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Development and Application of Color Appearance Phenomenon and Color Appearance Model

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Abstract: *In the study on chromaticity of human eye color vision rules, the qualitative and quantitative expression of color can not be separated from the three color perception experience elements: illumination body, color source and observer. The chromaticity stage is established on the basis of color matching and chromatic aberration stage, namely the third stage of the development of CIE chromaticity. Because the traditional CIE LAB color space hue lacks visual uniformity, chromatic aberration calculation is only suitable for the color difference under specific observation conditions. In order to solve the influence of color adaptation, color contrast and other related color appearance model phenomenon, and accurately predict the morphological parameters of color under different light sources, lighting levels, observation background and media, etc., the color appearance model was proposed and continuously developed, which has important application value for the research on the replication and transmission of cross-media color information.*

Keywords: *Color appearance phenomenon, Color appearance model, Visual characteristics*

1. Introduction

CIE chroma system defines three elements: illumination body, color source and observer based on color vision experience. The measurement and expression of color and chromatic aberration are all limited under the fixed three conditions. Due to the lack of visual uniformity in traditional color space, chromatic aberration calculation has its limitations. When people observe the color of samples with the same tristimulus value under different observation conditions, involving lighting conditions, background, medium and observer, their visual perception is different, and the color adaptation, color contrast and other effects caused by them are not accurately predicted in terms of magnitude. In order to meet the requirements of accurate transmission and communication of digital and color, a color appearance model was proposed, which was the third stage of the development of chromatics. It is still necessary to constantly revise the mathematical expression or mathematical model used to predict the color appearance under specific observation conditions.

2. Color Appearance and Its Attributes

The so-called color appearance is defined in GB/T 5698-2001 "color terms" as "subjective expression of color related to color stimulation and material texture". That is to say, it refers to the complex appearance phenomenon caused by the physical conditions of color stimulation and the subjective factors of the observer [1]. The influencing factors mainly include spatial characteristics (size, shape, position, surface texture structure, etc.), temporal characteristics (static, dynamic, flicker, etc.), spectral radiation (brightness distribution), and the observer (attention, memory, motivation, emotion, etc.).

2.1. Hue

Based on the concept of hue in NCS color system, the hue is the visual perception caused by the similarity between a certain color stimulus and one of the four basic colors (red, green, blue, yellow) or the proportion of two of them.

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2.2. Brightness

The brightness refers to the perceptual intensity or subjective brightness of the observer to the brightness of the observed color stimulus.

2.3. Lightness

The lightness refers to the ratio of the brightness perceived by the observer to that of the complete diffuse reflector under the same illumination condition.

$$L=B/Bw \tag{1}$$

2.4. Colorfulness

The colorfulness refers to the amount of color presented by a certain color stimulus or the absolute response value of the human eye to the color stimulus.

2.5. Saturation

The saturation refers to the relative ratio value between the colorfulness and the brightness perceived by the observer according to a certain amount of color stimulus.

$$S=C/B \tag{2}$$

2.6. Chroma

The colorfulness refers to the amount of color presented by a certain color stimulus or the absolute response value of the human eye to the color stimulus.

$$Ch=C/Bw \tag{3}$$

3. Color Appearance Phenomenon

When the CIE tristimulus values (XYZ) of two colors are the same, the human retina has the same visual perception of two colors. But the visual perception of the same two colors is the same only when the surrounding environment, background, sample size, sample shape, sample surface characteristics and lighting conditions are the same, that is, to achieve the matching effect. The main reason for color appearance phenomenon is that two identical colors are placed under different observation conditions, although the tristimulus values are the same, people's visual perception will change. When observing colors in a certain environment, all environmental factors will affect our visual perception, and the color appearance attributes of samples will also change [2].

3.1. Bezold-Brucke Hue

When the brightness changes, the hue of a single stimulus will drift. That is, the hue of the sample does not remain constant when the brightness of the illumination changes. When the brightness value of the light source changes, the hue will shift with the brightness change. The boundary of different hues, such as the transition between the obvious red-orange and blue-purple color regions, will move left and right with the increase or decrease of brightness (as shown in Fig. 1). If it does not move, it is the reason for the display and other devices.

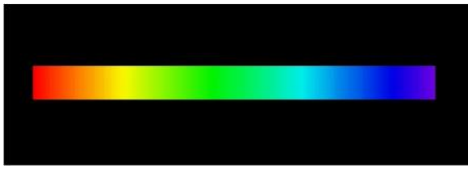

Figure 1: Bezold Brucke hue shift simulation

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3.2. Shift Abney Effect

When a monochromatic light is mixed with white light, the color purity of the illuminated state will be changed, and the hue of the sample will change according to the hue drift effect.

3.3. Helmholtz-Kohlraysch Effect

When the brightness is constant, the brightness increases with the increase of color saturation, which not only depends on the tristimulus Y value.

3.4. Hunt Effect

Chroma varies with the overall brightness, involving lightness and chroma (for example, the color appearance of an object appears bright in the afternoon of summer and becomes soft in the evening).

3.5. Stevens Effect

The lightness contrast increases with the increase of brightness.

In addition to the above color appearance phenomena, it also involves the simultaneous contrast that can be intuitively felt, including the contrast of brightness caused by different backgrounds and the boundary contrast caused by the change of light and shade, as well as the color adaptation, color constancy and memory color related to human visual sense. The human visual system automatically adjusts the response sensitivity of various photoreceptor pyramidal cells on the retina to form a stable vision and automatic color balance phenomenon.

4. Color Appearance Model and Its Development

Color appearance model refers to the mathematical model or expression that can transform the physical quantity and observation condition of color stimulus into the related perceptual attributes of color. It is an extension of basic chromatics and aims to predict the color attributes under various observation conditions. CIE definition: "a color appearance model is any one that includes at least the prediction of relative color appearance attributes. For a model that can reasonably predict these attributes, it includes at least one color adaptation transformation form. If the prediction of absolute color appearance attributes, the brightness, the colorfulness and the interpretation of color appearance phenomenon, a more complex color appearance model is needed" [4]. With the deepening of evaluation research, the color appearance model is constantly developing and changing, and the prediction accuracy is constantly improved.

4.1. Basic Architecture of Color Appearance Model

The forward model of color appearance:

4.1.1. Input Parameters

CIEXYZ transforms to respond to human cone cells to make them more suitable for the next step of color adaptation transformation. Parameters such as white dot tristimulus value, absolute brightness and adaptation factor of adaptation field need to be input before and after the transformation.

4.1.2. Color Space Transformation

The adaptive cone response is transformed into a color space which is suitable for calculating the color appearance attributes. Generally, the HPE space is used to describe the biological response of cone cells.

4.1.3. Nonlinear Compression

It simulates the dynamic nonlinear characteristics of the vision system, quickly adapts to the nonlinear response compresses, applied to the output of the equation.

The reverse model of color appearance: In the process of color adaptation transformation, the source side becomes a reference condition, and the target side is another observation condition. Contrary to the forward model, the consistency of the two parameters can be controlled to solve the problem of cross

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media color reproduction [5].

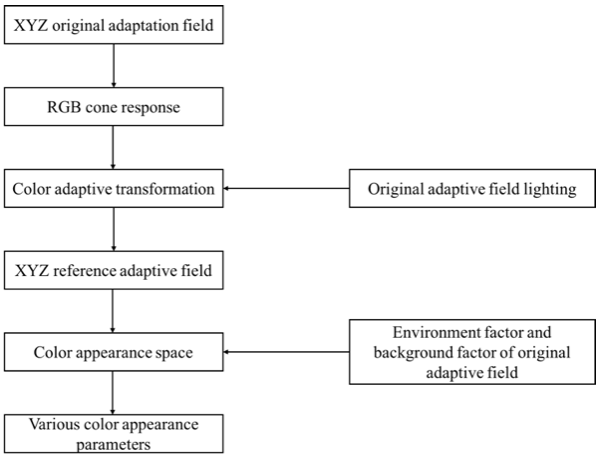

Figure 2: The flow chart for the forward model of color appearance

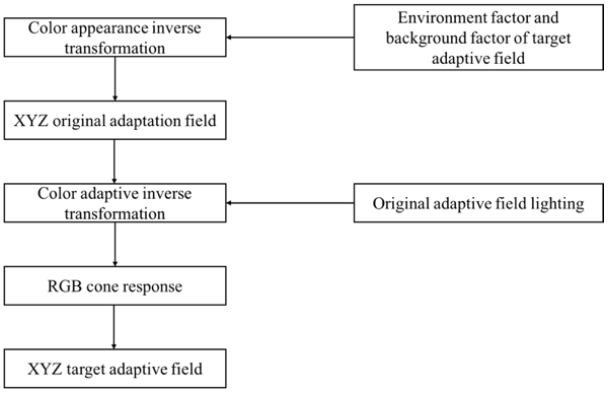

Figure 3: The flow chart for the reverse model of color appearance

4.2. Development of Color and Appearance Model

Initially, CIELAB was actually a uniform color space designed for calculating color difference. It can predict the lightness, the chroma and the hue, which belongs to the rudiment of simple color appearance model [6]. According to (4) and (5), it includes the standardization of the reference white point as the XYZ value, that is, simulating the Von Kries color adaptation transformation, the nonlinear cube root, that is, simulating the visual nonlinear compression and the lightness L, and the chromaticity and the hue can be calculated from the opposite color coordinates a and b.

$$\begin{cases} L^*=116F\left(\frac{Y}{Y_n}\right)-16 \\ a^*=500\left[F\left(\frac{X}{X_n}\right)-F\left(\frac{Y}{Y_n}\right)\right] \\ b^*=200\left[F\left(\frac{Y}{Y_n}\right)-F\left(\frac{Z}{Z_n}\right)\right] \end{cases} \tag{4}$$

$$F(\omega)=\begin{cases} (\omega)^{1/3} & \omega>0.008856 \\ 7.787(\omega)+\frac{16}{116} & \omega\leq 0.008856 \end{cases} \tag{5}$$

But the main problems of CIE LAB include:

Wrong color adaptation transformation: Color adaptation, namely white spot standardization, is not carried out in physiological cone response space, but in XYZ tristimulation space. When the Breneman 1987 corresponding color data is used to evaluate the prediction effect of color adaptation transformation, the prediction result deviates from the actual chromaticity to a certain extent.

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Prediction of lightness L: The purpose of non-linear cube root power function is to simulate the compression relationship between physical measurement and psychological perception. For dark stimuli, the cube root power function should be replaced by a linear function.

Prediction of the brightness and the colorfulness: Only 100% adaptation to white spot is assumed, and incomplete adaptation is not considered.

Influence of ambient light: Only the influence of lighting source color on color appearance is considered, but the factors such as brightness level, surrounding environment and visual perception are not taken into account.

Non uniformity of spatial hue.

The brightness and the chroma are inconsistent.

Following CIELAB, some representative mathematical models for quantitative calculation of color appearance were put forward in the early 1990s. The color appearance under the observation condition and its reverse calculation can be calculated from CIE chromaticity parameters (tristimulus value, chromaticity coordinates, color temperature, etc.) of the preset observation conditions (lighting source, observation field of view, etc.), which provides the necessary theoretical basis for the transmission and communication of color information resources and the color reproduction on the interactive interface [7].

Hunt color appearance model: The Hunt color appearance model was proposed by the British R.W.G Hunt in 1982, which was more elaborate and complex [8].

Nayatani color appearance model: The Nayatani color appearance model was proposed by the Japanese Y. Nayatani in 1986 to predict the color rendering of light source.

RLAB color appearance model: The RLAB color appearance model was proposed by the USA professor Fairchild of Munsell laboratory in 1993 on the basis of color adaptation.

LLAB color appearance model: The LLAB colorappearance model was proposed by the British M.R.Luo in 1996 under the accumulation of a large amount of data.

Based on the above models, a large number of experimental results of color vision physiology and psychology were summarized, and CIECAM97s color appearance model was established. Considering various environmental factors, the calculation examples based on the mathematical model were as follows.

Table 1: The calculation data of CIECAM97s color appearance model

	Parameters		
Stimulus sample	x=0.3618	y=0.4483	Y=23.93
White point of adaptation field	xw=0.4476	yw=0.4074	Yw=90.0
Background	xb=0.4476	yb=0.4074	Yb=18.0
Reference white (isoenergetic light source)	xr=1/3	yr=1/3	Yr=100
Adaptive field brightness	LA=20 (cd/m^2)		
Surrounding environment	F/FLL=1.0	C=0.69	Nc=1.0
Output data	a=-0.4035	b=-0.0246	h=183.5
	H=229.9	Hc=30B.70G	Q=22.29
	s=113.83	C=49.46	M=44.08

According to the calculation example, the color appearance parameters of the stimulus samples were obtained in the environment and brightness factor. But there is an exponential parameter P in the blue channel, and the forward and reverse operation results can not be consistent, so the further correction is needed.

CIECAM02 considers the color of the object under different illumination, observation, background and other conditions, and corrects the existing problems of CIECAM97s. The prediction performance of most perceptual attributes is greatly improved.

The advantages of CIECAM02 color appearance model are as follows.

CIECAM02 adopts the revised linear transformation. It not only considers the influence of compatibility, sharpening and error transfer on the chromaticity scale, but also improves the saturation under different adaptive field luminance (LA). The linear color adaptive transformation greatly reduces

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the computational workload.

CIECAM02 has better spatial uniformity. As a general color model, it has all the functions of color description, color difference calculation and color appearance prediction [9].

CIECAM02 can predict many kinds of human visual phenomena, including Hunt effect, hue drift, illumination refraction and so on, but does not include simultaneous contrast or color induction.

Accordingly, there are still some problems in CIECAM02 color appearance model.

It is not an ideal uniform color space. For example, CIECAM02 color appearance model's visual uniformity of the brightness is not ideal, in addition, the visual uniformity of the hue is not ideal (such as obvious yellow area), which increases the difficulty of gamut mapping algorithm design and color difference formula establishment in color information conversion between media or devices [10].

The color prediction based on a single color block is not suitable for the complex images with different tones and gradation changes.

Color appearance, image quality evaluation and image processing, which are related to spatial and temporal characteristics, have been solved in an independent way without the combination with color appearance model.

The observation conditions of stimuli, such as the background and the environmental factors, are only roughly divided, and they must be under non color background and bright environment, so the accuracy and application scope need to be further improved.

The main function of iCAM model is to complete the traditional color appearance attribute, spatial visual attribute calculation and color difference measurement at the same time. At present, iCAM06 color appearance model is recommended. Based on the feature that the uniform color space of color appearance model does not depend on a specific observation space, each pixel can be treated as an independent color stimulus, and the observation conditions are consistent, which can also be used for complex image stimulus [11].

Its input parameters mainly include: tristimulus values of image and adaptive field, which can be obtained by low-pass filtering of image and used for color adaptive transformation. The absolute brightness that adapts to the field and environment comes from the brightness channel of the low-pass filter image, and the low-pass filter image with a larger spatial range than the image can also be used to predict the contrast of the image.

The input observation conditions of iCAM color appearance model are obtained from images, which effectively simplifies the experimental process. If the prediction of color appearance phenomenon, image color difference calculation, quality evaluation and processing are integrated into iCAM color appearance model, it will achieve better application effect.

5. The Applications of Color Appearance Model

The color appearance models are mainly used to solve the problem of color reproduction in different media under different observation conditions, backgrounds and environments. It is of great scientific and practical value to study color appearance models. The basic research field of color science can be directly used to solve the problems of uniform color space and standard color difference theory. In the field of application research, it can solve the problem of color fidelity between cross media, such as color management system (CMS), computer aided design (CAD), computer color matching system (CCM), low light level imaging system and real color information transmission among Internet users in color reproduction [12].

5.1. Color Correction

The color appearance models can correct the color based on the traditional chroma matching technology, and complete the device characterization, color adaptation conversion and device gamut mapping, so that the color presented by the device is visually consistent.

5.2. Color Management of Screen Soft Proofing

In the color management process of cross media color reproduction, the corresponding colors of

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different media and observation conditions are calculated to ensure the consistency of image color appearance. In the screen soft proofing, using the display screen to simulate the output effect of the printer, it is necessary to convert the image printed by the characteristic printer into XYZ color space, and then input the XYZ image into the color appearance model [13].

5.3. Color Space Uniformity and Color Difference Evaluation

For a uniform color space, in any part of the space, the same brightness difference should correspond to the same visual brightness difference, and the same distance difference should correspond to the same visual difference. It can be combined with Munsell color system to detect the uniformity of each attribute in the color space by using the color appearance models. All data sets need to be converted to the color space of the color appearance model.

6. Conclusion

At present, the research on color appearance and color appearance model is still expanding, including the influence of color stimulus size on color appearance, background influence and simultaneous contrast, color appearance research in large brightness range and large display environment, complex stimulus research and new color appearance model research.

For the color appearance models which are still in the research stage, it is necessary to further improve the color appearance models including CIECAM02 model to simulate the visual process, put forward a more comprehensive model on the basis of the existing models, and carry out the visual experiments to study the visual effects, so as to accumulate a lot of visual data. At the same time, extensive application research and continuous inspection are needed to carry out to solve the problem of true color reproduction [14].

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