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 $V(\lambda)$ since 1924

Published by CIE, CIPM

1924 $V(\lambda)$ for photopic vision, 2° FOV ($\geq 5$ cd/m$^2$)
(adopted by CIPM in 1933)
1951 $V_M(\lambda)$ Judd correction (CIE 86-1990)
1951 $V'(\lambda)$ for scotopic vision ($\leq 0.005$ cm/m$^2$)
1964 $V_{10}(\lambda)$ for 10° FOV
1983 $V(\lambda)$ and $V'(\lambda)$ 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 $V(\lambda)$, $V'(\lambda)$, $V_{10}(\lambda)$, $V_{mes,m}(\lambda)$ adopted by CIPM in *Principles Governing Photometry, 2nd ed.* (Rapport BIPM 2019/05)

Currently 1924 $V(\lambda)$ is used for all photometric units (lumen, candela, ..) in practical applications.
CIE 170-1:2006

COMMISSION INTERNATIONALE DE L’ECLAIRAGE
INTERNATIONALE BELEUCHTUNGSKOMMISSION

TECHNICAL REPORT

FUNDAMENTAL CHROMATICITY DIAGRAM WITH PHYSIOLOGICAL AXES – PART 1

ISBN 3 901 906 46 0

CIE 170-1:2006
UDC: 612.84 Descriptor: Physiological optics, vision Colourometry

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Significance of Cone-Fundamentals

Current (1931) CIE Colorimetry System

Color matching experiments

Wright (1929)
Guild (1931)

Physiological studies
• Field size
• Age

CIE 170-1 (2006)

Cone fundamentals
(Cone sensitivity functions)

CIE 170-2 (2015)

Also in CIE S 026

Cone-fundamental-based Color Matching Functions

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

(CIE XYZ Concept)

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

Photometry

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

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.

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.
CIE 2015 2° CMFs (solid lines)

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

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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', v', 10°) chron (u', v') diagrams

Figure 2 – Planckian locus on (u', v') and (u', v', 10°) diagrams

Figure 3 – Comparison of CIE 2015 10° CMFs and CIE 1931 for calculated CCT and Duv values of 187 SPDs¹ data from the TM-30 SPD data library

Figure 4 – Comparison of CIE 2015 2° CMFs and CIE 1931 for calculated CCT and Duv values of 187 SPDs² data from the TM-30 SPD data library
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)
Improved Method for Evaluating and Specifying the Chromaticity of Light Sources

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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 (σ, ι), 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
Cone-fundamental-based chromaticity coordinate \((s, t)\)

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

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

**Table 1. Summary of existing and proposed terminology.**

<table>
<thead>
<tr>
<th>Status</th>
<th>Written</th>
<th>Abbreviation</th>
<th>Symbol</th>
<th>Chromaticity Diagram</th>
<th>CMFs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing</td>
<td>Color temperature</td>
<td>CT</td>
<td>(T_e)</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Existing</td>
<td>Correlated color temperature</td>
<td>CCT</td>
<td>(T_{cr}^*) ((u, v) [u’, 2/3 v’])</td>
<td>1931 2°</td>
<td></td>
</tr>
<tr>
<td>Existing</td>
<td>Distance from the Planckian locus</td>
<td>Duv</td>
<td>(D_{uv}) ((u, v) [u’, 2/3 v’])</td>
<td>1931 2°</td>
<td></td>
</tr>
<tr>
<td>Proposed</td>
<td>(s)-based correlated color temperature</td>
<td>CCTst</td>
<td>(T_{ss}) ((s, t))</td>
<td>2015 10°</td>
<td></td>
</tr>
<tr>
<td>Proposed</td>
<td>(s)-based distance from the Planckian locus</td>
<td>Dst</td>
<td>(D_{st}) ((s, t))</td>
<td>2015 10°</td>
<td></td>
</tr>
<tr>
<td>Proposed</td>
<td>Correlated color temperature</td>
<td>CCTxx</td>
<td>(T_{xx})</td>
<td>Generic</td>
<td></td>
</tr>
<tr>
<td>Proposed</td>
<td>Distance from the Planckian locus</td>
<td>Dxx</td>
<td>(D_{xx})</td>
<td>Generic</td>
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</table>

*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).
For Cone-Fundamental-Based COLORIMETRY

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 $V(\lambda)$ functions

An example of experimental methods

Metameric pairs of SPDs

NIST spectrally tunable lighting facility

Compare 2 pairs:
A) Luminance matched with $V(\lambda)$
B) Luminance matched with $V_{F,10}(\lambda)$

Compare broadband lights (same $R_t$) at different CCTs for A), B)
For Cone-Fundamental-Based PHOTOMETRY – CIE Research Forum

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(\lambda) and Future of Photometry

Date: Monday, June 3, 2024 (one day) in conjunction with CCPR 26\textsuperscript{th} 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 100\textsuperscript{th} anniversary of V(\lambda), 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 $V(\lambda)$ and other spectral luminous efficiency functions including 1964 $V_{10}^{10}(\lambda)$
• 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 $V_{F10}^{10}(\lambda)$ in practical applications
• Results experiments on brightness with $V_{F10}^{10}(\lambda)$, 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)

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<table>
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<th>September</th>
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<tr>
<td>7 – 8th</td>
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<td>CCPR WG</td>
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