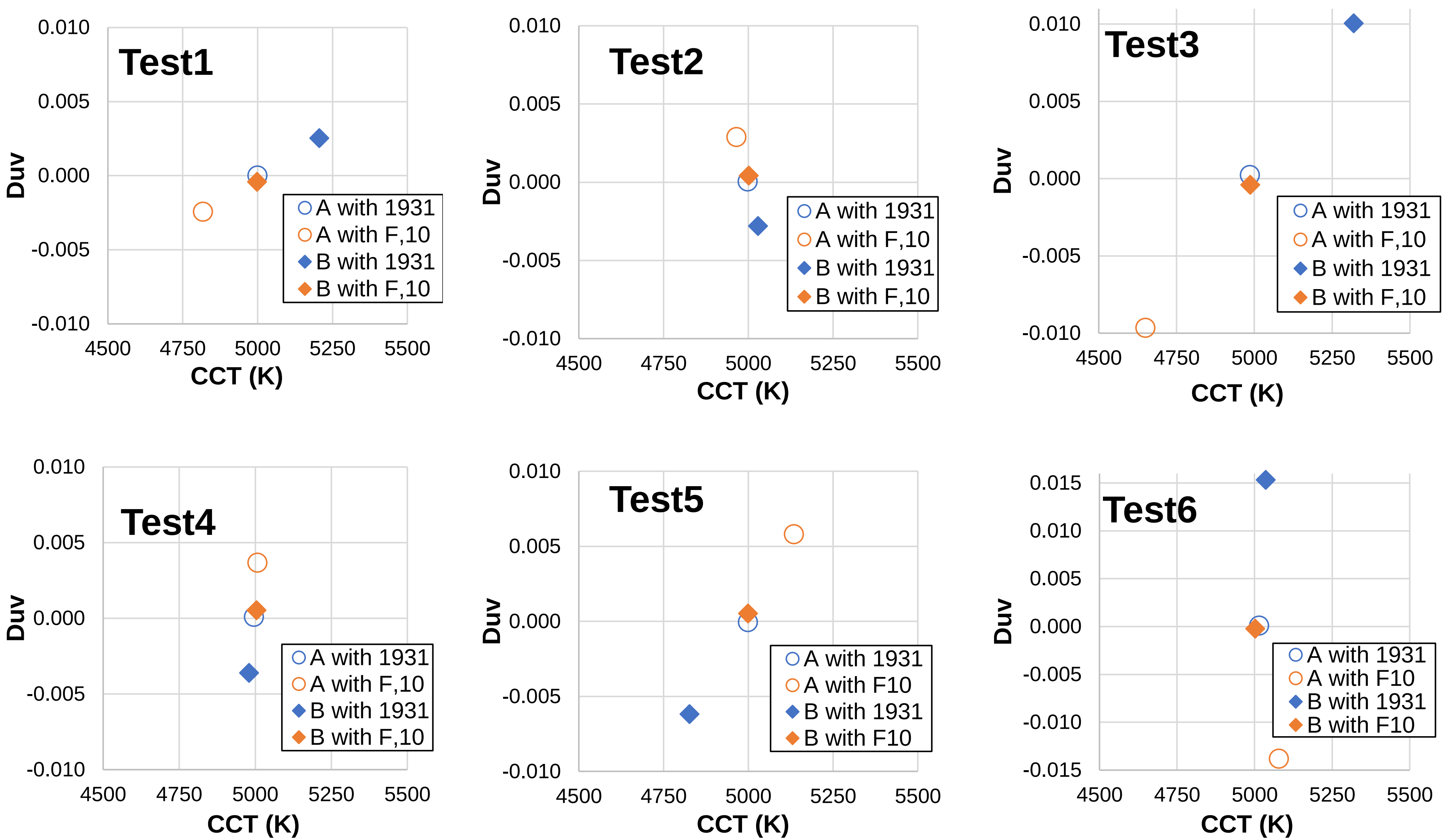
Test Lights CCT & Duv (3000 K)



Test Lights SPD (5000 K)



Test Lights CCT & Duv (5000 K)



Experiment Procedures

Experiment scene

Adaptation at 5000 K for 5 min.

Practice session (during adaptation):

- Ishihara test
- instructions
- practice.

Session 1 6 pairs of light at 5000 K.

Session 2 Repeat above

Adaptation at 3000 K for 2 min.

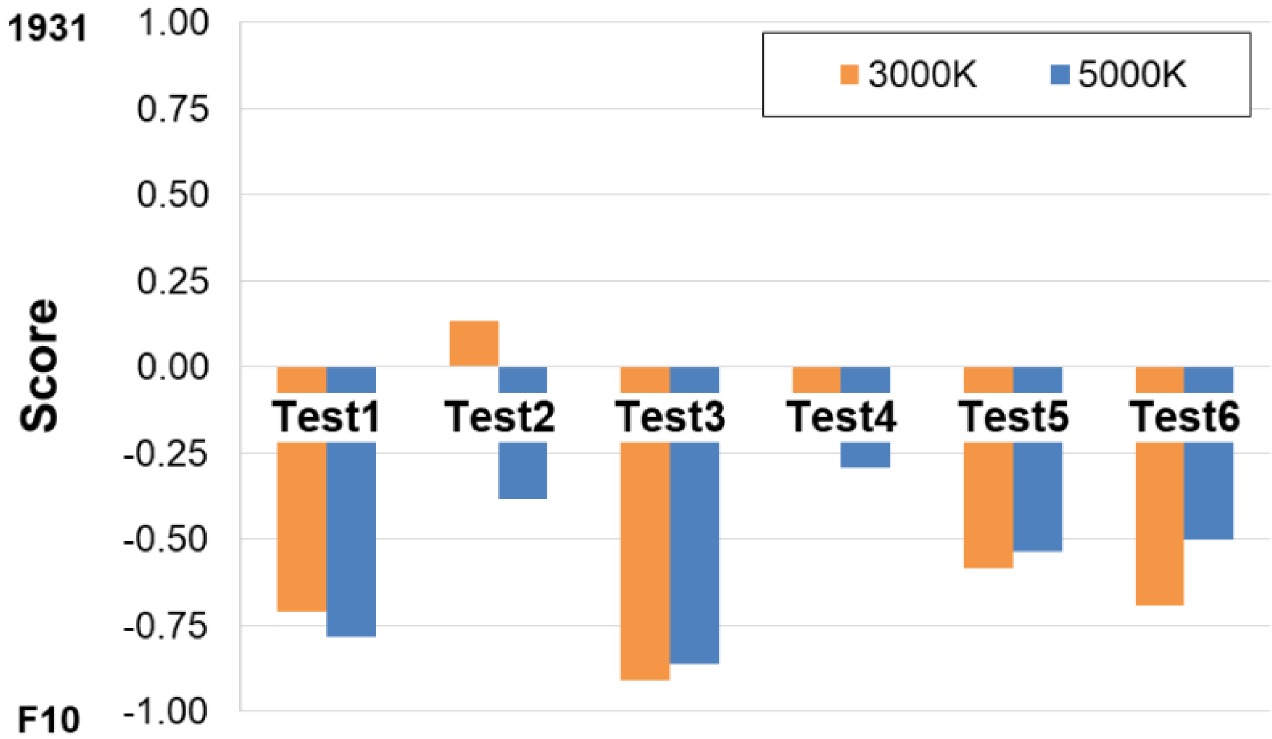
Session 3 6 pairs of light at 3000 K.

Session 4 Repeat above

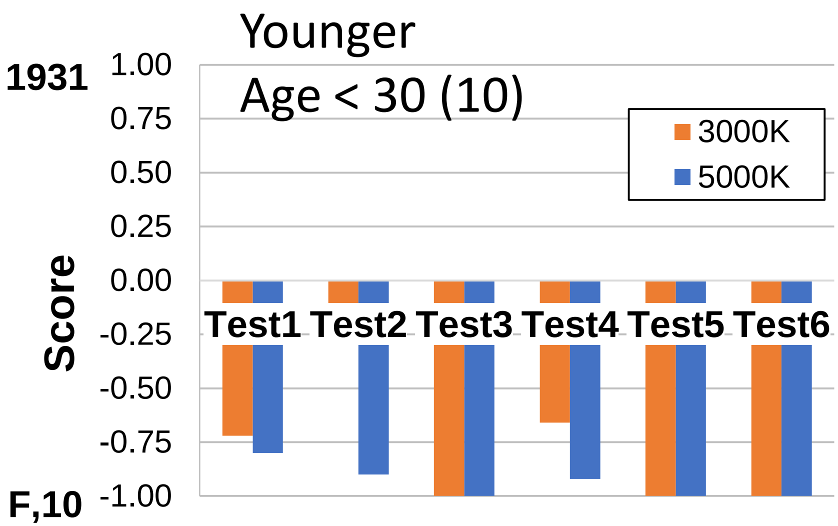
Total experiment time ~ 30 min / subject.

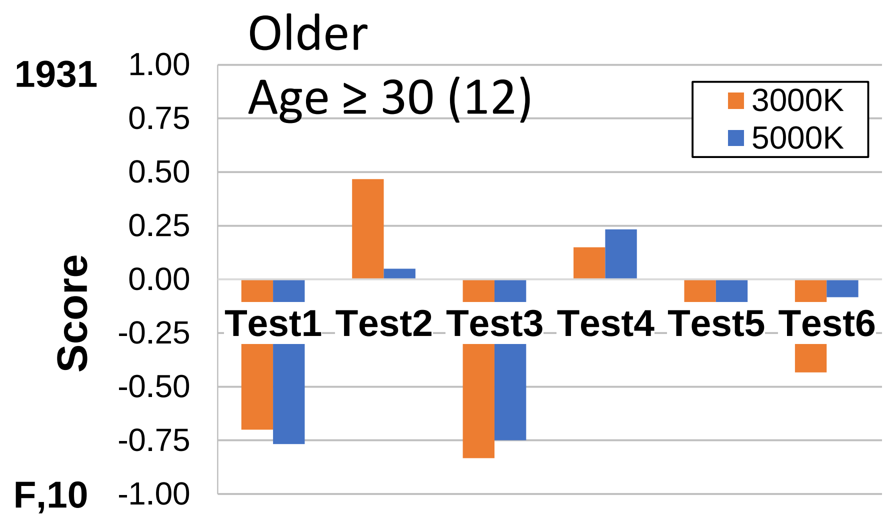
Results (average for all 22 subjects)

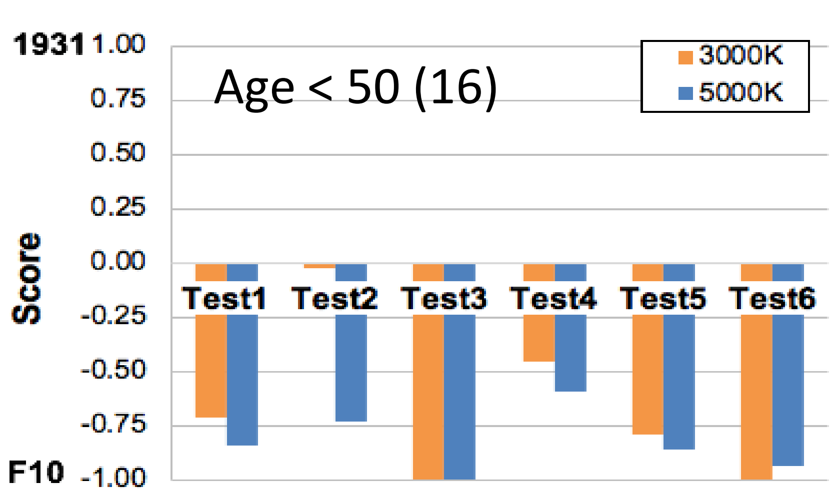
Score for each subject = 1.0 for answer “A”, -1.0 for answer “B”, 0 for “difficult”

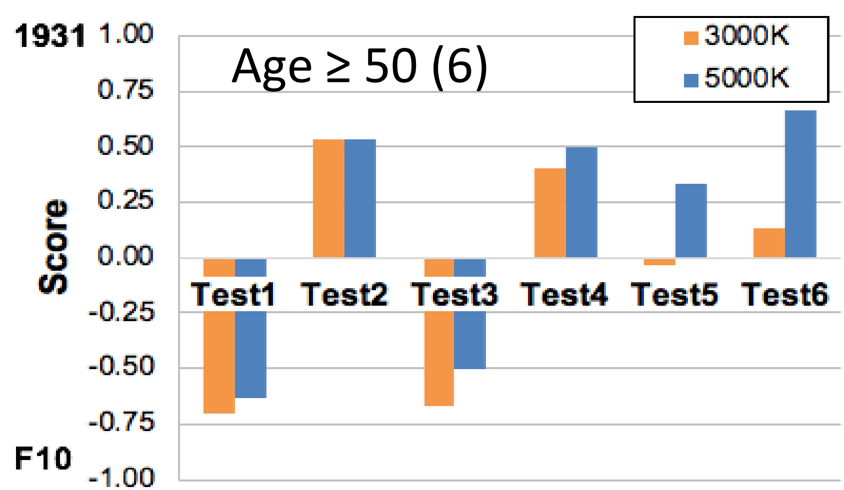


Results (Age Groups)









Conclusions

- if the CMFs are changed to CIE F,10, the values of CCT and Duv of lighting products would change significantly. (All existing product specifications on CCT and/or Duv (e.g., ANSI C78.377) would have to be re-evaluated and revised.)
- This vision experiment showed that CIE F,10 works better overall, but not necessarily better for older age groups.
- CIE F,10 works better for typical phosphor LEDs, but may not work well for some other types of spectrum.
- It is premature to implement CIE 2015 10° CMFs to lighting applications. Further study is needed on the effect of age (some information available in CIE 170-1) and the impact on product specifications and lighting experience.

THANK YOU FOR YOUR ATTENTION

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