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.

CCPR/CIE Joint Workshop on the topic of this TG for June 2024 is proposed.

First task: Organize a CCPR workshop on cone-fundamental-based photometry for June 2024 at BIPM.

Members of TG 16

Chair Yoshi Ohno (NIST)

From CCPR

Marek Smid (CMI), WG-CMC Chair
Ana Alvarenga (INMETRO)
Willian Tavares Sousa (INMETRO)
Maria Luisa Rastello (INRIM), CCPR President
Gaël Obein (LNE-CNAM)
Peter Blattner (METAS), CIE President
Liu Hui (NIM)
Teresa Goodman (NPL)
Martin Dury (NPL)
Hiroshi Shitomi (NMIJ)
Minoru Tanabe (NMIJ)

From CIE

Tony Bergen (CIE Division 2, Research Forum 05), CIE-CCPR Liaison, CIE Div. 2 Director, CIE Vice President-Technical Elect (2023-9 -)
Kaida Xiao (CIE Division 1) CIE Div. 1 Director Elect (2023-9 -)
Lorne Whitehead (CIE TC 1-98)
Dong-Hoon Lee (CIE Division 2) CIE Div. 2 Director Elect (2023-9 -) … added Aug. 25, 2023

Ex-officio

Maria Nadal (NIST) WG-SP Chair
Joële Viallon (BIPM) CCPR Executive Secretary

CCPR WG-SP TG 16 Cone-fundamental-based photometry
First meeting Aug. 21, 2023

15:00 – 17:00 CEST

Attended by all 17 TG members!

Agenda

1. Welcome and members of Task Group (chair)
2. Introduction of participants (everyone)
3. Overview of the Task Group (chair)
4. Status of CIE activities related to cone fundamentals
   - CIE TC 1-98 (Lorne)
   - CIE RF05 and Workshop in CIE 2023 (Tony)
5. **Plan for CCPR/CIE joint workshop in June 2024**
6. Next Steps, next TG meeting

Overview of the Task Group

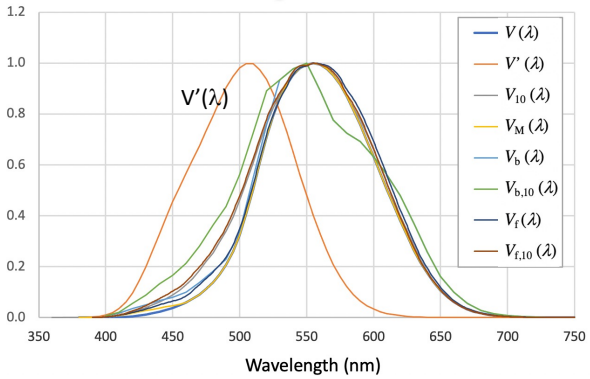
Background of TG 16 Cone-Fundamental-based photometry

Brief history of V(λ) since 1924

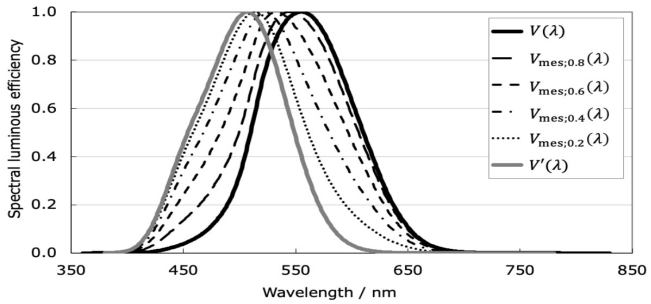
Published by CIE, CIPM

1924 V(λ) for photopic vision, 2° FOV (≥ 5 cd/m^2)
(adopted by CIPM in 1933)
1951 $V_M(\lambda)$ Judd correction (CIE 86-1990)
1951 V'(λ) for scotopic vision (≤ 0.005 cm/m^2)
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)

Currently 1924 V(λ) is used for all photometric units (lumen, candela, ..) in practical applications.



Mesopic luminous efficacy function



CIE 170-1:2006

ISBN 3 901 906 46 0

CIE

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

CONTENTS

CIE 170-2:2015

ISBN 978-3-902842-06-0

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

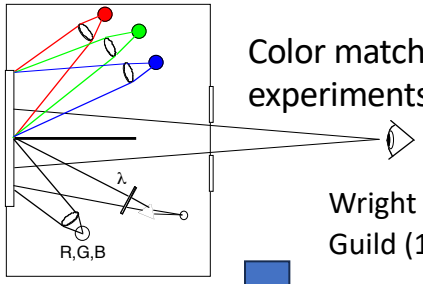
CIE 170-2:2015

UDC: 612.84 535.66 Descriptor: Physiological optics. vision Colorimetry

CONTENTS

Significance of Cone-Fundamentals

Current (1931) CIE Colorimetry System

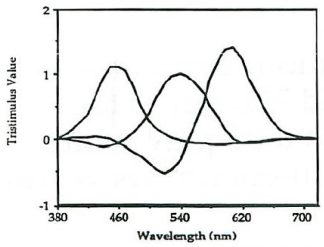


Color matching experiments

Wright (1929)
Guild (1931)

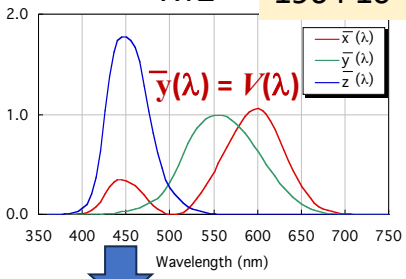
Color Matching Functions

RGB



XYZ

1931 2°
1964 10°



Color quantities: chromaticity coordinates x, y, u', v', CCT, Duv, ….

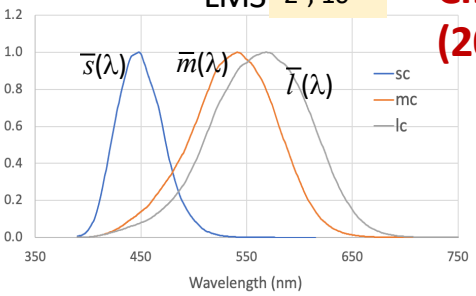
Cone-fundamental based Colorimetry (2006, 2015)

Physiological studies and data
- Field size
- Age

CIE 170-1 (2006)

Cone fundamentals (Cone sensitivity functions)

LMS 2°, 10°

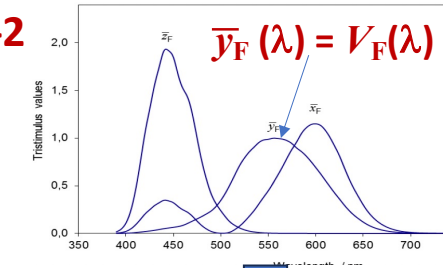


(Also in CIE S 026)

CIE 170-2 (2015)

(CIE XYZ Concept)

Cone-fundamental-based Color Matching Functions



Cone-fundamental-based Color quantities; $X_F Y_F Z_F$, chromaticity coordinates, ….

Cone fundamentals topic introduced by CCPR President at 25th CCPR (May 2022)

Key Scientific questions in the definition of the SI unit of luminous intensity, the candela

25th Meeting of the CCU

Bureau International des Poids et Mesures

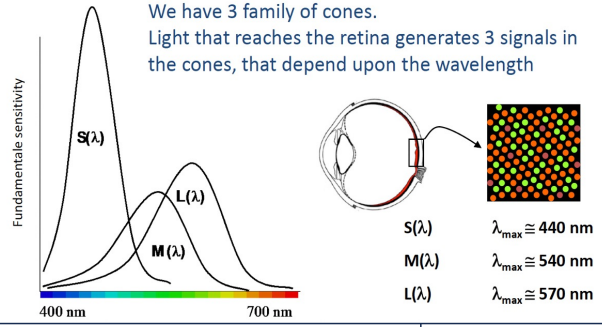
Photometry

Photometry is the science of the measurement of light, in term of its perceived brightness to the human eye.

www.bipm.org

Cones (L M S)

We have 3 family of cones.
Light that reaches the retina generates 3 signals in the cones, that depend upon the wavelength



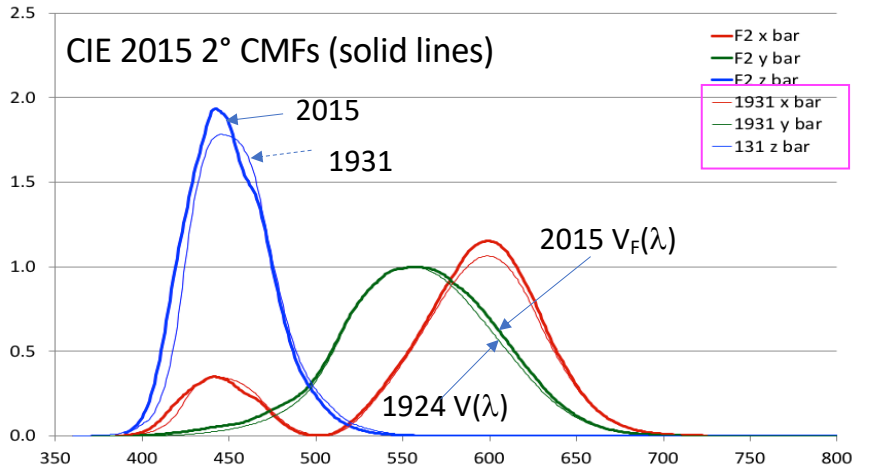
Taking into account the progress done so far and foreseeable in vision science and AI, there could be in few years some changes in the photometric quantities because of a much better understanding of the luminous perception using the cone-fundamentals system.

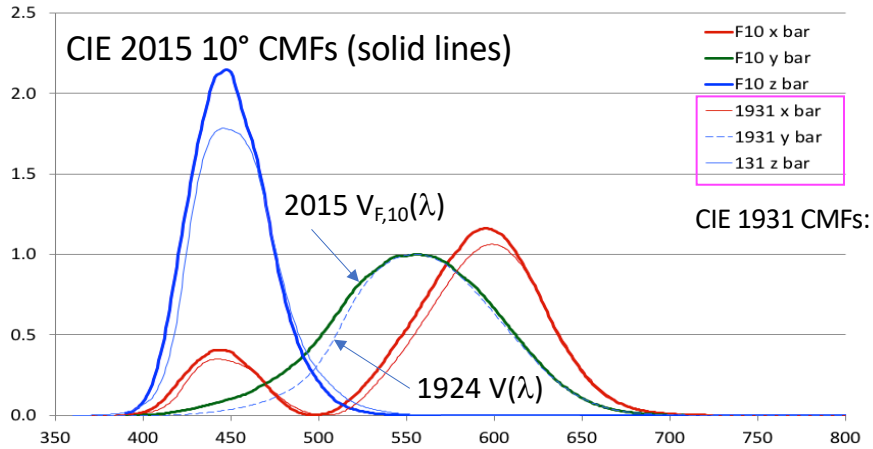
www.bipm.org

This cone-fundamental based photometric system would need a new link between photometry (lm, cd, lx,…) and radiometry (W, W/sr, W/m2…).

This link and its nature are the key scientific challenges in the definition of the candela for the next future.

Cone fundamental-based CMFs (CIE 170-2)





CIE 1931 CMFs:

Points for discussion

- The difference between $V_F(\lambda)$ and current $V(\lambda)$ seems small. The difference between $V_{F,10}(\lambda)$ and current $V(\lambda)$ seems significant.
- 10° CMFs (1964) are widely used in colorimetry (of objects), but $V_{10}(\lambda)$ not used in photometric practice.
- Colorimetry of light sources has also been using 2° CMFs only. 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? (standpoint of the industry) We will not go for the change for scientific reason only?

Recent studies on cone-fundamental-based colorimetry (two examples)

NIST 2019 CIE paper

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

VISUAL EVALUATION OF CIE 2015 CONE FUNDAMENTAL-BASED 10° COLOUR MATCHING FUNCTIONS FOR LIGHTING APPLICATIONS

Ohno, Y.[1], Kawashima, Y.[1], Oh, S.[2] and Kwak, Y.[2]
[1] National Institute of Standards and Technology, Gaithersburg, Maryland, USA
[2] Ulsan National Institute of Science and Technology, Ulsan, South Korea
ohno@nist.gov

DOI 10.25039/x46.2019.OP69

Abstract

The CIE 2015 cone fundamental-based colour-matching functions (CMFs), especially the 10° CMFs, are expected to improve visual colour matching in lighting applications. The chromaticity specifications for lighting products are based on the CIE 1931 CMFs (2° observer) and are given by correlated colour temperature (CCT) and the distance from Planckian locus (Duv). To study the impact of introducing the CIE 2015 CMFs, computational analyses were first made to determine the magnitude of changes in CCT and Duv values for various lighting sources. The results showed significant changes in both CCT and Duv. Then

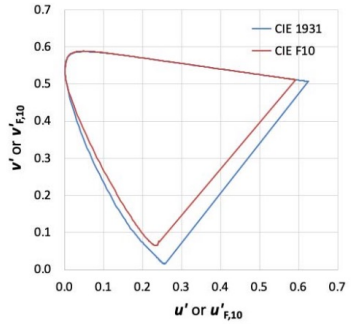


Figure 1 – (u, v,) and ($u'_{F,10}$, $v'_{F,10}$) chron (u', v')$_I$ diagrams

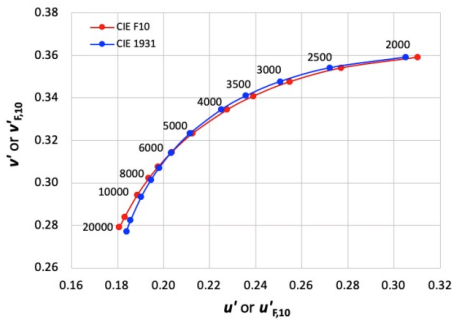


Figure 2 – Planckian locus on (u', v') and ($u'_{F,10}$, $v'_{F,10}$) diagrams

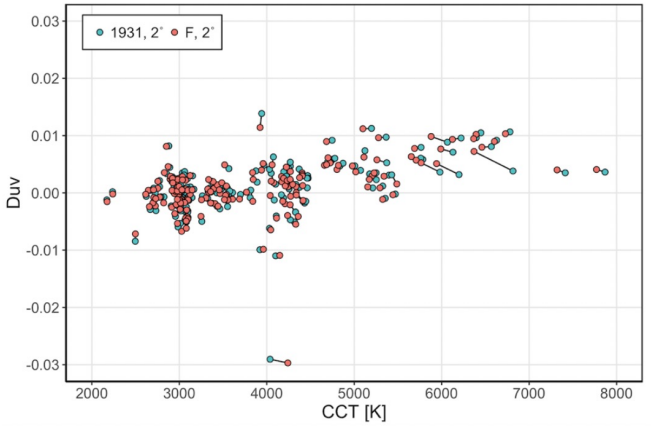


Figure 4 – Comparison of CIE 2015 2° CMFs and CIE 1931 for calculated CCT and Duv values of 187 SPDs' data from the TM-30 SPD data library

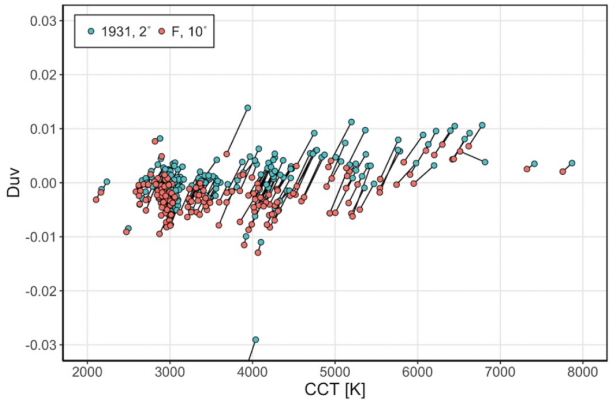
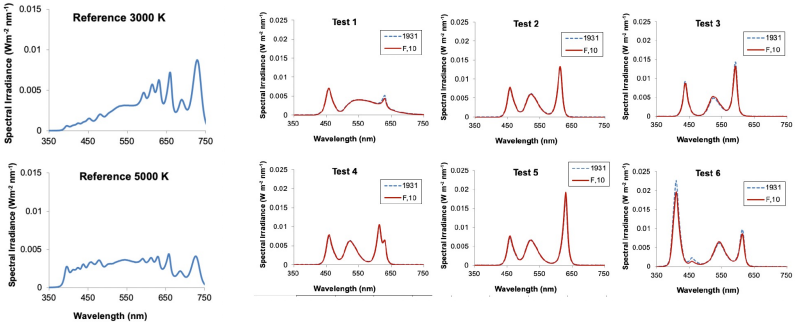


Figure 3 – Comparison of CIE 2015 10° CMFs and CIE 1931 for calculated CCT and Duv values of 187 SPDs' data from the TM-30 SPD data library

NIST 2019 CIE paper



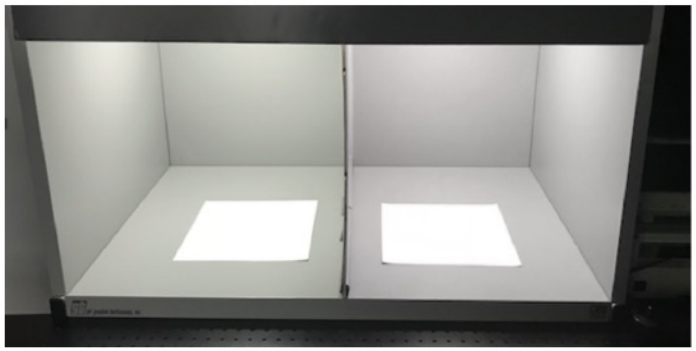
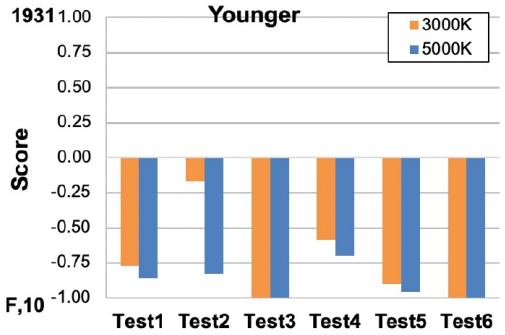


Figure 6 – Spectrally-Tuneable Double Booth used for the experiment

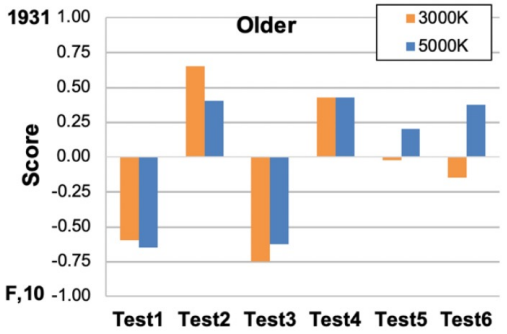
2 pairs

- 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)

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 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
Received 30 March 2021
Revised 24 December 2021
Accepted 6 January 2022

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

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

(Proposed symbols for CIE 2015 10° CF quantities)

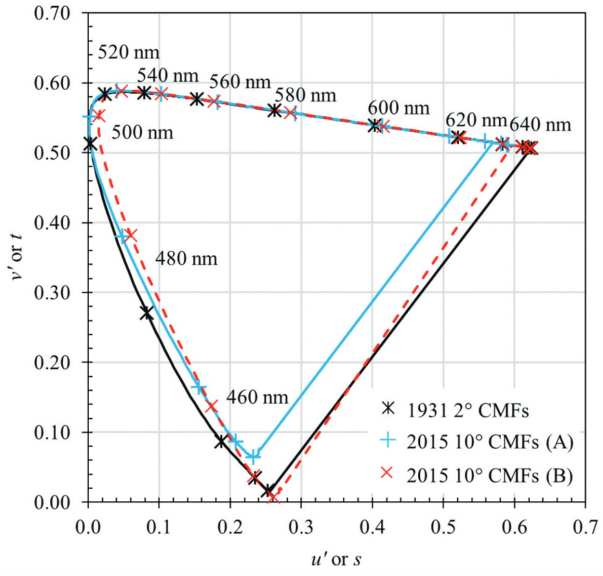


Table 1. Summary of existing and proposed terminology.

Status	Written	Abbreviation	Symbol	Chromaticity Diagram	CMFs
Existing	Color temperature	CT	T_c	NA	NA
Existing	Correlated color temperature	CCT	T_{cp}*	(*u*, *v*) [*u*′, 2/3 *v*′]	1931 2°
Existing	Distance from the Planckian locus	Duv	D_{uv}	(*u*, *v*) [*u*′, 2/3 *v*′]	1931 2°
Proposed	*st*-based correlated color temperature	CCTst	T_{st}	(*s*, *t*)	2015 10°
Proposed	*st*-based distance from the Planckian locus	Dst	D_{st}	(*s*, *t*)	2015 10°
Proposed	Correlated color temperature	CCTxx	T_{xx}	Generic	Generic
Proposed	Distance from the Planckian locus	Dxx	D_{xx}	Generic	Generic

*Future consideration may be necessary to align existing notations with proposed use of subscripts to indicate the chromaticity diagram used for calculation.

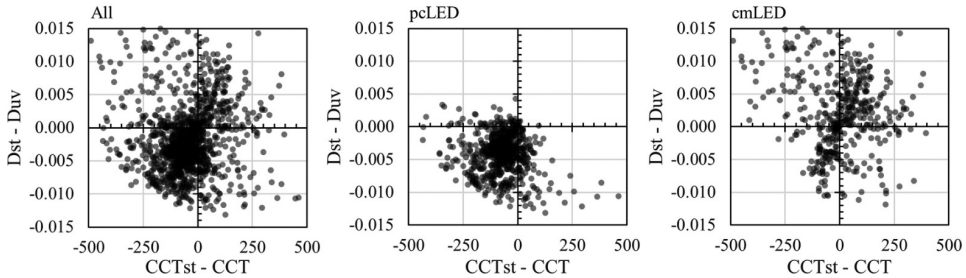
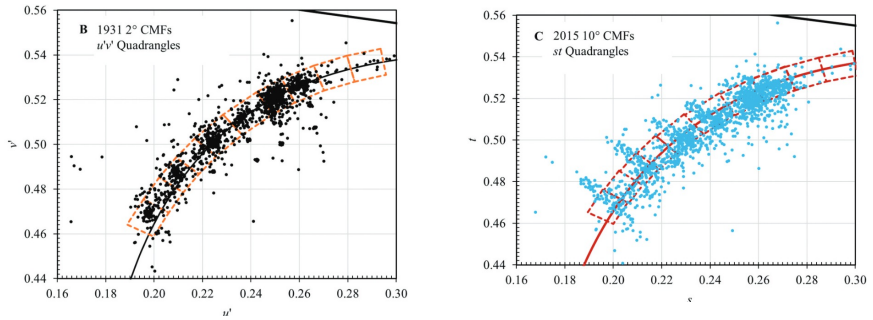


Fig. 8. Total change from the current to the proposed system, or difference between CCTst and CCT and Dst and Duv for 1,528 real SPDs (left) and subsets of 827 phosphor converted LED (pcLED) SPDs (middle), and 453 color-mixed LED (cmLED) SPDs (right).



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

(A)

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

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

For 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)

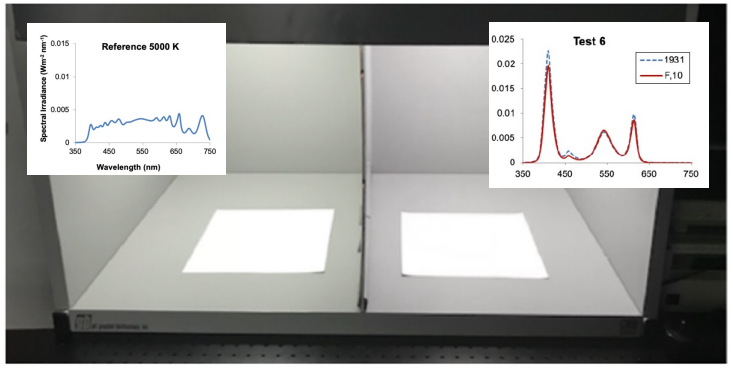
https://cie.co.at/technicalcommittees/roadmap-toward-basing-cie-colorimetry-cone-fundamentals

How about Cone-Fundamental-Based PHOTOMETRY?

We need experimental studies on brightness perception for cone-fundamental-based V(λ) functions

An example of experimental methods

Metameric pairs of SPDs



Compare 2 pairs:

A) Luminance matched with V(λ)

B) Luminance matched with $V_{F,10}(\lambda)$

NIST spectrally tunable lighting facility

Compare broadband lights (same R_f) at different CCTs for A), B)

For Cone-Fundamental-Based PHOTOMETRY – CIE Research Forum

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

5. Plan for CCPR/CIE joint workshop in June 2024

Proposal of Workshop in 2024

Title: CCPR/CIE Joint Workshop - 100 Years of V(λ) and Future of Photometry

Date: Monday, June 3, 2024 (one day) in conjunction with CCPR 26th meeting
(CCPR WGs June 4-5, CCPR plenary meeting on June 6 -7)
Also, CIE Division 2 and Division 1 annual meetings in Paris are proposed for the week before CCPR.

Venue: BIPM, Sèvres, France (hybrid)

Description: The workshop will commemorate 100th anniversary of V(λ), overview the history of SI photometric units, spectral luminous efficiency functions, and introduce the cone fundamentals published by CIE (2006, 2015), then will discuss the future of photometry and colorimetry with cone-fundamental-based spectral luminous efficiency functions and color-matching functions.

Expected participants: ~50, up to 100 is possible (capacity of BIPM conference room)

Registration fee: expected to be free.

Organization: The workshop will be co-organized by CCPR and CIE (Division 2 and Division 1) supported by BIPM.

Workshop organizing committee

From CCPR: Y. Ohno (Chair), G. Obein (local organizer for CIE), M.L. Rastello
From CIE: T. Bergen, L. Whitehead, K. Xiao, D-H. Lee
From BIPM: J. Viallon (local organizer)

Logistics (registration, venue arrangements) to be supported by BIPM. CIE also to support in promotion of the workshop.

Outcome of the workshop may be published in Metrologia special issue (to be confirmed)

First Announcement with further details is expected for October 2023.

Ideas for contents of the workshop

Possible invited presentations – Understanding Cone Fundamentals (each 20 to 30 min + Q&A)

- History of 1924 V(λ) and other spectral luminous efficiency functions including 1964 $V_{10}(\lambda)$
- History of 1931 CIE colorimetry system including 1964 10° CMFs
- Introduction of CIE 170-1 and 170-2, with focus on CF-based spectral luminous efficiency functions
- CIE's direction for cone-fundamental based colorimetry (CIE Division 1 TC 1-98)
- CIE's direction for cone-fundamental based photometry (Division 2 RF-05)
- High level objective of photometry as a part of metrology
- SI definition of candela and relationship to spectral luminous efficiency functions (SI definition, defining constant K_{cd}, Principles Governing Photometry, further standards needed)
- Impact of introducing CF-based $V_F(\lambda)$ or $V_{F10}(\lambda)$ in practical applications
- Results experiments on brightness with $V_{F10}(\lambda)$, if done successfully (NIST or any labs)

Discussion on Future Directions (1 to 2 h)

- Needs for further verification of the benefits (scientific as well as practical) of CF-based photometry.
- How CCPR and CIE can collaborate on this topic. How this TG should work with CIE RF05 (already has platform for discussion, difficulties). (Precedence– JTC2, but JTC may be too early)
- What document(s)/standards to be developed if CF-based photometry is to be implemented.
- Discussion on industry perspective - benefits and impacts.

6. Next Steps, Next TG meeting

WG-SP approval requested for the workshop proposed

After approval by WG-SP

- Approval for the workshop by CIE Division 2 and Division1 (in Ljubljana, Sep. 22)
- Short announcement at CIE Quadrennial and NEWRAD, also for CIPM in October
- Develop 1st Announcement of Workshop, distribute to CCPR and CIE

Next TG meeting: planned for October 2023
(Finalize the 1st Announcement)

August
21st. TG meeting
September
7 – 8th CCPR WG 11-14th NEWRAD 18-23 CIE 2023 Quadrennial
October
Next TG meeting
1st Announcement of Workshop