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Workshop on the Future of the Candela

4 June 2024

BIPM, Sèvres, France

Adopt Cone Fundamentals to the K_{cd} definition

Yoshi Ohno

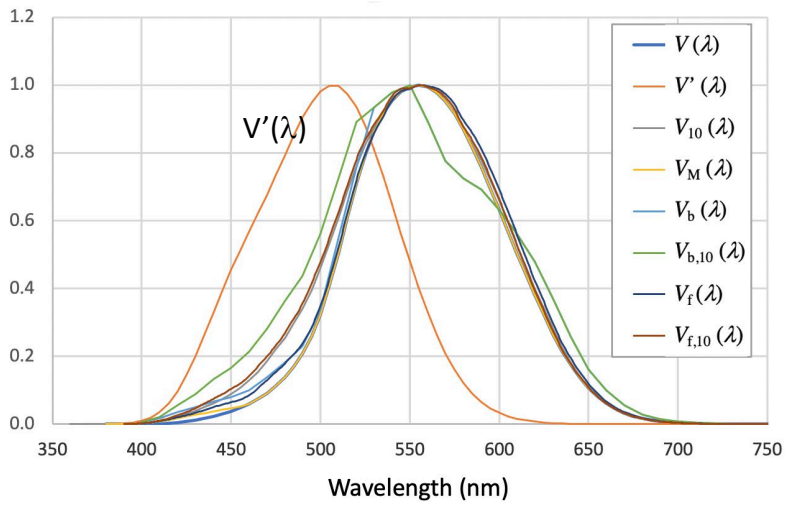
National Institute of Standards and Technology

Brief history of V(λ) since 1924

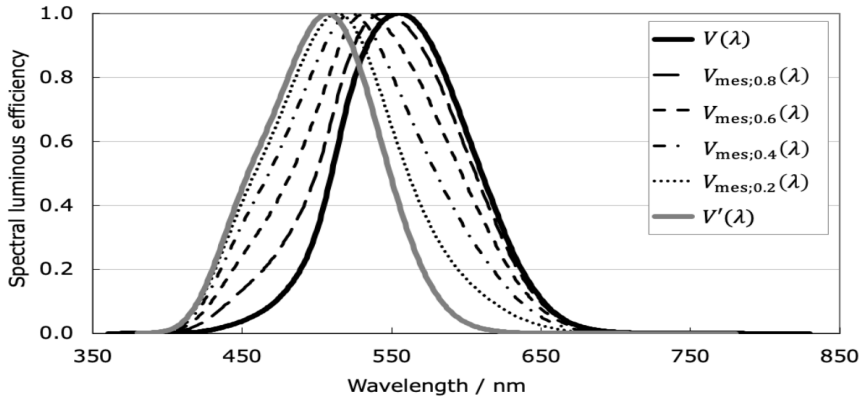
Published by CIE, CIPM

1924 V(λ) for photopic vision, 2° FOV (≥ 5 cd/m²)
(adopted by CIPM in 1933)
1951 $V_M(\lambda)$ Judd correction (CIE 86-1990)
1951 V'(λ) for scotopic vision (≤ 0.005 cm/m²)
1964 $V_{10}(\lambda)$ for 10° FOV
1983 V(λ) and V'(λ) adopted by CIPM in *Principles Governing Photometry, BIPM Monographie*
1988 $V_b(\lambda)$ for brightness matching (2°,10°) (CIE 75)
2010 $V_{mes,m}(\lambda)$ for mesopic vision (CIE 191, ISO/CIE 23539:2023)
2015 $V_F(\lambda)$, $V_{F,10}(\lambda)$ based on cone-fundamentals (CIE 170-2)
2019 V(λ), V'(λ), $V_{10}(\lambda)$, $V_{mes,m}(\lambda)$ adopted by CIPM in *Principles Governing Photometry*, 2nd ed. (Rapport BIPM 2019/05)

1924 V(λ) is the default, used for specifications of all lighting products, displays, …



Mesopic luminous efficacy function



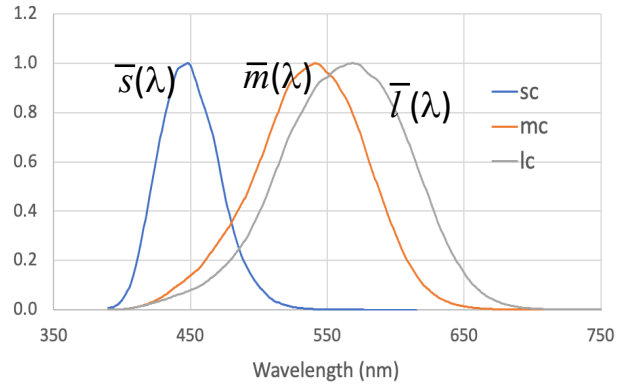
CIE 170-1:2006 and CIE 170-2:2015

ISBN 3 901 906 46 0

CIE 170-1

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

TECHNICAL REPORT



FUNDAMENTAL CHROMATICITY DIAGRAM WITH PHYSIOLOGICAL AXES – PART 1

CIE 170-1:2006

UDC: 612.84 535.66 Descriptor: Physiological optics, vision Colorimetry

- Cone fundamentals for the 2° Observers
- Cone fundamentals for the 10° Observers
- Field size and Age dependent observer

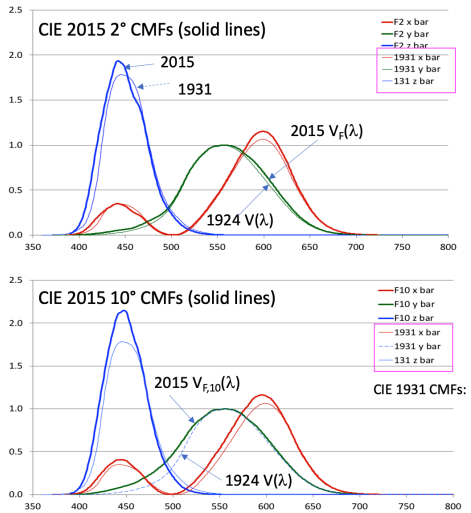
ISBN 978-3-902842-06-0

CIE 170-2

cie
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

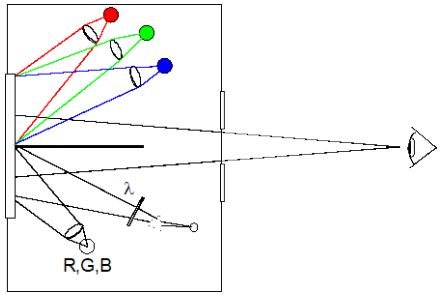


CIE 170-2:2015

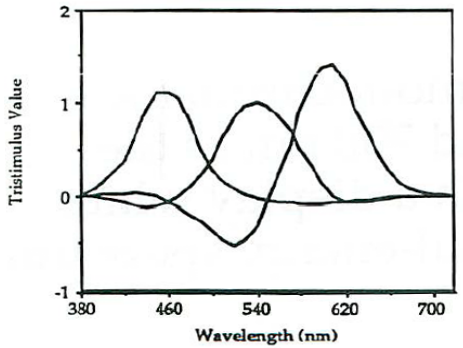
UDC: 612.84 535.66 Descriptor: Physiological optics. vision Colorimetry

- Cone-fundamental based color matching functions $\bar{x}_F(\lambda)$, $\bar{y}_F(\lambda)$, $\bar{z}_F(\lambda)$, $\bar{x}_{F10}(\lambda)$, $\bar{y}_{F10}(\lambda)$, $\bar{z}_{F10}(\lambda)$
- Cone fundamental-based spectral luminous efficiency functions $V_F(\lambda)$ for 2° observers and $V_{F10}(\lambda)$ for 10° observers

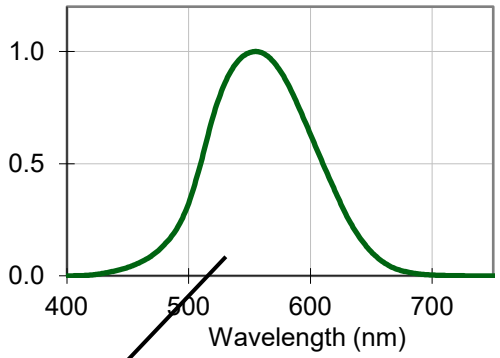
1931

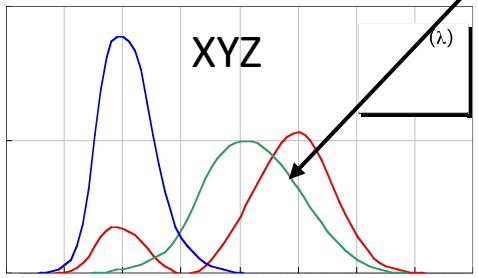


RGB



1924 V(λ)



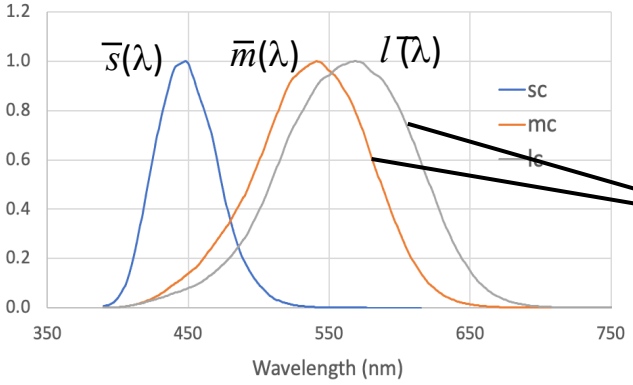


2015 (CIE 170-2)

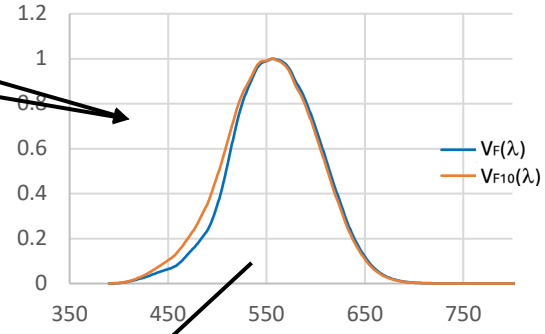
Physiological studies and data, models for
- Field size
- Age

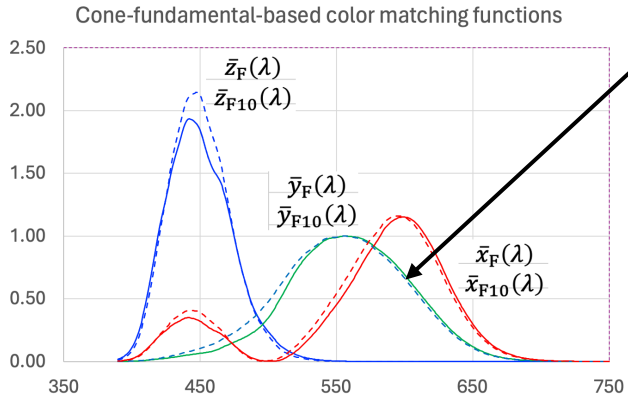
CIE 170-1 (2006)

LMS

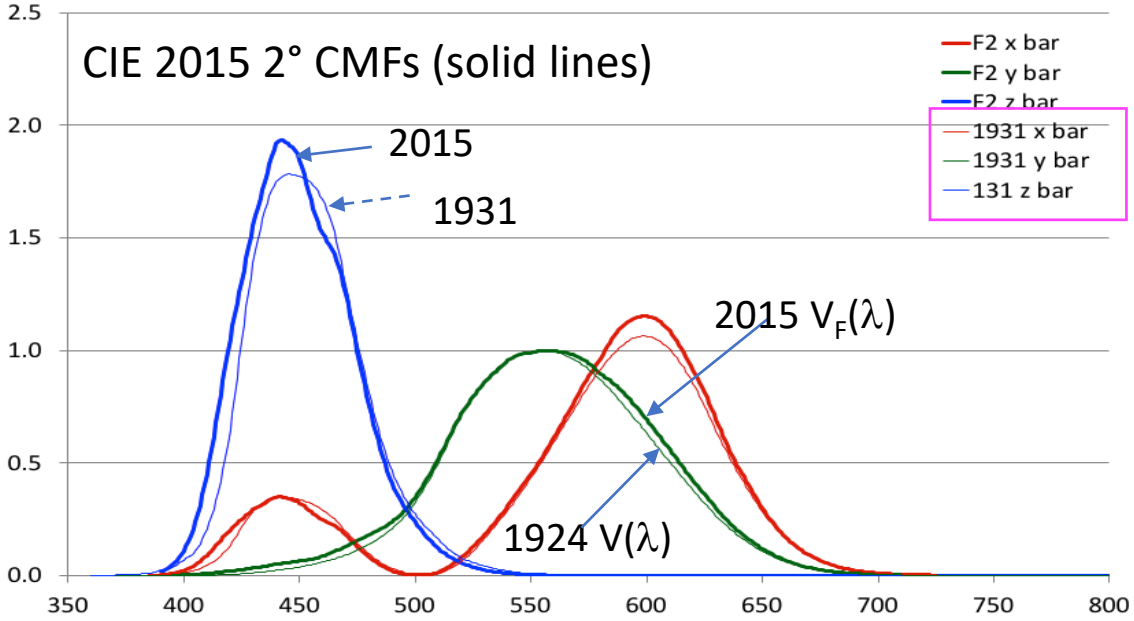


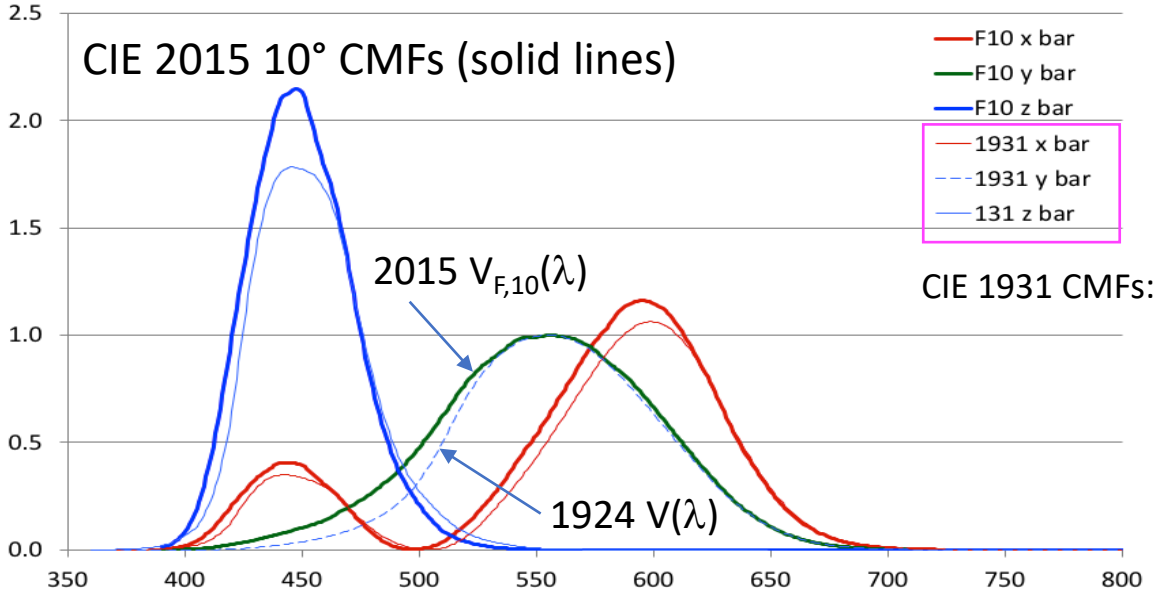
$V_F(\lambda)$, $V_{F10}(\lambda)$





Cone fundamental-based CMFs (CIE 170-2)





CIE 1931 CMFs:

Points for discussion

- The difference between $V_F(\lambda)$ (2°) and current V(λ) seems small. The difference between $V_{F,10}(\lambda)$ and current V(λ) seems significant.
- 10° CMFs (1964) are widely used in colorimetry (of objects), but not for light sources. Research direction is to use 10° CMFs for color specifications in lighting. Should photometry go for 10°?
- Will the cone-fundamental functions (2° or 10°) really better represent visual perception in our daily life?
- Will there be large enough difference and benefits for the change?

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Cone-Fundamental-Based COLORIMETRY

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

ABOUT THE CIE | TECHNICAL WORK | PUBLICATIONS | RESEARCH STRATEGY | NEWS AND EVENTS

1-98: A ROADMAP TOWARD BASING CIE COLORIMETRY ON CONE FUNDAMENTALS

To create a roadmap for the development of a new, complete, self-consistent system of CIE colorimetry measures based directly on cone fundamentals, with explicit consideration of the impacts of normal variations of the cone fundamentals due to age, field of view, and individual diversity.

Chair: Lorne Whitehead (CA)

https://cie.co.at/technicalcommittees/roadmap-toward-basing-cie-colorimetry-cone-fundamentals

Cone-Fundamental-Based PHOTOMETRY – CIE Research Forum RF05

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

ABOUT THE CIE | TECHNICAL WORK | PUBLICATIONS | RESEARCH STRATEGY | NEWS AND EVENTS

IMPLEMENTATION OF CIE 2006 CONE FUNDAMENTALS IN PHOTOMETRIC AND COLORIMETRIC MEASUREMENTS

RF Number RF-05

Since its beginning, colorimetry and photometry were directly related through the CIE colour matching function Y of the CIE 1931 standard colorimetric system which was set to be identical with the spectral luminous efficiency function for photopic vision, V(lambda). It is also well known that V(lambda) is not a perfect match to human vision and in particular it underestimates the visual response in the blue region. The physiology-based function, known as the cone-fundamental-based spectral luminous efficiency function, V_F(lambda), is based on the latest research and again relates photometry to modern (i.e. cone-fundamental based) colorimetry.

Establishment:
Tuesday, April 25, 2023
Convener Name: Tony Bergen

https://cie.co.at/researchforum/rf-05

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CCPR WG-SP TG 16 Cone-fundamental-based photometry

Established: January 25, 2023 (Call for participants)

Chair Y. Ohno (NIST)

Terms of Reference

To investigate the needs and benefits of introducing the cone-fundamental-based spectral luminous efficiency functions (and the color-matching functions) defined in CIE 170-2:2015 into the SI photometric quantities, and if appropriate, to propose approaches and strategies for introducing the cone-fundamental-based functions and resulting photometric quantities (and basic colorimetric quantities) in the SI.

Organized CCPR/CIE Expert Workshop on 100 years of V(λ) and Future of Photometry.

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Considering implementation of cone-fundamental-based spectral luminous efficiency functions

In the current SI, the candela is defined with a fixed defining constant, K_{cd} (683 lm/W), without reference to any spectral luminous efficiency functions. Thus, only changing the V(λ) would not require revision of the candela definition in the SI.

However, changing the V(λ) would result in change of photometric values of real lighting sources.

Such changes of photometric values (like lumen rating of lamps) could be a serious problem for the industry and market

Approach

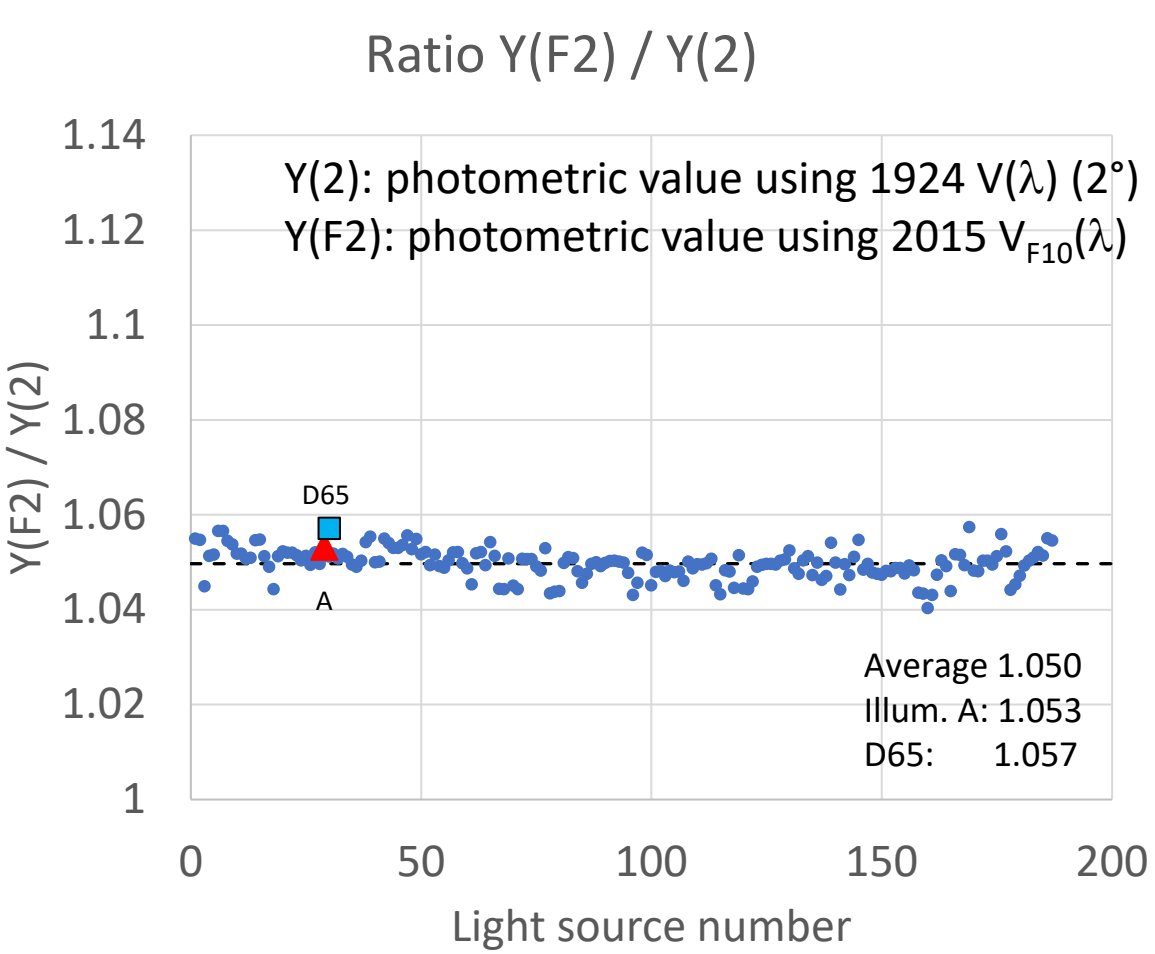
(1) Revise the value of K_{cd}

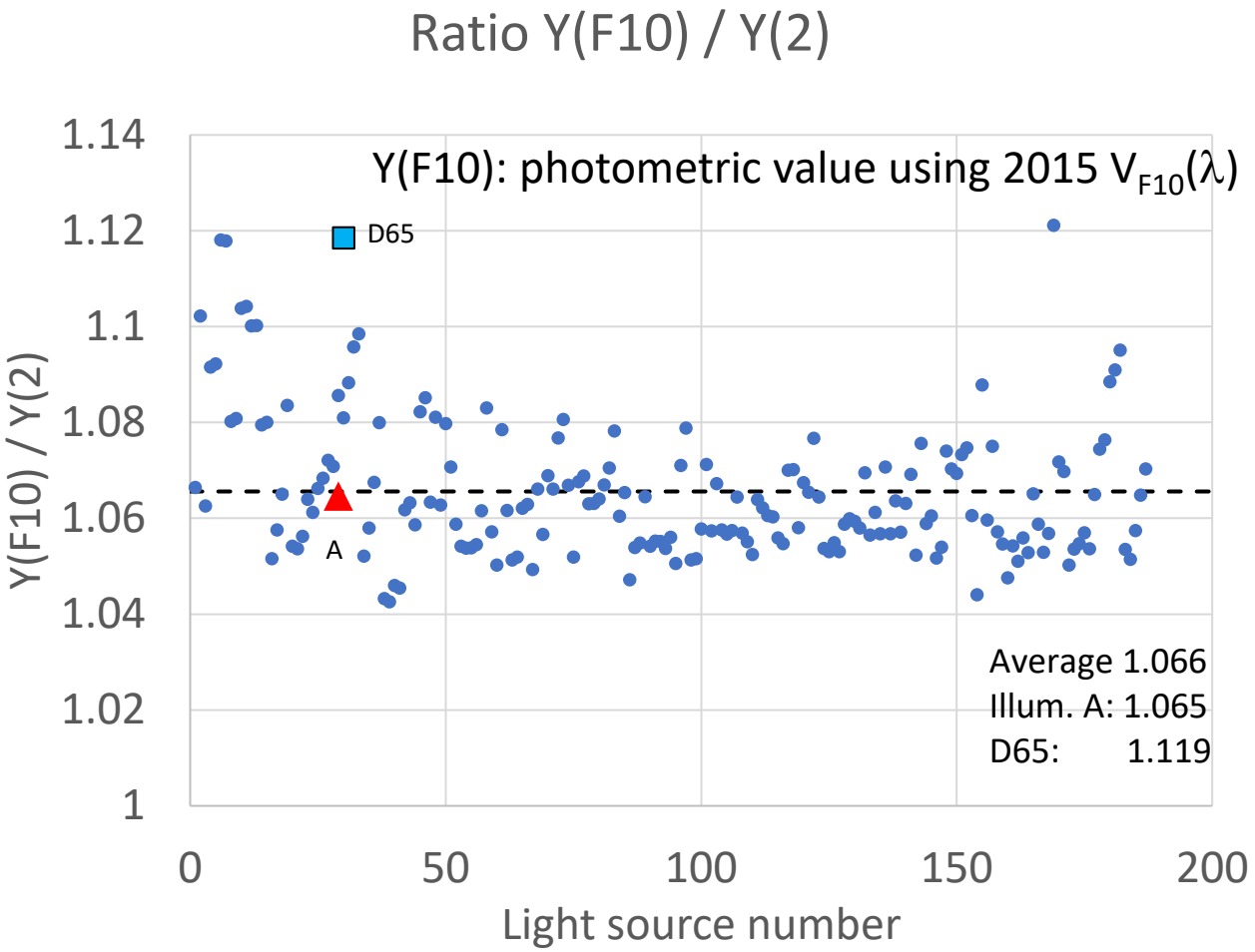
(2) Re-scaling the $V_F(\lambda)$, $V_{F10}(\lambda)$ functions

(3) Correction factor

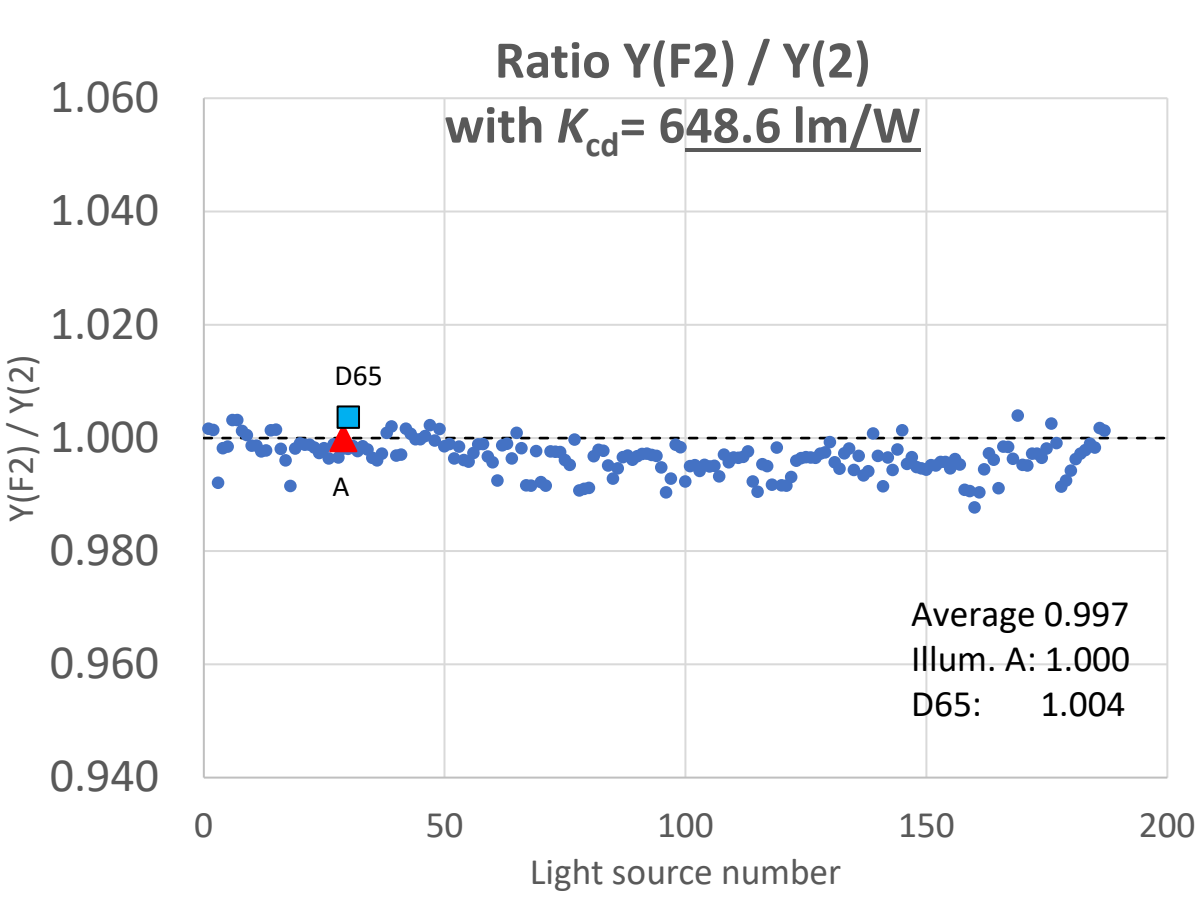
(2) will not be a viable option because there is a convention in CIE/CIPM that all action spectra (including spectral luminous efficiency functions) must be normalized to 1 at peak.

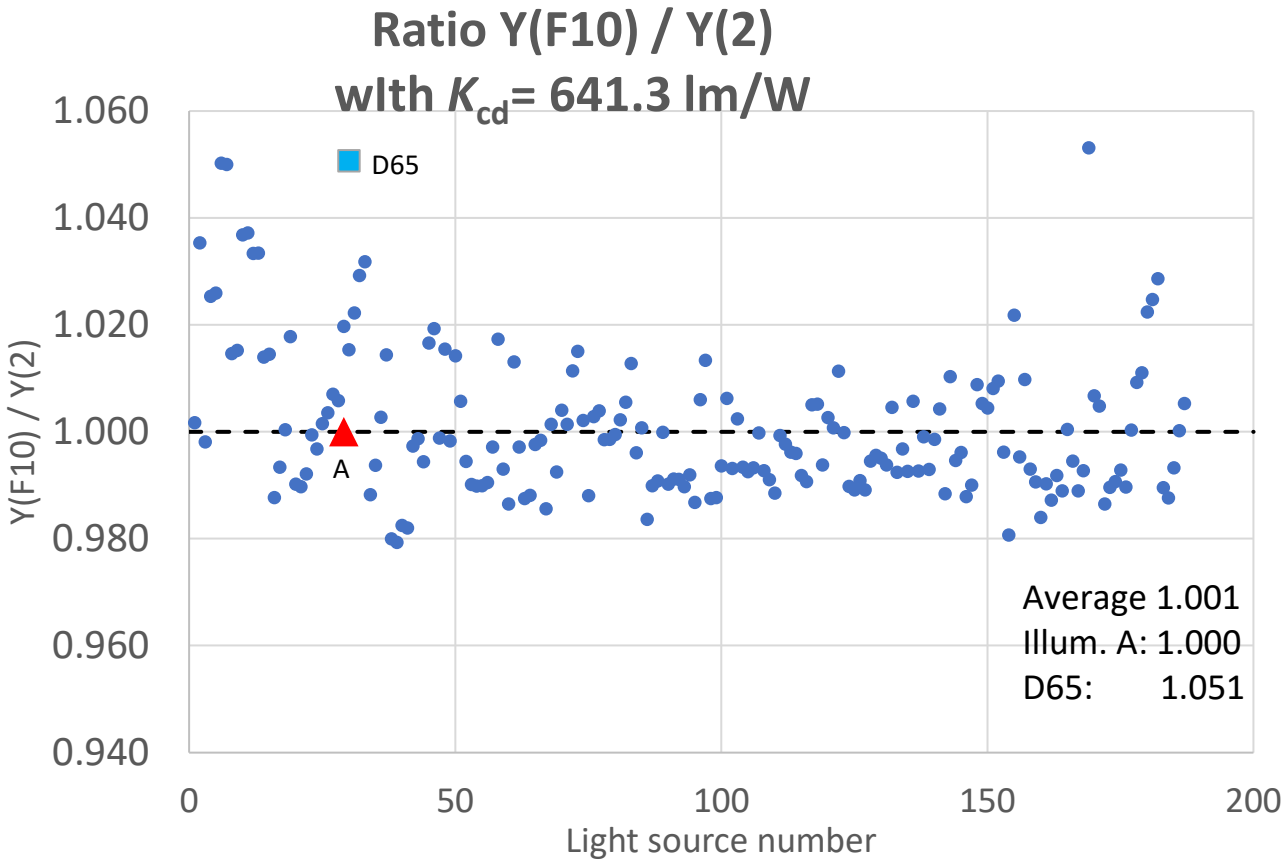
Analyses for 187 commercial products (FL, HID, LED) in IES TM-30 Library





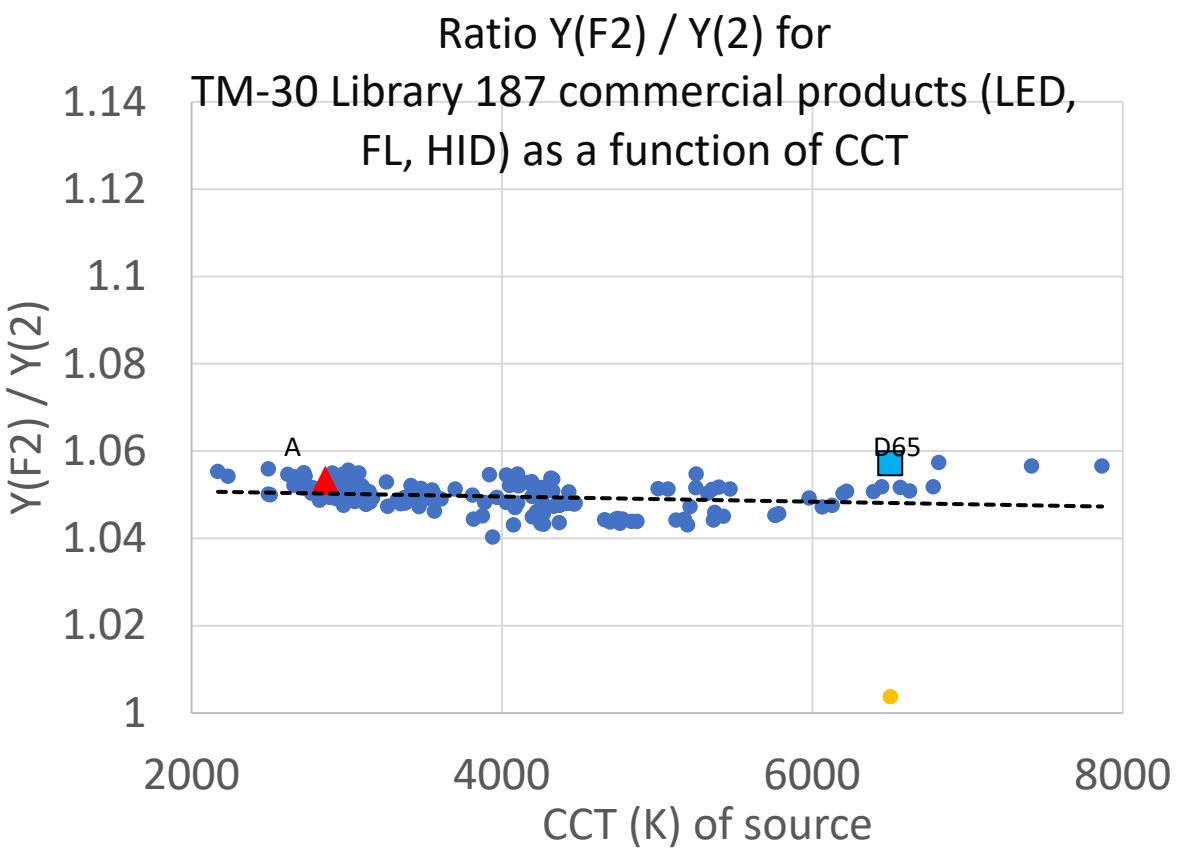
If we change K_{cd} (normalized to Illuminant A)

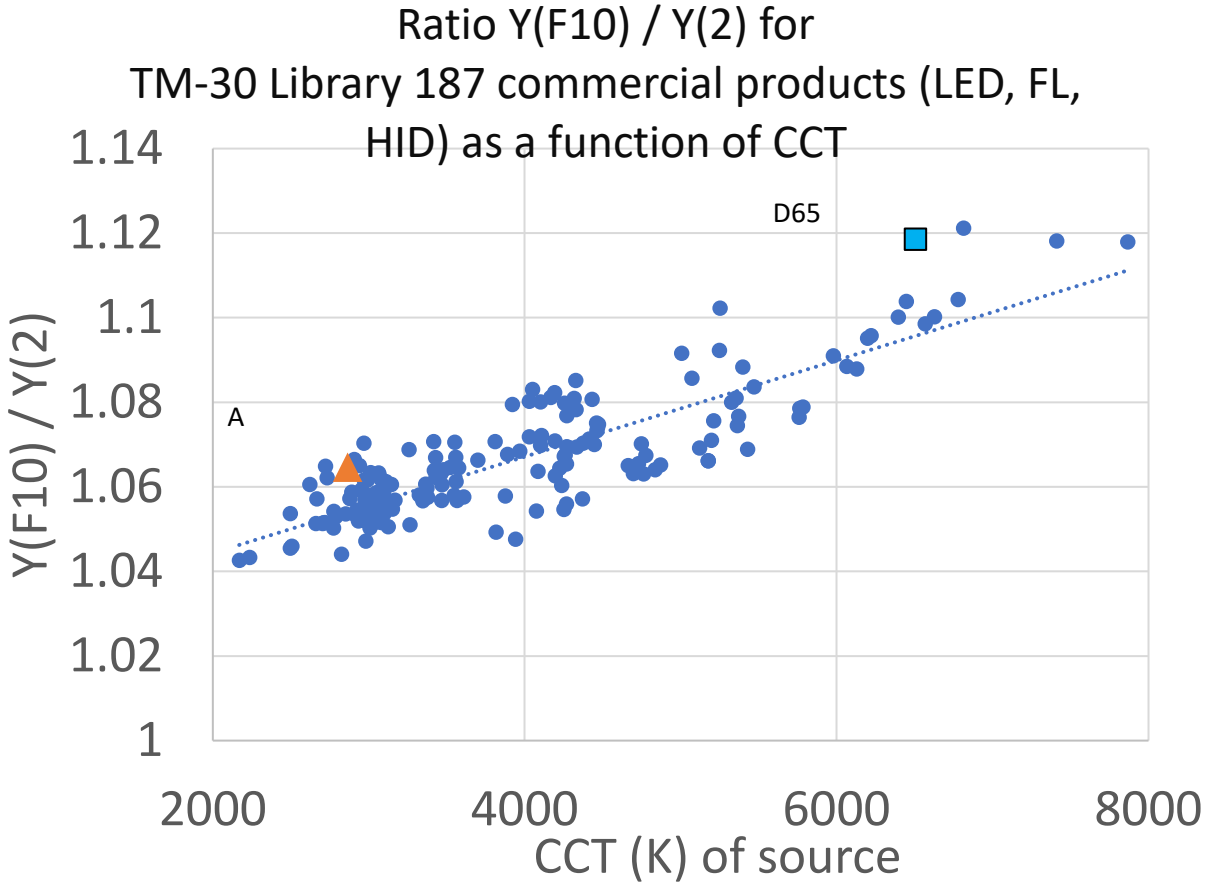




Analyses for 187 commercial products (FL, HID, LED) in IES TM-30 Library

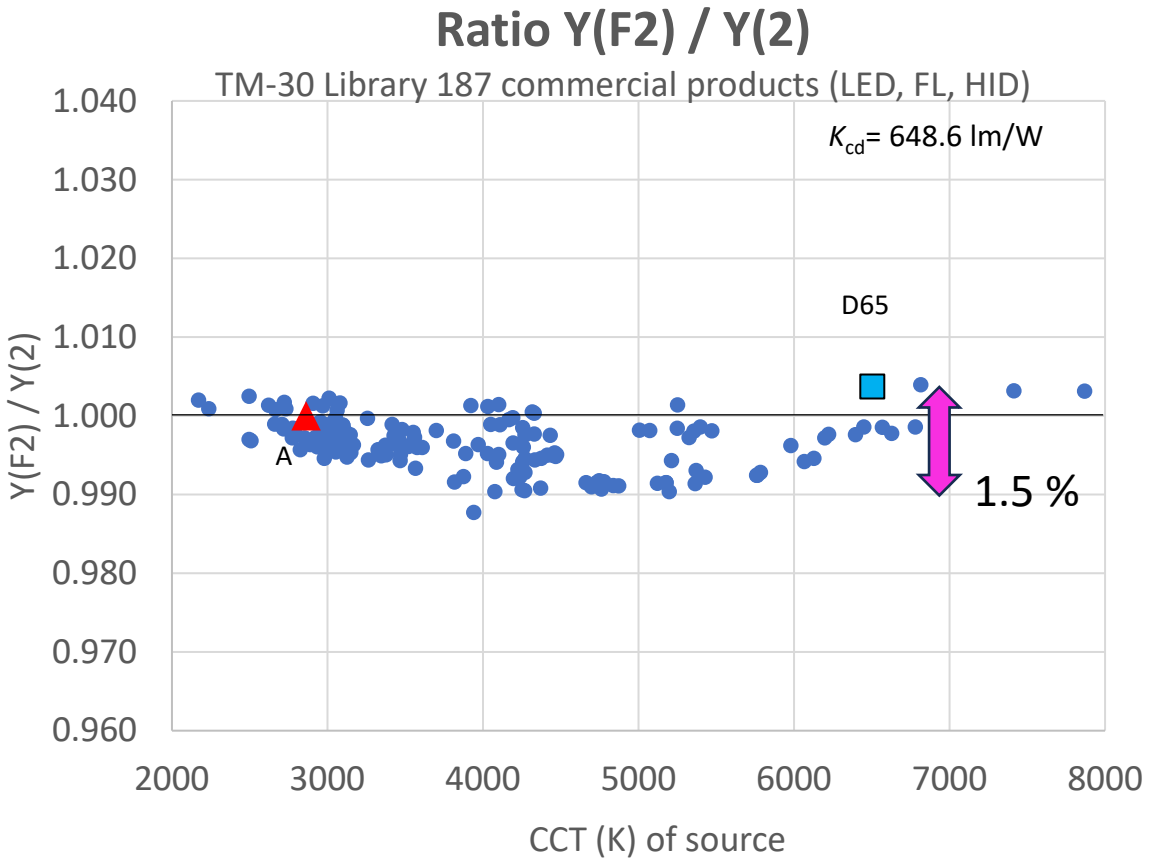
As a function of CCT

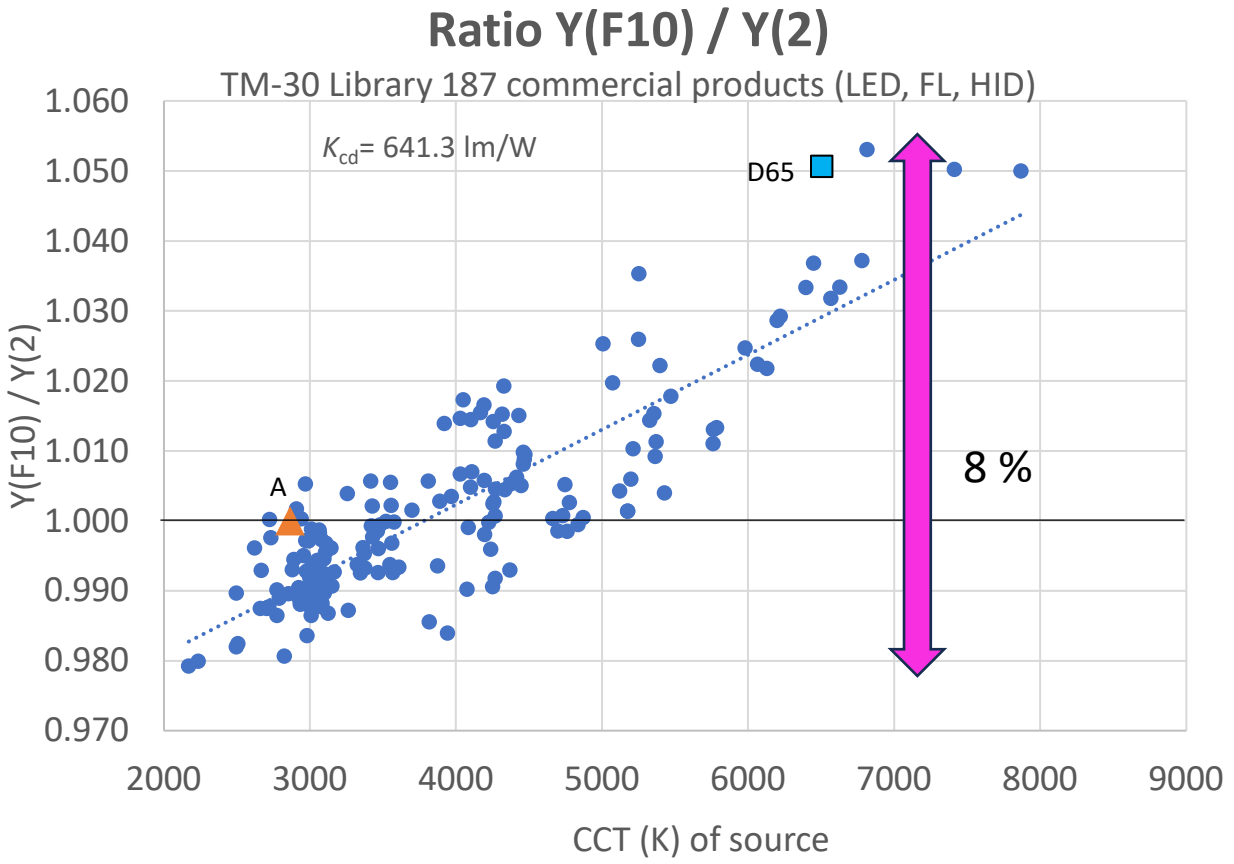




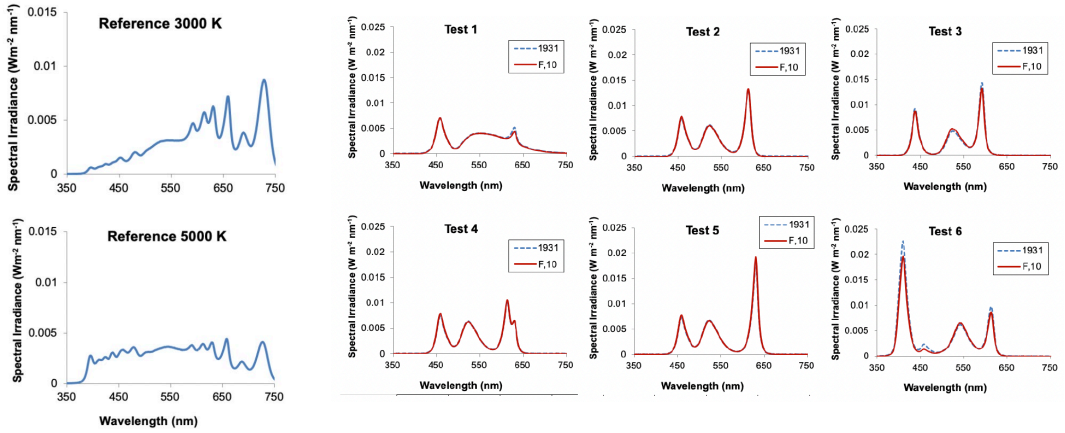
Analyses for 187 commercial products (FL, HID, LED) in IES TM-30 Library

As a function of CCT, normalized to Illuminant A





NIST 2019 CIE paper: Vision experiment on 2015 10 ° CMFs



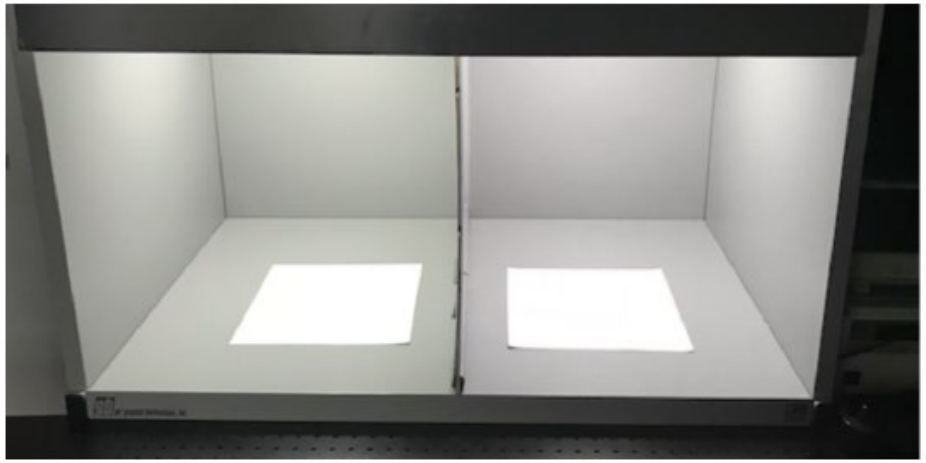
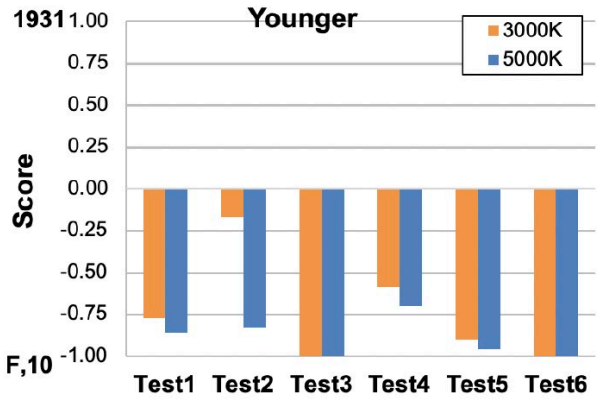


Figure 6 – Spectrally-Tuneable Double Booth used for the experiment

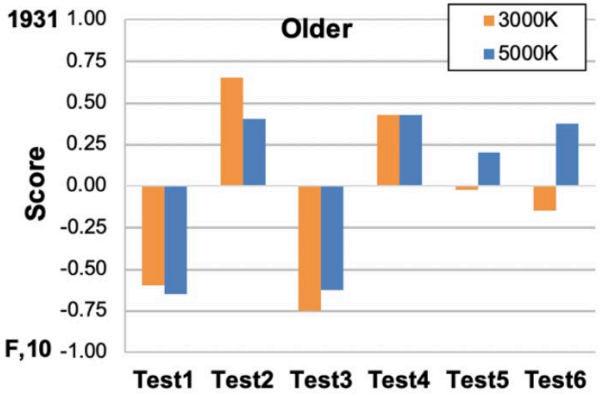
2 pairs

- Matched with CIE 1931 CMFs (1976 u',v')
- Matched with CIE 2015 10° CMFs ($u'_{F,10}$,$v'_{F,10}$)

Results: comparing CIE 1931 2° CMFs and CIE 2015 Cone-fundamental 10° CMFs



(a) Younger (under 40 years)



(b) Older (40 years and above)

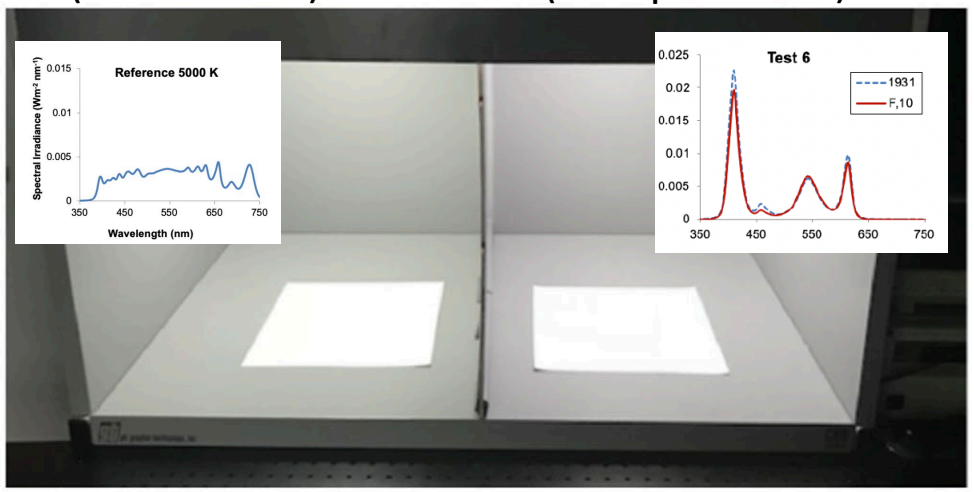
https://files.cie.co.at/x046_2019/x046-OP69.pdf

NIST Experiment on Evaluation of Cone Fundamental $V_{F10}(\lambda)$ (2024-)

Presentation by Jiaye Li at CCPR-CIE Expert Workshop June 3

Reference light. (broad band)

Test light (RGB primaries)

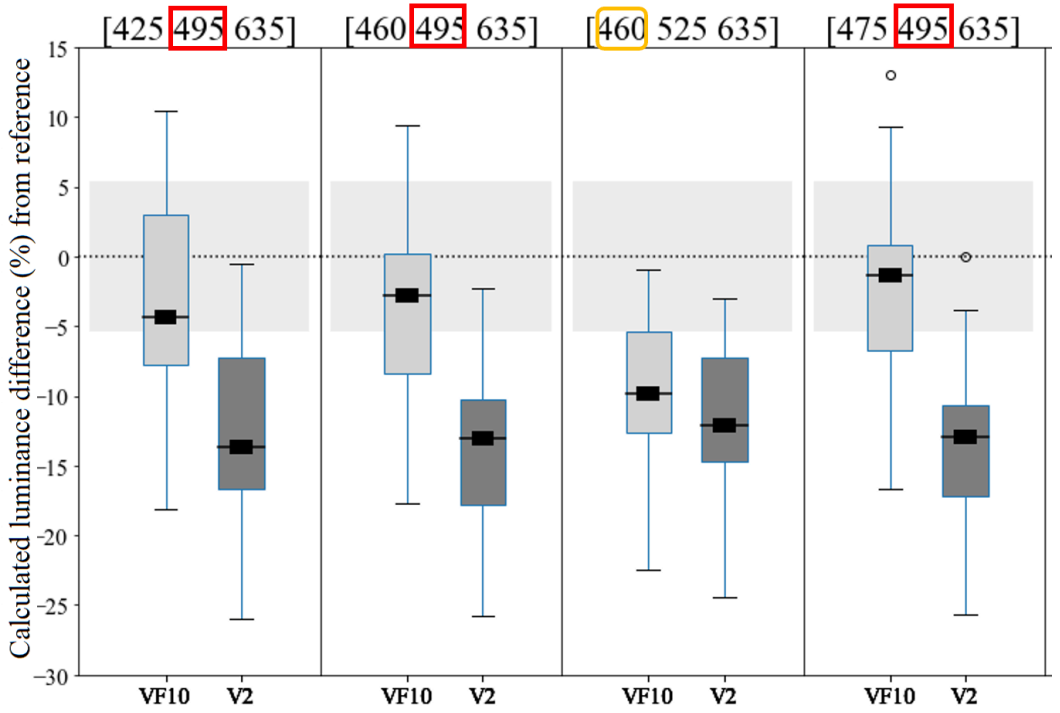


Subjects **match color and brightness** of two sheets
Measure spectral radiance of the sheets

- Luminance calculated with V(λ) for Test and Ref
- Luminance calculated with $V_{F,10}(\lambda)$ for Test and Ref

14 subjects so far.

Results (very positive!)



A research paper - Proposal for implementation of Color Quantities based on Cone-Fundamental 10° CMFs

LEUKOS
2023, VOL. 19, NO. 1, 35–52
https://doi.org/10.1080/15502724.2022.2029710

Illuminating Engineering Society | Taylor & Francis Group

Check for updates

Improved Method for Evaluating and Specifying the Chromaticity of Light Sources

Michael Royer [a,b], Michael J. Murdoch [c], Kevin Smet [d], Lorne Whitehead [e], Aurélien David [f], Kevin Houser [a,b], Tony Esposito [g], Jason Livingston[h], and Yoshi Ohno[i]

[a]Pacific Northwest National Laboratory, Portland, Oregon, USA; [b]School of Civil and Construction Engineering, Oregon State University, Corvallis, Oregon, USA; [c]Munsell Color Science Laboratory, Rochester Institute of Technology, Rochester, New York, USA; [d]ESAT-WaveCore/Light&Lighting Laboratory, Ku Leuven, Ghent, Belgium; [e]Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, Canada; [f]Google LLC, Mountain View, California, USA; [g]Lighting Research Solutions, Philadelphia, Pennsylvania, USA; [h]Studio T+L, New York, New York, USA; [i]Sensor Science Division, National Institute of Standards and Technology, Gaithersburg, Maryland, USA

ABSTRACT
This article describes a method for calculating and specifying light source chromaticity using the International Commission on Illumination (CIE) 2015 10° color matching functions (CMFs), which, according to analysis of existing psychophysical experiment data, can reduce visual mismatch compared to specifications based on the traditional CIE 1931 2° CMFs in architectural lighting applications. Specifically, this work evaluates, documents, and recommends for adoption by lighting standards organizations a supporting system of measures to be used with the CIE 2015 10° CMFs: a new uniform chromaticity scale (UCS) diagram with coordinates (*s*, *t*), a measure of correlated color temperature (CCTst), and a measure of distance from the Planckian locus (Dst). It also presents options for updating nominal classification quadrangles. A complete method of this nature has not yet been standardized, which may be contributing to the slow uptake of the CIE

ARTICLE HISTORY
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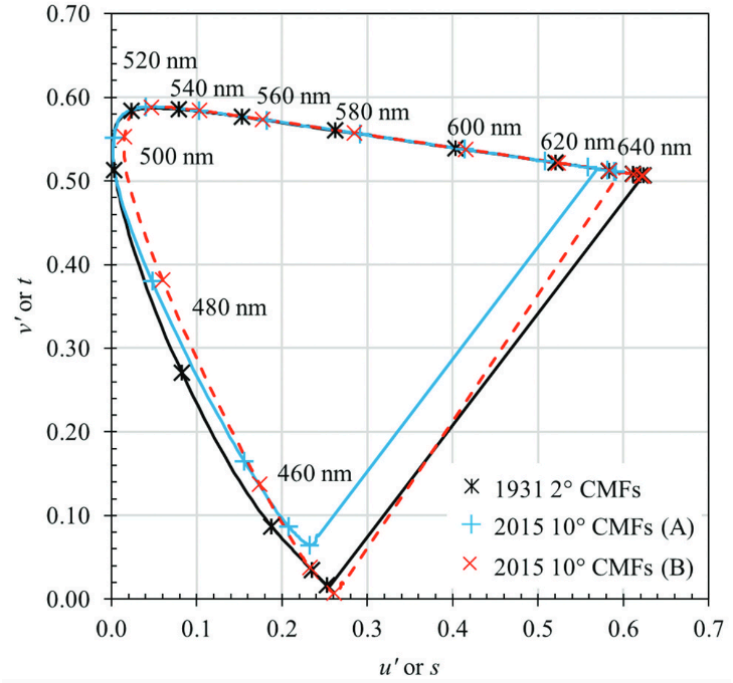
KEYWORDS
Chromaticity; CCT; Duv; CCTst; Dst; color matching functions



st-based correlated color temperature — CCTst — T_{st}

st-based distance from the Planckian locus — Dst — D_{st} 4)

Cone-fundamental-based chromaticity coordinate (*s*, *t*)

$$s = \frac{4X_{F,10}}{X_{F,10} + 15Y_{F,10} + 3Z_{F,10}} \quad (7)$$

$$t = \frac{9Y_{F,10}}{X_{F,10} + 15Y_{F,10} + 3Z_{F,10}} \quad (8)$$

https://www.tandfonline.com/doi/epdf/10.1080/15502724.2022.2029710?needAccess=true&role=button

June 3, 2024, BIPM

Outcome (tentative)

Discussion points

- What are the problems to be solved?
- Needs from display applications (2° not working well)
- Consideration for daylight applications (windows measurement, etc.)
- Associated costs for changing instruments (photometers and spectroradiometers)
- Current 2° V(λ) is needed for essential tasks (reading, ..)
- $V_{10}(\lambda)$ (from colorimetry) does not have good experimental basis
- Discussion needed in each Division of CIE

Conclusions

- Further research is needed for the needs, benefits, and impact in wide range of applications
- Discussion should continue in CIE RF05 and CCPR WG-SP TG16.

(For colorimetry, new TC proposals will be discussed in CIE after TC-98 report published.)