## CCPR-CIE Expert Workshop on 100 years of $V(\lambda)$ and Future of Photometry

## Invited Presentations
## Abstracts

### A Short History of Light Measurement in the CIE

*Jennifer A. Veitch, CIE President*

The history of *V(λ)* is intertwined with the history of the International Commission on Illumination and with developments in lighting technology in the early 20th century. Gas light gave way to electric light and societies of "illuminating engineering" began to form in several countries. It became evident that international agreement on definitions, terms and measurement techniques would enable industrial development and practical applications. This presentation will present the development of *V(λ)* and the beginnings of physical measurement of optical radiation in the context of the early years of the CIE.

### The BIPM and the CIE: 100 years of cooperation – An overview of the main developments in the definition of the photometric units

*Celine Fellag Ariouet, BIPM*

The integration of photometry and radiometry, and the development of the definition of the candela, are both the result of a human adventure in which the BIPM participated, even before they were officially integrated into its activities.
This presentation will provide a historical retrospective focusing on the main actors who contributed to the major developments in the definition of photometric units. It will look back at the beginning of the international cooperation between the BIPM and the CIE which started 100 years ago.

### Derivation of 1924 $V(\lambda)$ and other spectral luminous efficiency functions

*Yoshi Ohno, NIST, USA*

Research by the scientists of National Bureau of Standards (NBS) that contributed to the definition of CIE 1924 $V(\lambda)$ function will be overviewed. The two major vision experiments conducted by Coblentz and Emerson (1918) and Gibson and Tyndall (1923) will be focused, with technical details of the experimental set up and how they measured visual sensitivity of human eyes accurately in that early time and how the standardized visual efficiency function was derived based on their experimental results as well as other researchers data, from over 250 subjects in total, and discuss the scientific significance of the definition of the 1924 $V(\lambda)$ as well as its shortcomings. This talk will also include a summary of the background and the experiments done for 1964 10° and other spectral luminous efficiency functions.

**High level objective of photometry and SI definition of the candela**

*Peter Blattner, METAS, Switzerland (CIE Past President) & Gael Obein, LNE-CNAM, France*

Today's definition of the SI is based on seven defining constants. Relevant to photometry is the luminous efficacy of monochromatic radiation of frequency 540 × $10^{12}$ Hz, Kcd. This was implicitly already defined in the previous definition. In the new SI, all the photometric quantities are directly linked to the corresponding radiometric quantities and expressed in terms of the defining constants. Photometry is defined as the "measurement of quantities referring to radiation as evaluated according to a given spectral luminous efficiency." This is explicitly described in the BIPM "Principles Governing Photometry," which was drafted jointly by the CCPR and CIE. This definition dodges the difficulty of the problem. In fact, the 'high level' objective of photometry is the measurement of quantities as they are seen by a human observer. When we say this to people, they invariably respond with the question 'but we are all different, do we all see the same thing?' The answer is 'no'. There are intra-individual and extra-individual variations. The present definition of the SI fits already well for the purpose as it is flexible enough to take into account intra-individuals variations. In the future, knowledge on vision and technical progress may allow us to reduce the gap between the standard observer and the individual by taking into account extra individuals variations.

**History of CIE 1931 and 1964 standard colorimetric systems**

*Sophie Jost, ENTPE, France*

The history of the CIE standard colorimetric systems begins with early theories of color vision. Notably the foundational works by Mariotte (1717) and Young in the early 19th century. The concept evolved through the experimental work of Helmholtz, Grassmann, and Maxwell. In the late 1920's two sets of experiments conducted by Wright and Guild led to the determination of the 2° color matching functions of the CIE RGB system. Those data combined with the the spectral luminous efficiency function of the CIE photometric observer published in 1924 were derived to obtain the CIE XYZ colorimetric system. Later, in 1964 CIE published the supplementary standard colorimetric observer based on 10° colour matching data obtained by Stiles and Burch in England and Speranskaya in Russia.

Overall, the history of standard systems reflects an ongoing effort by CIE to establish internationally recognized frameworks for describing, measuring, and reproducing color accurately and consistently across diverse applications and industries.

**Development of cone fundamentals – CIE 170-1 and CIE 170-2**

*Andrew Stockman, University College London, UK*

Trichromacy depends on the long, middle- and short-wavelength-sensitive (L, M and S) cones and especially on their spectral sensitivity functions. These functions are also known as the "fundamental" colour matching functions (CMFs) or cone fundamentals. All other CMFs, including the XYZ CMFs, should be a linear transformation of the three cone fundamentals.

On the recommendations of TC 1-36, the CIE in 2006 adopted the cone fundamentals of Stockman & Sharpe (2000) as their "physiologically-relevant" international standard for LMS, and in 2015 defined a transformation of the cone fundamental to XYZ that incorporates a new estimate of $V(\lambda)$ by Sharpe *et al*. (2005, 2011). The derivation of these standards will be described.

New developments, including the generation of LMS CMFs that are a continuous function of wavelength and a new trichromator with which we are testing the CIE 2006 standards, will also be discussed.

**CIE's direction for cone-fundamental based colorimetry**

*Lorne Whitehead, University of British Columbia, Canada (Chair of CIE TC 1-98)*

CIE TC 1-98 is nearing the completion of its work to recommend a roadmap for the CIE, with respect to developing of a new, complete, self-consistent system of CIE colorimetric 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. A brief summary of that work will be presented. One possible outcome is that the CIE could make a slight modification to the existing values for the cone fundamentals, and possibly extend those values into the full wavelength range from 360 nm to 830 nm. This raises the possibility of making a corresponding small adjustment to the current luminous efficiency function $V(\lambda)$ so as to base it on cone-fundamentals.

**CIE's direction for cone-fundamental based photometry**

*Tony Bergen (Convenor of CIE RF05, CIE Vice-President Technical)*

Since the adoption of $V(\lambda)$ 100 years ago, photometry has been based largely on broadband sensors whose spectral responsivity is designed to match, as close as possible, the $V(\lambda)$ curve. Although there are new types of sensors, including hand-held devices which perform spectrally-resolved measurements and derive the luminous quantities from these measurements, broadband sensors today still form a vast majority of the measurement devices in use.

The CIE, and in particular the Research Forum RF-05, is considering the impact of a shift to cone-fundamental-based photometry within and beyond the measurement community, taking input from a range of stakeholders including laboratories, equipment manufacturers, lighting manufacturers, researchers and the wider industry. This includes studying methods of quantifying the benefits of changing from $V(\lambda)$ to a cone-fundamental-based observer and considering also the possible disbenefits and potential upheaval in making the change.

**Impact of introducing cone-fundamental-based $V_F(\lambda)$ or $V_{F10}(\lambda)$ in applications**

*Hiroshi Shitomi, NMIJ, Japan*

Cone-fundamental-based photometry proposed by CIE has been attracting attention as a concept that enables us to derive scientifically more reliable data for quantifying visual sensation. Such high expectation leads to intensive discussion about the possibility to adopt a revised spectral luminous efficiency function $V_F(\lambda)$ based on the CIE cone-fundamentals as a standard function to derive photometric quantities, instead of the current CIE standard spectral luminous efficiency function $V(\lambda)$.

In this talk, impact assessment on the introduction of $V_F(\lambda)$ in applications will be presented to provide relevant stakeholders with the basis for the discussion about applicability of $V_F(\lambda)$ for future photometry. The assessment has been made by analyzing potential change of photometric values as well as an instrument quality index for photometers, in the case that the standard photometric function $V(\lambda)$ is replaced with $V_F(\lambda)$.

**Vision experiment on brightness comparison for 1924 $V(\lambda)$ and cone-fundamental based $V_{F10}(\lambda)$**

*Jiaye Li, NIST, USA*

The currently widely used luminous efficiency function CIE 1924 $V(\lambda)$ has a potential underestimation in the short-wavelength region, addressed in many studies. Would the more recently developed cone-fundamental-based V($\lambda$) better represent human perception of brightness? The predictive accuracy of the CIE luminous efficiency functions (CIE 1924 $V(\lambda)$ and the cone-fundamental-based $V_{F10}(\lambda)$) at different wavelength regions have been characterized based on brightness matching data collected from two experiments conducted at KU Leuven and NIST, respectively. The cone-fundamental-based $V_{F10}(\lambda)$ function is found to predict the perceived brightness significantly better than the CIE 1924 $V(\lambda)$ based on the vision data, especially in the blue region. Such a systematic and thorough study on cone-fundamental-based photometry and colorimetry will contribute to the development and recommendation of a perceptually more comprehensive set of luminous efficiency function and color matching functions.

**Estimating brightness perception using the current standard and the cone-fundamental-based spectral luminous efficiency functions**

*Dorukalp Durmus, Pennsylvania State University, USA*

The CIE developed the 2-degree photopic luminous efficiency function in 1924, 10-degree in 1964, and physiological axes more recently. However, the comparative performance of these luminous efficiency functions has not been investigated. A psychophysical experiment was conducted to test the performance of vertical illuminance derived from 2-degree and 10-degree current standard and cone-fundamental based luminous efficiency functions at three chromaticities (2700 K, 4000 K, 6000 K) and three illuminance levels (50 lx, 100 lx, 300 lx) using a 2-alternative forced choice (2AFC) method. In half of the trials the standard observer, around 20% of the trials the alternatives, and in the remaining trials none of them performed well. The mixed results may underline the non-additive nature of brightness perception. Future studies will investigate the accuracy of simpler and more complex spatial brightness models.