CIE Colorimetry and Colour Displays

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Abstract

CIE colorimetry was standardised 65 years ago to describe colorimetric properties of signal lights. The first real application of CIE colorimetry occurred, however, in the textile and coating industries to describe colour matches between sample and reference. Thus also the experiments conducted to achieve a uniform colour scale diagram were performed by using material samples usually illuminated by a daylight simulator. Such experiments led to the recommendations for the CIELAB and CIELUV colour spaces. It has been a misinterpretation that CIELUV is more useful for self-luminous objects, derived from the fact that CIELUV has a chromaticity diagram and CIELAB has non.

In recent years much effort has been invested to obtain a colour appearance model to be able to describe not only colour matches but also the appearance of colours, both as material samples and in order to be reproduced on colour displays. The three fundamental questions in this respect are:

- Are the standard colour matching functions (cmf's) representative of average human colour vision?
- What is the proper description of chromatic adaptation?
- What are the auspices of a CIE colour appearance model?

A number of CIE Technical Committees are working on the different aspects of these questions. The paper presents a short review of the questions raised and, as far as feasible, will outline likely answers.

Introduction, Early History of CIE Colorimetry

Colorimetry evolved on two branches,

- based on vision research, trying to understand the human visual mechanism and building onto this a physically sound metrics; and
- based on artistic observations with the belief that colour sequences must show and order.

Without going into historic details we would like to call the attention to the recent overview of the physical–psychophysical route;[1] and on the route of colour order systems.[2] In the present paper we will follow the physical – psychophysical route, highlighting some of the major steps of the development of CIE colorimetry.

In the attempt to describe the visual impression a light sensation evokes, the CIE first dealt with the visibility of light and in 1924 defined the *relative visibility function,*[3,4] *now termed spectral luminous efficiency function*.[5] The CIE V(λ)-function still serves as basis of all practical light measurements, despite the facts that

- Judd pointed out as early as 1951 that the *V*(λ)-function is in error in the blue part of the spectrum,[6] and CIE introduced the corrected *V*M(λ) spectral luminous efficiency function[7] as a supplementary function to be used if the *V*(λ)-function does not supply accurate enough results (mainly used by vision scientists);
- it became apparent that luminance based on the *V*(λ)-function is not a good descriptor of brightness,[8,9] it describes, however, visual acuity well and thus is a good measure of task-performance, especially if the illumination has a colour that is nearly achromatic.

Following the standardisation of light sensation CIE dealt also with the colorimetric aspects of lights, and introduced the CIE 1931 standard colorimetric system at its meeting in Cambridge, UK.[10] During the past 65 years the system has been amended several times, introducing besides the original 2∞ Observer also a 10∞ Observer,[11] dealing with more complex questions, such as e.g. colour spaces and colour differences,[12-14] metamerism,[15] chromatic adaptation,[16] colour rendering[17] and more recently colour appearance.[18]

CIE Colour Matching Functions and Display Colorimetry

As mentioned, the CIE standardised two sets of colour matching functions, the *CIE 1931 standard colorimetric observer* (2∞ observer) and the *CIE 1964 supplementary standard colorimetric observer* (10∞ observer).[15] It was realised that the 2∞ Observer is in error as it is based on the 1924 V(λ) function, which needed correction.[6,7] With increased use of colorimetry in visual display terminal (VDT) work, and hard-copy – soft-copy comparison where patches that have to be colorimetrically identified are small and where target (e.g. print) and test-sample (VDT realisation) are highly metameric, the re-determination of the colour matching function became timely, and in 1991 the CIE set up a technical committee (TC) to "establish a chromaticity diagram with co-ordinates corresponding to physiologically significant axes" possibly for varying field size and a corresponding set of colour matching functions.

The committee agreed to start with the CIE 1964 colour matching functions (cmf's), transform these to a set of cone system action spectra (*L*(λ), *M*(λ), S(λ)), using Kônig's hypothesis of dichromacy (i.e. dichromacy is due to the complete loss of one cone system), and taking ocular media absorption into consideration. The work of this TC progresses well, and we can hope that in a not too far future we will have at least for the field angle range of 1∞ to 10∞ a continuous set of colour matching functions.[19]

An important question that had to be addressed by the committee was the variability of the cmf's. Investigations showed that photo-pigments have a considerable amount of polymorphism leading to individual differences in the L- and M-cone pigment absorption spectra.[20] Standardised cmf's are averages of many individual cmf's, thus they will be wider than the functions of the single observers. It is an open question how large the colour mismatch due to this individual versus average variation will be in case of the relatively spiky red phosphor of a cathode ray tube (CRT) display. It is, however, a question we will have to live with if visual observations are compared with standardised measurement results.

CIE Colour Difference Equations and Colour Spaces

CIE colorimetry was originally devised to describe colorimetric properties of signal lights. Soon after its introduction it became used in areas of surface colour matching, primarily in the textile, paper and coating industries. Colour difference investigations were conducted either as research items (mainly using aperture colours seen in a dark background) or using material samples in a lit environment (i.e. with chromatic adaptation to the usually achromatic background). Request for a standardised colour difference equation came from the industries using surface colour measurement.

The first officially recommended CIE chromaticity difference equation[11] was based on the work of MacAdam,[21] where a projective transformation of the CIE 1931 chromaticity diagram was used. This was then extended into a three dimensional colour difference equation and associated *U, V, W* colour space,[22] and later modified into the CIE 1976 $L^*U^*V^*$ (CIELUV) space and colour difference equation.[15] This space contains a chromaticity diagram with the coordinates:

$$u' = \frac{4X}{X+15Y+3Z}, \quad v' = \frac{9Y}{X+15Y+3Z} \tag{1}$$

It was often argued that the CIELUV space is for the description of self-luminous sources. This misinterpretation is solely due to the fact that the u',v' chromaticity diagram can be used in a similar form as the familiar x,y-diagram, but the u',v'-diagram is more equidistant than the x,y-diagram. One has to stress, however, that the underlying visual experiments for the construction of the CIELUV space and its testing were mainly conducted using material samples.

The lightness axis of the CIELUV space was devised to approximate the Munsell value scale, but in a much simpler form than the fifth order polynomial of the Munsell renotation.[23] The u^*, v^* co-ordinates of the space were devised to place the neutral axis into the middle of the space, but used only a simple vector translation (differences of the u', v' coordinates of the sample and of the reference white). Colorimetrist knew well that this is far from being an acceptable description of chromatic adaptation and warned from using CIELUV space under illumination other than D65.

During the 1960's and early 1970's a number of colour difference equations were devised, so in 1976 also a second space was accepted by the CIE, known now as CIELAB space. This is an approximation of the Adams-Nickerson space that has been standardised previously by the ASTM.[24] The CIELAB space uses the same L^* coordinate as CIELUV, but uses two further coordinates a^*, b^* constructed as differences of the cube-root of the *X, Y, Z* tristimulus values of the sample ratioed to those of "a specified white object colour stimulus."[15] Again all the underlying experiments were conducted with surface colours, and the relative equi-distantces of the space were tested only for D65 illumination, owing to the ratioing of the tristimulus values (not of cone excitations that would correspond to a von Kries correction) one hoped to have incorporated an approximation for chromatic adaptation into this space.

First the colour display community was devided in using the CIELUV or CIELAB formula. Both of them were experimentally checked against surface colour colour-differences or colour scales (it was well known that small colour differences and large step colour scales lead to different metrics). Visual observations of colour differences on VDTs came only later. In applying either formula one had to make arbitrary decisions on the vague statement of "specified white object colour stimulus" that had to be used in both of them. Now a days it is common practice to use the "peak white stimulus" that can be obtained on the VDT as "specified white" stimulus, and careful experimentators use a white border on their VDT picture to have this stimulus in the visual field.

During the past 20 years many experiments comparing the predictions of other formulae with those of the CIELUV and CIELAB spaces have been conducted. CIE itself continued to be active in the field and in 1995 published a colour difference equation,[14] based on the CIELAB formula, but superseding it considerably.

The new system distinguishes between *perceived colour-difference magnitude*, ΔV, and total colour difference, ΔE^*94:

$$\Delta V = k\mathrm{E}\text{-}1 \cdot \Delta E^*94 \tag{2}$$

where kE may be employed to account for variation in overall perceptual sensitivity under a given set of experimental conditions. The *CIE 1994 total colour-difference* is the distance between two colour samples in lightness, chroma and hue differences with weighting functions and parametric factors:

$$\Delta E^*_{94} = \left[\left(\frac{\Delta L^*}{k_\mathrm{L} S_\mathrm{L}}\right)^2 + \left(\frac{\Delta C^*_\mathrm{ab}}{k_C S_\mathrm{C}}\right)^2 + \left(\frac{\Delta H^*_\mathrm{ab}}{k_\mathrm{H} S_\mathrm{H}}\right)^2\right]^{1/2} \tag{3}$$

where kL, kC, kH are parametric factors, under reference conditions these are unity, but e.g. for textile industry applications kL = 2, kC = kH = 1 is recommended.

SL, SC, SH are weighting functions, adjusting the total colour difference for variation in perceived colour-difference with variation in the colour standard location in CIELAB space. Current best estimates are

$$SL = 1; SC = 1 + 0{,}045\ C^*ab; SH = 1 + 0{,}015\ C^*ab. \quad (4)$$

It will be the task of the next future to establish whether under VDT viewing conditions these parameters and weighting functions are appropriate or not.

Colour Appearance

In colour imaging applications standard colorimetry can be applied to identify the stimuli, but it is not adequate to describe the colour appearance of the originals to be duplicated, and of the soft-copy reproductions on the display. CIE TCs co-ordinate the global activity in this field and foster research to reach an agreed colour appearance model. This work seems to bring its fruits. This March the CIE organised an Expert Symposium dealing with colour standards for the image technology,[18] where the fundamental features of a CIE colour appearance model were laid down.

Dr. Hunt presented an overview of colour appearance model evolvement,[25] and formulated the desirable criteria during the round table discussion of the subject in the following form: The new model must

1. be comprehensive—but static only;
2. be useful from very dark object colours to very bright lights—s-shaped dynamic response function;
3. include an optional of rod intrusion effect correction (starlight to sunlight use);
4. be applicable with white, grey and black backgrounds—average, dim and dark surrounds;
5. function with XYZ or X10 Y10 Z10 and $V'(\lambda)$ inputs with a method of estimating scotopic values;
6. include all degrees of chromatic adaptation (0 to 100%) - cognitive effects and Helson-Judd effect as options;
7. have hue angle, hue quadrature, brightness, lightness, colourfulness, chroma and saturation predictors;
8. be reversible;
9. be as simple as possible;
10. have simplified versions as subsets of the main model;
11. show good performance;
12. have a version for unrelated colours (SE).

The present goal is to present a draft recommendation to the CIE Division 1 by May 1997.

Further CIE Activities Related to Colour Displays and Conclusions

With current importance of VDTs both in vision research and technical applications, the work of almost every CIE TC is related to display use. Appendix 1 summarises the CIE TC number, the title and the Terms of Reference of those TCs, that are most directly involved in colour display work. More detailed report can be obtained on request from the CIE Central Bureau or the relevant TC Chairman. For a complete overview of CIE activities we would like to refer to the CIE home page at http://www.cie.co.at/cie/home.html.

As can be seen from this enumeration, there are more than 20 committees active in the field, covering items of understanding basic visual phenomena up to measurement and calibration issues of VDTs and viewing booth for observation.

CIE is often thought of as an organisation that laid down the fundamental rules of colorimetry—partly perhaps overtaken by modern technologies—but does not contribute to present day needs. I hope I could convince you that this is not the case, CIE is active in many fields, not only in colour, but light and lighting in general, visibility and signalling on roads, questions of actinic effects, etc. What we have to stress, however, is that as new applications of photometry and colorimetry evolve, CIE needs the input of the experts, in this respect we would like to invite you all to contribute to help to identify and solve the pressing problems of using colour in display devises.

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Appendix 1. CIE Technical Committees working on colour display related subjects.

No.	TITLE	TERMS
121	Testing of Supplementary Systems of Photometry	To test existing methods of photometry to evaluate lights for assessing comparative brightness relationships.
126	Individual Variation of Hetero-chromatic Brightness Matching	To analyze existing data on heterochromatic brightness matching in terms of individual variation. To develop a simple test of individual characteristics for brightness matching.
127	Specification of Colour Appearance for Reflective Media & Self-Luminous Display Comparisons	To study and make recommendations for the specification of a colour appearance match between a reflective image and a self-luminous display image.
130	Luminous Efficiency Functions	To approve an ISO/CIE Standard on luminous efficiency functions which classifies and specifies the existing luminous efficiency functions $V\mathrm{p}(\lambda)$, $V(\lambda)$,$V\mathrm{b}(\lambda)$, $V\mathrm{m}(\lambda)$ and $V\mathrm{b},10(\lambda)$ and the colour matching function.
134	Testing of Colour Appearance Models	To investigate the performance of models based on their ability to predict the colour appearance of surface colours in simple and complex scenes under various illumination conditions.
136	Fundamental Chromaticity Diagram with Physiologically Significant Axes	Establish a chromaticity diagram of which the coordinates correspond to physiologically significant axes.
137	Supplementary System of Photometry	To establish a system of photometry to assess lights in terms of their comparative brightness relationship.
138	Compatibility of Tabular Spectral Data for Computational Purposes	To prepare guidelines for tabulating CIE spectral data to promote compatibility of sets of data for computational purposes, considering such factors as spectral range, spectral interval, band-pass function, truncation, interpolatin, extrapolation.
204	Secondary Standard Sources	Produce a technical report on the selection and operation of stable secondary standard sources.
216	Characterization of the Performance of Tristimulus Colorimeters	To produce a report recommending methods for assessing the performance of tristimulus colorimeter heads for measuring chromaticity coordinates.
224	Users Guide for the Selection of Illuminance and Luminance Meters	Prepare a users' guide for the selection and use of illuminance and luminance meters.
226	The Relationship between Digital and Colorimetric Data for Computer-controlled Colour CRT Displays	To produce a Technical Report describing how digital data can be related to colorimetric data for computer-controlled colour CRT displays based on a limited number of digital settings and their measurement.
228	Methods of Characterizing Spectrophotometers	Write a CIE report on the characterization of spectrophotometers by means of reference materials and other methods, with particular reference to linearity, wavelength error, stray light, and integrating sphere errors.
230	Diode Array Radiometry	Prepare an annotated bibliography for the CIE Journal on diode array radiometry. Make appropriate recommendations for future work in diode radiometry.

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233	Re-formulation of CIE Standard Illuminants A and D65 (Revision of CIE/ISO 10526)	To re-write CIE Standard S001 in terms of thermodynamic temperatures, and in a manner such that the spectral distributions of the standard illuminants are preserved, but are independent of international temperature scales.
235	CIE Standard for *V*(l) and *V'*(l)	To prepare a new CIE Standard on the present *V*(l) and *V'*(l) functions.
140	Critical Flicker Fusion Frequency	To investigate fundamental parameters affecting critical fusion flicker frequency (CFF) for the evaluation of flicker in CRT display.
142	Colour Appearance in Peripheral Vision	To prepare a technical report on colour appearance zones for coloured lights in terms of unique hues in peripheral vision.
143	Rod Intrusion in Metameric Colour Matches	To write a report giving a step by step procedure for calculating the effect of rod intrusion on a trichromatic colour match. To use the procedure to calculate the effect of rod intrusion on typical industrial metameric colour matches.
240	Characterizing the Performance of Illuminance and Luminance Meters	Convert the present CIE Technical Report No. 69 into an ISO/IEC Standard. Prepare a combined CIE/ISO standard describing the definitions of quantities influencing the performance of illuminance and luminance meters, as well as defining measurement procedures.
144	Practical Daylight Sources for Colorimetry	1. To intercompare existing daylight sources for colour measuring instruments and colour matching booths. 2. On the basis of this intercomparison, to recommend practical methods for simulating daylight illuminants.
145	Revision of CIE Publication 51 to Include D50 Simulators	To prepare revision of CIE Publ. 51 “A method for assessing the quality of daylight simulators for colorimetry”, including assessment of D50 simulators.
146	Concept and Application of Equivalent Luminance	To write a Technical Report describing the fundamental concepts of equivalent luminance and provide guidelines on how to apply those concepts.
242	The Colorimetry of Visual Displays	To produce a Technical Report summarizing recommended practice for the measurement of the colorimetric and spectroradiometric properties of visual displays.