Research Review of Color Appearance Phenomenon and Models

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Abstract. Color appearance models are of significance for researching in the area of color science, especially the cross-media color reproduction and transfer of images. These models can be used to solve series of problems with color appearance phenomenon, such as color contrast and chromatic adaptation, and can also be used to accurately predicted the perceptual attributes of color appearance under various viewing conditions included light source, illumination level, visual background and medium. In this article, a research review of color appearance models are provided with the illustration of the definition, the characteristics and suitable range, and a summary of the basic framework and development process, application values and areas are also included in this paper with the problems of color appearance models to be solved, aiming to offer the references for the same trades working in color transfer and reproduction related fields.

Keywords: Color appearance phenomenon · Color appearance model · Human color vision

1 Introduction

In the International Commission on Illumination (CIE) standard colorimetric, the color stimulus based on reflecting materials is defined very strictly. It should be viewed in specific conditions with illumination level, uniform background, medium and view geometry, and the color differences are approximate perceived by calculating the length from one stimulus to another in the color space CIELAB [1]. While virtually the changes with color appearance under different conditions cannot be provided with a numberical description due to the non-uniform CIE color space on vision [2]. Thus, the color appearance models are constantly developed by related scientists, which can be used to predicted the perceptual attributes of color appearance accurately, and taking the color appearance phenomenon into consideration, such as chromatic adaptation and color contrast etc.

Color appearance is defined as the perceptual attributes of color stimuli which is related to complicated visual stimulus and varies viewing conditions. Such a series of attributes include brightness, lightness, colorfulness, chroma, saturation, and hue, are

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playing important roles. In terms of the theory of Wyszecki [3], a single color attribute is presented individually, the practical threats of colorimetry are made quite obvious, due to the subjective factors with observers illumination, medium or background. The detail descriptions of attributes are as following:

(1) **Hue**. As one of the judgments of Munsell color order system with the fundamental scaling, the hue is shown by a roundness devided into ten parts of color perception [4]. In fact, in terms of the NCS system, the color appearance can be specified by its similarity to essential color based on different scaling [3].
(2) **Chroma**. It is referred to a numerical scale with maximum and minimum values, which minimum chroma is zero represented a white, or black. With the extending for the chroma numbers, the perception of color will be more evident. On the chroma scaling, two coordinate distances are represented coordinate variations in perceived chroma [5].
(3) **Lightness**. The lightness can also be called the value, is defined on a numerical scaling, in which ranges from zero appointed to have the equal lightness as black, and to ten appointed to have the equal lightness as white for the same color [5].
(4) **Brightness, Colorfulness and Saturation**. To give the color appearance illustrations, these attributes are provides with a kind of transformations between some colors and scaling [6]. Included are scales for brightness (a receptive degree of lightness based on human vision), colorfulness (a absolute value for a color stimuli), and saturation (relative proportion of the colorfulness to brightness based on a stimuli of human color vision, expressed in Formula (1)).

$$S = {}^{C}\!/_{B} \tag{1}$$

When the lowest-level sensory responses of an average human observer are factored in, the phenomenon of color appearance has been entered [7]. More complex visual stimulus can not be illustrated by physical measurements or illumination easily and independently [1]. Besides, some phenomenon of colorimetry have been provided really and truly with characteristics beyond description in human daily life. For example, the scenes usually appear more darker and colorless contrast on an overcast day than on a sunny day [2], or stars disappear from sight during the day time [2].

Some significant phenomenons of color appearance with human color vision are listed as following:

(1) **Bezold-Brücke Hue Effect**. The Bezold-Brücke phenomena, refers to the situation in which the hue of visual stimulus will change when the illumination increases, was defined by Brücke. It is yellower at yellow-green spots and high luminance with the enhance of hue [8]. In addition, the theoretical hue shift is a function of comparison of hues in the color mixture system, it is the matter with displays and other devices, if the hue doesn't shift.
(2) **Shift Abney Effect**. A bundle of monochromatic light, when mixed with white light, not only becomes desaturated but also changes in hue in terms of the Abney effect. Abney published a quantitative study of this effect that has been named after him. The effect describes hue shifts as a function of purity [9]. At that time,

Abney's white was produced by a carbon-arc lamp with a color temperature of nearly 3700 K [10]. However, the choice of white light is crucial when used for adaptations or color-plus-white experiments [11].

(3) **Helmholtz-Kohlrausch Effect**. For a specific color source, the H-K effect is the influence of color purity on the perceived brightness that not only depend on the tristimulus Y value, but also can enhance color saturation with the constant luminance. The so-called Helmholtz- Kohlrausch effect can be provided with the empirical significance of differently saturated colors, which is also related with the description of brightness or luminance discrepancies [12].

(4) **Hunt Effect and Stevens Effect**. Some colors occurs more saturated to the light-adapted eye than to the dark-adapted eye [13], such as the color appearance of objects is more soft and bright in the summer afternoon than in the evening, which are descripted by Hunt. It refers to the brightness of color perception will arise when the level of illuminance is arose, and for the same image, it is explained that the enhance of brightness of illuminance can influence color contrast in terms of Stevens effect.

In addition, some example of color appearance phenomenon related with images are lightness contrast, crispening, hue spreading, color constancy and color memory. etc.

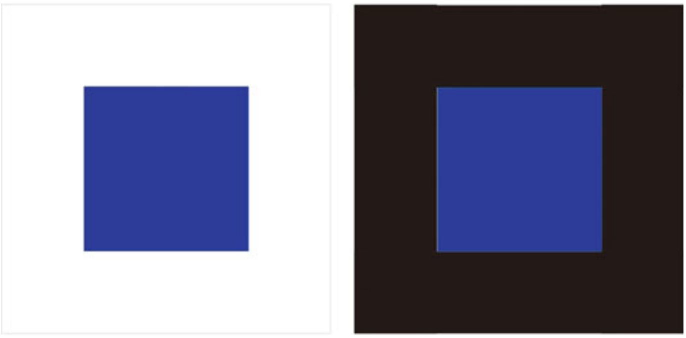

Fig. 1. Demonstration of simultaneous lightness contrast

As can be seen from the Fig. 1, two small blue squares of different lightness, higher on the dark background and lower on the light background, in spite of the fact that they are the same lightness when calculated from their spectral reflectance (physically identical). Moreover, Fig. 2 demonstrates hue spreading, a blurry light-blue annulus in the figure can be observed although the stimulus consists of only gray and blue lines on a uniform white background [14, 15].

More recently, the color appearance model is playing an important role in the modern color research, especially the image appearance model (iCAM) which allows images to reproduce and transfer between two different mediums, and view in different environments [2]. This work provides a review of the description of color appearance

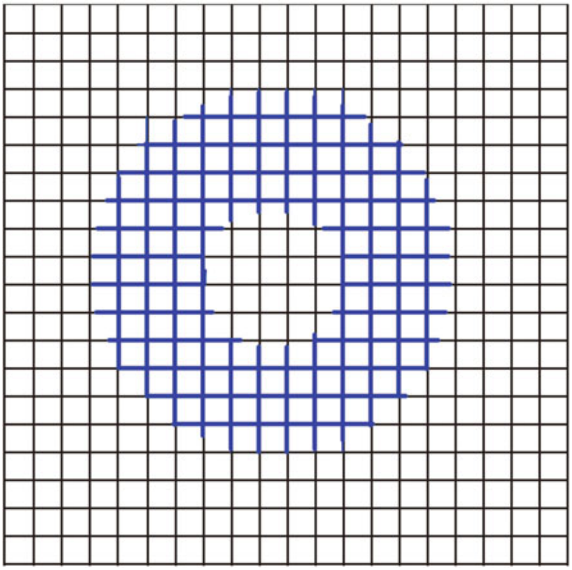

Fig. 2. Demonstration of hue spreading phenomenon

science, including its phenomenon, development process of models and practical application, and related flow framework are also discussed.

2 Color Appearance Models with Basic Framework

Based on the basic colorimety, the color appearance models aim to extend these basal color measurement technologies mathematical model to illustrate the color difference perceptions and color of stimulus in complex viewing environments. Such models have been founded in the late twentieth centuries. There are many models that have been proposed from the CIELAB color space to the iCAM model, among them, CIECAM02 is the symbolic model in modern colorimety.

2.1 Early Models Developed from CIELAB

The CIELAB is a color space that coordinates referred to the 1976 L*a*b*, and it is the prototype of color appearance model because the perceived attributes and their correlates of color can be calculated well from L* (lightness), a* (redness-greenness) and b* (yellowness-blueness) [16]. Figure 3 illustrates the calculation process in which the CIEXYZ values for a stimulus and a white under perfect viewing environments are convert into color appearance in the CIELAB coordinates as approximate connections. Firstly, inputting CIE XYZ values of stimulus and an ideal white, XnYnZn, and then a von Kries-type model of chromatic adaptation acts on the tristimulus values that are standardized to the white point [1]. A cube-root function is represented the standardized values that are controlled to a non-linearity compression, as shown in Formula 2.

Finally, combining with these compressed signals, the values of perception that include L*, a* and b* are expressed by these correlates [2].

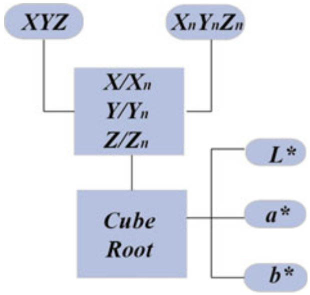

Fig. 3. Flow chart of computation of CIELAB coordinates

$$\begin{cases} L* = 116\left(Y/Y_n\right)^{1/3} - 16 \\ a* = 500\left[\left(X/X_n\right)^{1/3} - \left(Y/Y_n\right)^{1/3}\right] \\ b* = 200\left[\left(Y/Y_n\right)^{1/3} - \left(Z/Z_n\right)^{1/3}\right] \end{cases} \quad (2)$$

However, in the CIELAB, the color differences and tolerances cannot be represented as simple distances so simply, because of the space is non-uniform [17]. Some early attempts have been made to develop the color appearance models with a quantitative calculation in the early 1990s. At first, more quantified models were extended by RWG Hunt in 1982, which is called Hunt color appearance model [18, 19], and by Y. Nayatani and his coworkers, which is called Nayatani color appearance model. Afterwards [20, 21], RLAB color appearance model were proposed by Professor Fairchild on the foundation of color adaptation in 1993, then LLAB color appearance model is proposed by M. R. Luo and coworkers. There is also neural models such as the ATD model proposed by Guth [22, 23]. Another color appearance model is the Retinx theory proposed by E. Land that considers a special distribution of all pixels in the field of view [24].

2.2 CIECAM97s Color Appearance Model

Figure 2 illustrated the asymmetric matching framework of the CIECAM97s color appearance model, which shows two stages [5].

In the first stage, starting with computing the CIEXYZ tristimulus coordinates of a test stimuli with the information of light, and next step is to transform the tristimulus to the cone responses of adaptation under a standardized viewing conditions, and output these adapted cone responses depends on the context that specifying parameters set by users, it can be illustrated in the sigmoidal nonlincarity figure [5]. In the second stage, an illustration of the transformation between color appearance attributes and adapted cone responses is given. It is opponent process model that counts in which these signals are divided into achromatic (A), yellow/blue (Y/B), red/green (R/G), each of them could be provided a set of adapted cone signals, and then transformed the six attributes' values (Fig. 4).

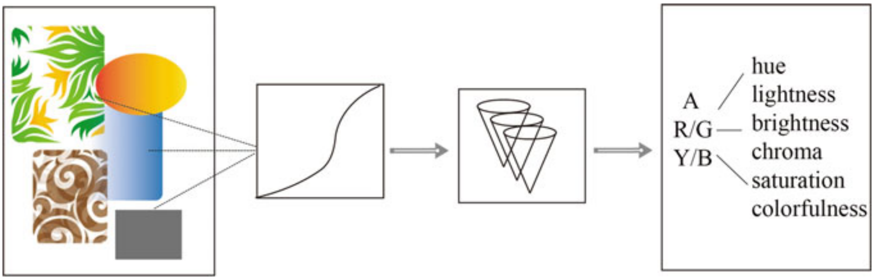

Fig. 4. Flow chart of CIECAM97s, as used to predict color appearance attributes

In general, the research of CIECAM97s bridges basic visual processing with applying on color order system, which takes a various of complex factors into context, such as the adapted of state of observer, the shape and size of stimulus and its global surroundings, and further studies are needed to be done.

2.3 CIECAM02 Color Appearance Model

A basic chart framework of the description of CIECAM02 is shown in Fig. 5. Mainly, some complex factors are considered with the levels of luminance and the relative luminance of surroundings [1]. Through the CAT02, an implicit reference viewing

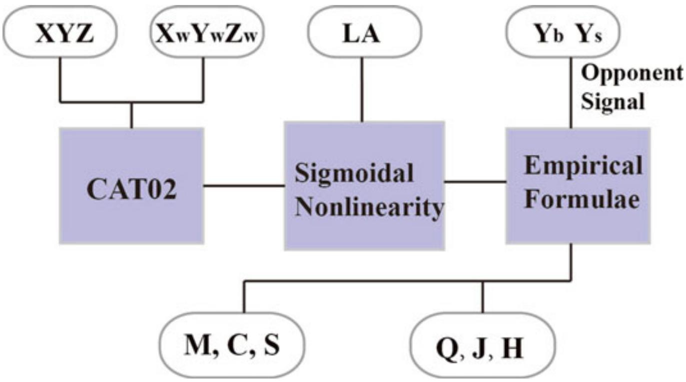

Fig. 5. Basic framework of CIECAM02 with additional input information and output correlates

environment on corresponding colors can be inputted. Those results, outputting computational attributes of chroma (C), brightness (Q), colorfulness (M), lightness (J), saturation (S), and hue (H) through inempirical formulae.

What's more, they still have several issues are not addressed [25], in which can cause the different position between spectrum locus and physiological cone primaries, and it is difficult to acquire the action of primary octant adaptation [26].

2.4 Image Color Appearance Model—iCAM

When the image is transferred and reproduced across different media or display, its color can not be accurately expressed. The object of image color appearance model (iCAM) was to predicted the appearance of complicated conditions and images for practical applications [27]. The framework and initial implementation of the model are presented with examples that illustrate its phenomenon for chromatic adaptation, color difference, appearance scales crispening, spreading, HDR image rendering, and image quality measurement [15].

All the input observation conditions of the iCAM color appearance model are obtained from the image, which framework is classified as two parts. In the first part, to input these tristimulus values that are switched into chromatic adaptation transformation, called CAT02 by a series of computational process. After completing color adaptation, the X'Y'Z' is switched into Image Processing Transform (IPT) [28], which the flow as is illustrated in Fig. 6 [29].

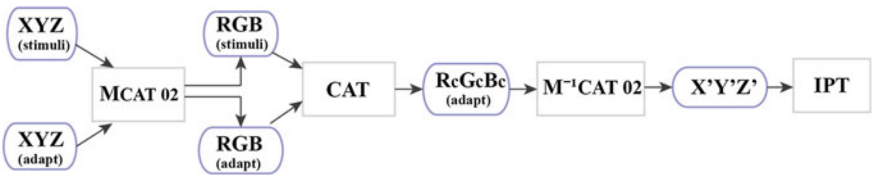

Fig. 6. Flow chart of iCAM to creat IPT color gamut mapping model

Currently, the new iCAM06 color appearance model has been recommended. Combining with the characteristic of uniform color space about color appearance model, the Pixels could be treated as independent color stimuli with consistent viewing conditions, and also can be used for complex image stimuli [27]. It is expected that the implementation of this model framework will be refined as new data become available. What's more, the CAM16 color appearance model with great predictions of color correlates for many application has been given, which can produce high quality and visual experimental results [30]. As a more comprehensive current color appearance model, CAM16 has the applicability of adapt the augmented reality (AR) environments [31].

3 Application and Values of Color Appearance Models

Such color appearance models have been required for practical applications, which not only could be utilized for image collection and related instrumentation in the industry, but also applied with cross-media color reproduction of image.

Firstly, these models are researched on smart display or image capture, in which continuous functions to calculate different surround parameters. It is widely used for mobile phones, PDA and Portable DVD players [32]. They are small and convenient to be carried around and viewed under various surround conditions.

What's more, on the application field of color management technologies, it is divided into CMS (color management systems), CAD (computer-aided design), CCM (computer color matching system), low-light image system, and truly transfer of information for color handlers [33]. To make sure the consistent color appearance of image, an accurate calculating of the corresponding colors under different media and observation conditions should be provided [34]. It is common to see that the soft proofing of the screen can also not be separated from color management system based on color appearance models [35].

Thirdly, the color appearance model can be carried out non-linear color correction, device characterization, color adaptive conversion and device gamut mapping on the foundation of traditional chroma matching technology [36]. Some related research on the influence between color compression and correction are given to match some factors.

Finally, it is possible to extend the use of color appearance models to describe image quality metric, combining with a uniform color space that corresponds with perceptual appearance. A color difference metric also allows to calculate meaningful changes between standard material, and a reproduction of this color. It can be typically achieved by predicting the quality difference between two images. Meanwhile, using their framework as a video quality metric is similar to the image quality metric [37], and it can output in perceptually meaningful terms, such as changes in lightness, saturation, or sharpness.

4 Conclusions

The characteristic color appearance mode is widely utilized in various areas of application in daily life or industrial production, such as standardized CIECAM97s, CIECAM02, and iCAM that are based on traditional colorimetry [38]. Each color appearance model has its own representative framework and contents, with the capacity of transforming from color stimuli of a spatially-simple under specify viewing conditions to practical color appearance attributes that include chroma, saturation, brightness, lightness, and colorfulness.

In this article, a review of popular color appearance models recently used with the illustration of single model framework characteristics, combining with the actual influence of color appearance phenomena on human color vision and viewing conditions [1]. Finally, the application fields and values of these common models are given, mainly performed with the images transfer and cross-media color reproduction. It has been further studied that advances in color appearance models would require more rigorous treatment of spatial appearance phenomenon and a great deal of visual data.

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