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TECHNICAL REPORT

The CIE 2016 Colour Appearance Model for Colour Management Systems: CIECAM16

CIE 248:2022

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612.843.31

Descriptor: Perception of colour
Colours of objects
Colour vision

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This Technical Report has been prepared by CIE Joint Technical Committee (JTC) 10 of Division 8 "Image Technology" and Division 1 "Vision and Colour" and has been approved by the Board of Administration, Division 8 and Division 1 of the Commission Internationale de l'Eclairage. The document reports on current knowledge and experience within the specific field of light and lighting described, and is intended to be used by the CIE membership and other interested parties. It should be noted, however, that the status of this document is advisory and not mandatory.

Ce rapport technique a été élaboré par le Comité Technique mixte (JTC) 10 de la CIE Division 8 "Technologie des images" et Division 1 "Vision et Couleur" et a été approuvé par le Bureau, Division 8 et Division 1 de la Commission Internationale de l'Eclairage. Le document expose les connaissances et l'expérience actuelles dans le domaine particulier de la lumière et de l'éclairage décrit ici. Il est destiné à être utilisé par les membres de la CIE et par tous les intéressés. Il faut cependant noter que ce document est indicatif et non obligatoire.

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THE CIE 2016 COLOUR APPEARANCE MODEL FOR COLOUR MANAGEMENT SYSTEMS: CIECAM16

Summary

A colour appearance model provides a viewing-condition-specific method for the transformation of the tristimulus values, X , Y , Z , to or from perceptual attribute correlates. This document describes a specific colour appearance model, CIECAM16, which may be useful for colour management systems that involve related colours. This model is based on the CAM16 colour appearance model and consists of a chromatic adaptation transform and equations to calculate a set of perceptual attribute correlates using the CIE 1931 standard colorimetric observer. It maintains the same simplicity and prediction performance for visual data as the previous model, CIECAM02. The evolution and application of this colour appearance model are presented, as is additional information about the use of the model in practical applications. This Technical Report replaces CIE 159:2004 "A colour appearance model for colour management systems: CIECAM02".

LE MODÈLE D'APPARENCE COULEUR CIE 2016 POUR LES SYSTÈMES DE GESTION DE LA COULEUR: CIECAM16

Résumé

Un modèle d'apparence couleur fournit une méthode spécifique, en fonction des conditions de visualisation, pour transformer des valeurs trichromatiques, X , Y , Z , en ou à partir des attributs perceptuels corrélés à ces valeurs. Ce document décrit un modèle d'apparence des couleurs spécifique, CIECAM16, qui peut être utile pour les systèmes de gestion des couleurs. Ce modèle est basé sur le modèle d'apparence couleur CAM16 qui comprend une transformation d'adaptation chromatique et des équations permettant de calculer un ensemble de corrélats d'attributs perceptuels en utilisant observateur de référence colorimétrique CIE 1931. Il conserve la même simplicité et les mêmes performances de prédiction pour les données visuelles que le modèle précédent, CIECAM02. L'évolution et l'application de ce modèle d'apparence des couleurs sont présentées, ainsi que des informations supplémentaires sur son utilisation dans des applications pratiques. Ce rapport technique remplace la norme CIE 159:2004 intitulée «A colour appearance model for colour management systems: CIECAM02» («Modèle d'apparence des couleurs pour les systèmes de gestion de la couleur: CIECAM02»).

DAS CIE 2016 FARBERSCHEINUNGSMODELL FÜR FARBMANAGEMENTSYSTEME: CIECAM16

Zusammenfassung

Ein Farberscheinungsmodell bietet eine für die Betrachtungsbedingung spezifische Methode für die Transformation der Farbwerte, X , Y , Z , in oder aus Korrelationen von Wahrnehmungsattributen. In diesem Dokument wird ein spezifisches Farberscheinungsmodell, CIECAM16, beschrieben, das für Farbmanagementsysteme mit verwandten Farben nützlich sein kann. Dieses Modell basiert auf dem CAM16-Farberscheinungsmodell und besteht aus einer chromatischen Anpassungstransformation und Gleichungen zur Berechnung eines Satzes von Wahrnehmungsattributkorrelaten unter Berücksichtigung des CIE 1931 farbmetrischen Normalbeobachters. Es ist genauso einfach und leistungsfähig bei der Vorhersage visueller Daten wie das Vorgängermodell CIECAM02. Die Entwicklung und Anwendung dieses Modells für das farbliche Erscheinungsbild werden vorgestellt, ebenso wie zusätzliche Informationen über die Verwendung des Modells in praktischen Anwendungen. Dieser Technische Bericht ersetzt CIE 159:2004 "A colour appearance model for colour management systems: CIECAM02" ("Ein Farberscheinungsmodell für Farbmanagementsysteme: CIECAM02").

1 Introduction

1.1 Overview

This document provides revisions to the CIE colour appearance model for colour management systems that involve related colours, CIECAM02 (CIE, 2004a). The new model, CIECAM16, is mainly based on the CAM16 colour appearance model described by Li et al. (2017), with small changes based on (Wang et al., 2019) and (Gao et al., 2020). It provides forward and reverse transformations. Relevant terminology is presented as well as the evolution and application of the model. The specific revisions are described, and some guidelines and examples are presented to aid in setting the model parameters and to verify the forward and reverse transformations (with a worked example).

1.2 Purpose

The objective of this document is to recommend a new colour appearance model, CIECAM16, to replace CIECAM02 (CIE, 2004a). It also provides additional information about the derivation and use of this model for practical applications to related colours, i.e. colours perceived to belong to an area seen in relation to other colours. This document provides the necessary level of detail for specific implementations of the forward and reverse transformations as appropriate.

1.3 Scope

This document provides a colour appearance model which is applicable for colour management systems, used in the imaging industries, that involve related colours. The main applications of the model are the evaluation of photographic prints (which requires a light source for viewing) and self-luminous displays, where the colours will be perceived as related colours. Background information is provided with respect to basic terminology and the evolution of the model, but it is assumed that the reader is familiar with the basics of colour science (Hunt and Pointer, 2011; Berns, 2019) and colour management (Green, 2010). For additional information regarding the complexities of gamut mapping and colour encoding, interested readers should refer to CIE publication 156:2004 (CIE, 2004b).

There are a number of possible applications for this model, and it is informative to provide a partial list of potential uses. Gamut visualization is a critical aspect in the evaluation of the colour capabilities of a given imaging device, medium or process. CIECAM16 can be useful for the comparison of device gamuts based on a set of perceptual attribute correlates. It is also possible to use CIECAM16 to provide a colour space for gamut mapping. Use of CIECAM16 does not define the domain, range or methodology for the mapping but it does provide perceptual attribute correlates to aid the understanding of the process. As with CIELAB, it is also possible to use CIECAM16 for interpolation, quantization, compression and other image-based applications. Use of CIECAM16 for these applications, however, will require a full understanding of the processing requirements, such as the processing speed, memory requirements, etc. CIECAM16 has been shown to be as good as CIECAM02 (Li et al., 2017) in terms of processing speed, and at the same time it overcomes the problems that have been shown to exist with CIECAM02 (Brill, 2006; Gill, 2008).

It should be noted that the original colour appearance model, CIECAM02, and the new model, CIECAM16, have not been shown to be applicable to the colour appearance of unrelated colours, for example light sources seen in isolation. CIECAM02 and CIECAM16 are also only applicable to photopic levels where the eye is adapted to an average luminance greater than $5 \text{ cd}\cdot\text{m}^{-2}$. CIE TC 1-96 is currently working on the extension of this range down to mesopic and scotopic levels.¹

2 Terminology

A colour appearance model provides methodologies and equations to transform physically measurable quantities to and from viewing-condition-specific perceptual attribute correlates. As a minimum, the model should consist of a chromatic adaptation transform and equations to

¹ The work of TC 1-96 "A Comprehensive Model of Colour Vision" is still in progress. Please check the CIE website regularly for updates regarding the publication of this TC.

derive the perceptual attribute correlates (Fairchild, 2013). This document specifies how the CIE 1931 tristimulus values, X , Y , Z (ISO/CIE, 2019a), can be transformed to and from perceptual attribute correlates. A perceptual attribute correlate is a fundamental univariate colour description or metric. CIELAB (ISO/CIE, 2019b) and CIELUV (ISO/CIE, 2016) include formulae that provide correlates for lightness, chroma and hue. CIECAM16 also provides formulae for these three correlates, as well as for saturation and for the absolute correlates of brightness and colourfulness.

It is useful to define the difference between the adopted and the adapted white points. An adopted white point is the computational reference white point used by a colour appearance model (CIE, 2020, 17-32-033), while an adapted white point relates to the observer or internal human visual system white that results from adaptation in a given viewing condition that includes the test illuminant. Note that the adopted white point may or may not be the same as the adapted white point. One of the most common applications of an adopted white point is to achieve an optimally reproduced device white. For example, an adopted white point corresponding to a given medium may be used in place of an adapted white point when no colorants are used to create a white. An adapted white point can be determined using psychophysics, may be estimated based on a model or otherwise derived. Further complications arise when there are multiple white points, as discussed in CIE 162:2010 (CIE, 2010).

An example for calculating the adaptation luminance, for the evaluation of reflection prints, displays and projected images, is provided in Clause 4 and is applicable for simple stimuli as presented in Figure 1. This simple approximation for the adaptation luminance may not be applicable to other conditions and configurations.

There are also terms (Hunt and Pointer, 2011; CIE, 2004a) related to the visual field that must be defined, and which are illustrated in Figure 1. The stimulus is generally a colour subtending approximately two degrees in the centre of the field of view. The proximal field is the immediate environment of the stimulus, extending typically for about two degrees from the edge of that stimulus in all or most directions. In Figure 1, the proximal field region is represented by a different grey (achromatic) level, but in practice the proximal field can be part of a uniform background surrounding the stimulus, where the background is the approximately ten-degree region that immediately surrounds the stimulus. A useful guideline is that a thumb at arm's length subtends approximately two degrees, and a clenched fist at arm's length subtends approximately ten degrees. The adapting field is considered as everything outside of the stimulus. The surround is the field outside the background and is a categorical term. Its effect can be determined by calculating the surround ratio, which is defined as the ratio of the average luminance of the surround white, L_{SW} , divided by the luminance of the device white, L_{DW} . Both these luminance values should be expressed in $\text{cd}\cdot\text{m}^{-2}$ and can be determined by measurements of the specific device for the viewing conditions under consideration. Additional discussion on the surround is provided in Clause 4. As noted by Hunt and Pointer (2011), the visual patterns of scenes viewed in practice are infinitely variable. The regime of fields described above is an attempt to simplify the situation sufficiently to make it feasible for modelling, while making it possible to include the most important factors that affect the colour appearance under these simplified viewing conditions.

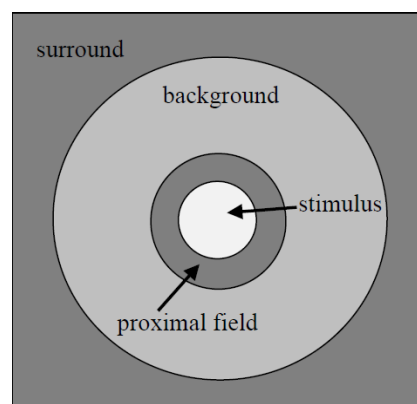


Figure 1 – Illustration of components of the viewing field

The proximal field is not used at present but is included to facilitate future modelling of the effect of simultaneous contrast. The stimulus is considered to subtend a two-degree viewing angle. Thus, the colour appearance model is considered to transform the CIE 1931 tristimulus values, X , Y , Z , to perceptual attributes. It is a fact that the CIECAM97s (predecessor of CIECAM02), CIECAM02 and CIECAM16 colour appearance models, and indeed all earlier models such as those proposed by Hunt (1982) and Hunt and Pointer (1985), were optimized using datasets that were defined in terms of tristimulus values calculated using the CIE 1931 standard colorimetric observer. Although in practice the CIE colour appearance models CIECAM97s and CIECAM02 have also been used to predict colour appearance from tristimulus values calculated using the CIE 1964 standard colorimetric observer, X_{10} , Y_{10} , Z_{10} , there is no experimental research to support this practice.

CIECAM16, like its predecessors CIECAM02 and CIECAM97s, is referred to as a simple colour appearance model in that it predicts the colour appearance of related colours. CIE Technical Committee 1-96 *A Comprehensive Model of Colour Vision* is developing a comprehensive colour appearance model, which will include the size effect for samples that are ten degrees or larger, as well as the appearance of unrelated colours. Much relevant research work has been published, including research for the size effect (Xiao et al., 2010; 2011; 2012; CIE, 2014; Li et al., 2018a), for unrelated colour appearance (Fu et al., 2012; Withouck et al., 2015) and for comprehensive colour appearance (Wei et al., 2017).

3 Evolution of the model

CIECAM16 is based directly on CIECAM02 and was developed to fit all the visual datasets that were used in the development of that model. These visual datasets included colour appearance datasets (Luo et al., 1991a; 1991b; Luo 1993a; 1993b; Luo and Hunt, 1998b; Juan and Luo, 2000; 2002) and corresponding-colour datasets (Helson et al., 1952; Lam, 1985; Breneman, 1987; Mori et al., 1991; Kuo et al., 1995; Braun and Fairchild, 1996; Luo and Hunt, 1998b).

In summary, the CIECAM02 model has the following steps:

- i. the input CIE 1931 tristimulus values, X , Y , Z , are converted into illuminant colour adaptation signals via a linear chromatic adaptation transform, referred to as CAT02;
- ii. the model maps the illuminant colour adaptation signals into cone-like responses using the HPE (Hunt-Pointer-Estévez) matrix (Hunt and Pointer, 1985);
- iii. the model applies a non-linear post-adaptation response compression function to the cone-like responses;
- iv. the model predicts the perceptual attribute correlates from the post-adaptation cone-like signals.

It was found that the CIECAM02 model had the so-called “yellow-blue” and “purple” problems (Brill, 2006; Süssstrunk and Brill, 2006; Brill and Süssstrunk, 2008), which caused unexpected computational failures in certain real applications. In addition, the hyperbolic non-linear post-adaptation response compression function in CIECAM02 had an infinite slope at its origin, which caused an instability problem for both the forward and reverse transformations, when applied in image processing applications. Various solutions have been proposed to these two problems (Gill, 2008; Li et al., 2009; 2012a; 2012b; 2013; 2014; Jiang et al., 2015; Li et al., 2015a; 2017; Wang et al., 2019). The decision on which solutions to choose for the CIECAM16 model (Li et al., 2017; Wang et al., 2019) was made based on both the performance of the revised model in predicting the visual data, and the requirement of computational simplicity. Quantifying the performance is non-trivial but, in general, emphasis was given to at least match the performance of CIECAM02 (Li et al., 2017), while overcoming the problems of this model. Unless otherwise noted, in this Technical Report all terms, parameter names and abbreviations used in CIECAM02 are also used for CIECAM16.

Although CIECAM16 replaces CIECAM02, which had replaced CIECAM97s, the older models will still co-exist for a period of time. Therefore, it is suggested that parameters derived using the earlier models are designated using the subscript “02”, for example lightness J_{02} , for

CIECAM02, and “97s”, for example lightness J_{97s} , for CIECAM97s, while for CIECAM16 unsubscripted variables are used.

3.1 Colour and luminance adaptation

Originally, in the CIECAM02 model, the colour and luminance adaptation took place in different spaces. The colour adaptation process took place in a CAT02 sharp-sensor space and the luminance adaptation process took place in an HPE cone-like space. In the new model the two adaptation processes take place in the same space, which is a new cone-like space. This cone-like space is defined by the matrix M_{16} (Li et al., 2017)

$$M_{16} = \begin{pmatrix} 0,401\,288 & 0,650\,173 & -0,051\,461 \\ -0,250\,268 & 1,204\,414 & 0,045\,854 \\ -0,002\,079 & 0,048\,952 & 0,953\,127 \end{pmatrix}. \quad (3.1)$$

Thus, the CAT02 matrix and the HPE matrix in the original CIECAM02 model are replaced by this new matrix M_{16} , which was derived such that:

- the cone-like response signals (see Equation (5.14) in Clause 5) are non-negative for all input CIE 1931 tristimulus values, X , Y , Z , with their corresponding chromaticity coordinates within the domain enclosed by the spectrum locus and the purple boundary;
- the associated chromatic adaptation transform (named CAT16) fits the corresponding-colour datasets; and
- the resulting colour appearance model fits the colour appearance datasets as best as possible.

In general, chromatic adaptation transforms (CATs) are used for predicting ‘corresponding colours’, defined as pairs of colour stimuli that have the same colour appearance when one is seen in one set of viewing conditions (e.g. a first illuminant) and the other is seen in another different set (e.g. a second illuminant). CIECAM02 and the now introduced CIECAM16 include two one-step CATs (CAT02 and CAT16 respectively): a forward (one-step) transform to convert data from a first illuminant to CIE illuminant E (CIE, 2020, 17-23-023), plus a reverse (one-step) transform to convert the results from CIE illuminant E to a second illuminant. Illuminant E was chosen for two reasons: First, it represents a mid-range colour temperature that corresponds to average daylight, and second, its spectral power distribution has the same energy for each wavelength and hence the relative power has no influence on the colour of an object. Sometimes one-step chromatic adaptation models, that avoid the use of the intermediate illuminant, have been used. This practice, however, is deprecated (Li et al., 2018b), because tests using the one-step CAT16 indicate failures of both the symmetry and transitivity properties, except in the case where the degree of adaptation, D , (defined in Clause 4) is equal to unity. The magnitude of these failures depends on the specific illuminants selected and increases as the degree of adaptation decreases.

From four possible two-step CAT16 models, two were identified that obey the symmetry and transitivity properties, and one of these gives slightly better predictions of the experimental corresponding-colour datasets available in the literature (Li et al., 2018b). Furthermore, with the two-step CAT16 (Li et al., 2018b), the scaling factors D_R , D_G and D_B for each channel (see step 3 in the appendix of Li et al., 2018b) are functions of the Y tristimulus values of the test and reference illuminant, Y_w and Y_{wr} , respectively. The results of an investigation by Gao et al. (2020) however, have shown that it is better to set both Y_w and Y_{wr} equal to 100 when calculating the scaling factors D_R , D_G and D_B . Hence a two-step CAT16 (Li et al., 2018b), with the scaling factors D_R , D_G and D_B , suggested by Gao et al. (2020), is recommended to calculate corresponding colours. The full procedure is described in Annex A.

3.2 Modified hyperbolic post-adaptation response compression function

The use of a hyperbolic function (strictly, a modified hyperbolic function) in CIECAM02 seemed reasonable, based on physiological evidence. Such a function, however, has an infinite slope at the origin (Brill, 2006), which causes instability in both the forward and reverse transformations of CIECAM02. Various proposals (Gill, 2008; Brill and Mahy, 2013; Li et al.,