Systematic Color Vision Model: Its Applications to Electronic Imaging

Yan Liu
GIA Research, Gemological Institute of America
Santa Monica, California 90404

Abstract

The systematic color vision model is a comprehensive model based on both the zone theory and the retinex theory. This model merges these two theories by a hypothesis of systematic negative feedback control (SNFC) for the human visual system. The SNFC includes two loops: an absolute negative feedback loop which controls the absolute light sensitivities of the cone photoreceptors for achromatic adaptation, and a relative negative feedback loop which controls the relative light sensitivities for chromatic adaptation. Under SNFC the three types of cone photoreceptors have independent light sensitivities. They function as the retinexes in the retinex theory. The color vision signals are processed zone by zone as assumed by the zone theory.

This model also provides a color calculation algorithm and a visual processing framework for the first two zones. This algorithm is based on the von Kries coefficient law and the spectral sensitivities of the three types of cone photoreceptors. Since this algorithm omits the transformation from RGB to XYZ, color modeling for an electronic imaging system becomes easy and accurate. Potential errors of color calculation caused by using the CIE color-matching functions, such as abnormal hue-angle change, can also be avoided.

Keywords: CIELAB, color, imaging, negative feedback control, photoreceptor, visual system, vision.

1. Introduction

The trichromatic theory of color vision is based on the fundamental assumption that there are three independent kinds of cone photoreceptors in the eye. Each kind of cone photoreceptor has a different spectral sensitivity. When the three types of cone photoreceptors absorb light, they generate three types of visual signals. These visual signals are transmitted directly to the brain where color sensations are experienced.[1-2] This theory explains color-matching well by means of an additive mixture of color stimuli. However, the trichromatic theory is inadequate for explaining the way color stimuli appear to an observer. Hering proposed an opponent-colors theory as an alternative to the trichromatic theory.[3] The opponent-colors theory assumes the existence of six basic sensations occurring in opponent pairs: red-green, yellow-blue, and black-white. The opponent-colors theory properly explains color perception or appearance of color stimuli.

Müller first introduced a zone-theory which merged the trichromatic theory and the opponent-colors theory.[4] The zone theory assumes that the three types of cone photoreceptors absorb light and generate three types of visual signals in the first zone. In the second zone, the visual signals are converted to three opponent-color visual signals. Subsequent zones further process the visual signals. The visual signals are finally sent to last zone, which located in the cortex, for color sensation.

Land[5-7] proposed a retinex theory of color vision. “This theory assumes that there are three independent cone systems each starting with a set of receptors peaking, respectively, in the long-, middle-, and short-wavelength regions of the visible spectrum. Each system forms a separate image of the world in terms of lightness that shows a strong correlation with reflectance within its particular band of wavelengths. These images are not mixed, but rather are compared to generate color sensations.”[8]

Chromatic adaptation is a very important phenomenon of color vision. It is more complicated than the von Kries coefficient law and the opponent-colors theory imply.[9] Many studies have shown the existence of negative feedback in the retina.[10-16] This negative feedback control of the visual system is indispensable in the visual processing. However, none of the previous color vision theories took the negative feedback control of the visual system into account.

Both the zone theory and Land’s theory can explain many color vision phenomena. However, each still has difficulties to explain some other color vision phenomena. This paper presents a systematic color vision model which takes the whole visual system, including negative feedback control, into account.[17,18] The systematic color vision model merges the zone theory and the retinex theory by using the systematic negative feedback control of the visual system. The combination of the two color vision theories complement each other to explain color vision phenomena. This systematic color vision model explains all color vision phenomena.

In colorimetry, the color-matching functions are used to calculate color.[19] The CIELAB color space is a uniform color space. It is primarily selected for color calculation and color modeling of electronic imaging systems. However, a recent study of the “alexandrite effect” in gemstones found an abnormal hue-angle change caused by using CIELAB to calculate colors.[20] The cause of the abnormal hue change is due to the color matching functions which are different from the spectral sensitivities of the cone photoreceptors.

Many efforts have been made to improve the systematic color vision model. This paper introduces the negative feedback control of the visual system and the systematic color vision model. This model has a sound theoretical foundation. The systematic color vision model provides a color calculation algorithm based on the spectral sensitivities of the cone photoreceptors and the von Kries coefficient law. This color calculation algorithm solved the abnormal hue-angle change problem. This paper also discusses the method of using the color algorithm for color calculation and color modeling of electronic imaging systems.

2. Negative Feedback Control of the Visual System

Negative feedback control has been shown to exist in the visual system,[10-16] as in any systems. It is vital for the proper functioning of the human visual system. Without it the visual system can not function properly. The SNFC has been hypothesized for the visual system.[17,18] The SNFC regulates the vision processing and maintains a stable visual system. The basic function of the SNFC is to control the sensitivities of the three types of cone photoreceptors. Under SNFC the visual system optimally adapts to the visual surroundings in both achromatic adaptation and chromatic adaptation.

Gouras *et al*[21,22] observed that some cells in the striate cortex respond mainly to brightness and others respond to color contrast, even though all of them share the same cone photoreceptors. Fletcher and Voke pointed out that the separation of luminance information and wavelength information is maintained throughout the visual pathway to the striate cortex.[23] Although the SNFC of the visual system is not fully understood, it can be simplified into two loops due to the separation of luminance information and wavelength information. The two loops are the absolute negative feedback control loop which provides absolute negative feedback control (ANFC), and the relative negative feedback control loop which provides relative negative feedback control (RNFC). The ANFC regulates the absolute sensitivities of the cone photoreceptors, while the RNFC regulates the relative sensitivities. The absolute sensitivities of the cone photoreceptors refer to the sensitivities response to the brightness of the light surroundings, and the relative sensitivities refer to the relative responses of the three types of cone photoreceptors compared to each other.

The ANFC enables the visual system to adapt to a very large change in the brightness of the visual surroundings. The ANFC decreases the sensitivities of the three kinds of cone photoreceptors when the brightness of the visual surroundings increases, and increases the sensitivities when the brightness of the visual surroundings decreases. In some brightness range, the ANFC also adjusts the size of the pupil with the brightness change of the visual surroundings. The pupil size decreases with an increase in brightness, and *vice versa*. The ANFC signal for controlling the size of the pupil is transmitted from the brain to the pupil though a special pathway.

The RNFC adjusts the relative sensitivities of the three kinds of cone photoreceptor to adapt to the color of the visual surroundings. For example, if the visual surroundings increase in redness, such as a decrease in the correlated color temperature of the light source, the RNFC reduces the relative sensitivity of the red cone photoreceptors and increases the relative sensitivity of the blue cone photoreceptors. The major role of RNFC is to maintain the maximum chromatic adaptation to the visual surroundings.

3. The Systematic Color Vision Model

The zone theory assumes that the three types of visual signals generated in the first zone are coded into two chromatic signals and one achromatic signal in the second zone. However, the Land's theory assumes that the three image signals generated by the retinex systems are independent throughout the whole visual processing. According to the Land's theory color perception comes from a comparison of these three image signals. It seems that these two theories are in contradiction. In fact, these two theories are not in contradiction at all. In the first zone, under SNFC, the three types of cone photoreceptors have independent light sensitivities and function just like the retinexes in Land's theory. In the second zone the three independent R, G, and B visual signals are coded into two chromatic visual signals and one achromatic visual signal. Under SNFC, the zone theory and Land's theory naturally merge into one comprehensive model: the systematic color vision model.

Figure 1 shows a schematic diagram of the systematic color vision model. The colored bold lines represent the visual processing network which is similar to the color vision model scheme given by Walraven.[24] In this network, the first zone is the trichromatic photoreceptors zone, the second zone is the opponent processing zone. There are many subsequent zones before the striate cortex where color sensation is experienced. The thin lines represent the RNFC loop and thin dashed lines represent the ANFC loop. The directions of these two loops are backward from that of the visual processing network.

In the first zone, the three kinds of cone photoreceptors absorb light and initiate three independent R, G, and B visual signals. In the second zone, the red (R) and green (G) signals are converted to a yellow (Y) signal by a nonantagonistic process. The red and green signals are also coded into an opponent red-green (R-G) signal by an antagonistic process. The Y signal and the blue (B) signal are coded to an opponent yellow-blue (Y-B) signal. These two chromatic signals are then transmitted to the following zones. In the second zone, the R, G, and B visual signals are also coded into a brightness signal L. This bright signal is sent to the brain through the visual pathway for the brightness sensation.

In Figure 1 the circles in the negative feedback control loops are negative feedback control relays. In the RNFC loop, the relay N1 is responsible for the R-G negative feedback control and N2 is responsible for the Y-B control. The relay N1 receives a signal from the R-G signal, and outputs negative control signals to control the relative sensitivities of R and G cone photoreceptors. The relay N2 receives a signal from the Y-B signal and sends negative control signals to the R, G, and B cone photoreceptors. For example, if the R signal increases, the neutral R-G signal becomes a red signal. This red signal is transmitted to the next zone. At the same time, this red signal is also transmitted to the relay N1. Then the relay N1 sends a red negative control signal to the red cone photoreceptors. This negative control signal reduces the sensitivity of the red cone photoreceptors and thereby reduces the red visual signal output. Therefore, the RNFC loop maintains chromatic adaptation.

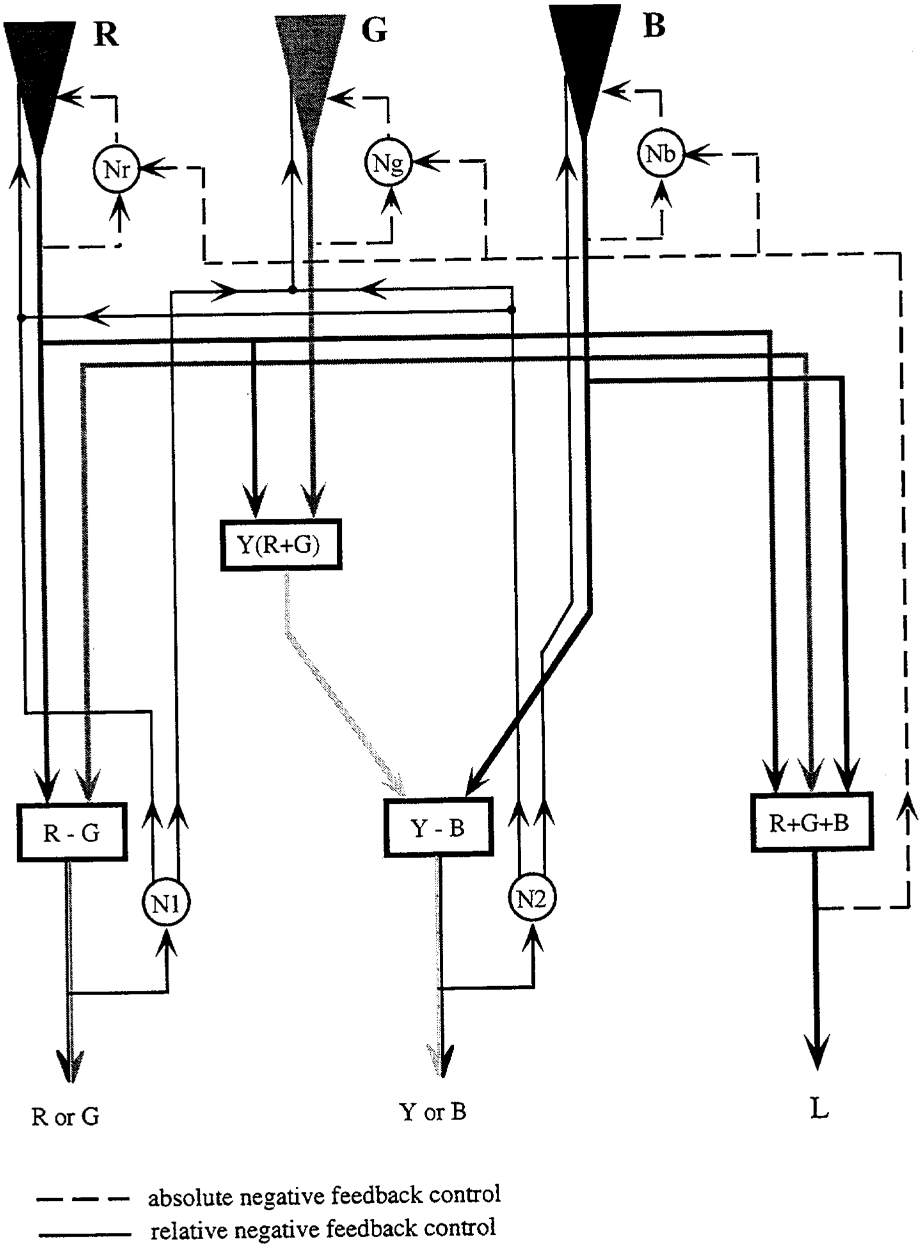

Figure 1. The systematic color vision model.

In the ANFC loop the relays Nr, Ng, and Nb are responsible for controlling the absolute sensitivities of the R, G, and B cone photoreceptors, respectively. Each relay receives signals from the two zones. For example, the relay Nr receives signals both from the R visual signal of the red cone photoreceptor itself and from the brightness visual signal L. If the brightness of the visual surroundings increases, the visual signals of R, G, and B cone photoreceptors increase. In this case, the intensities of the signals received by the relays increase accordingly, and the negative control signals of the three relays increase too. These increased negative feedback signals reduce the sensitivities of the R, G, and B cone photoreceptors, and the output visual signals tend to remain constant. Therefore, the ANFC loop maintains achromatic adaptation.

Under SNFC the three types of visual signals are totally independent of each other in the first zone. In this zone, the three kinds of cone photoreceptors create three separate image signals for a scene. Although these three images are mixed in the next zone, in the first zone they have all the properties of the three separate images of Land's theory. Under full adaptation, the output visual signals of the three types of cone photoreceptors can be assumed to be in a range from 0 through 100, just as in Land's theory.[6] The visual signals are 0 for no light to 100 for the brightest of the visual surroundings.

Figure 2 shows chromatic adaptation of the visual system under CIE standard light source A. Suppose the color of the visual surroundings is neutral, the relative power distribution of the visual surroundings is the same as

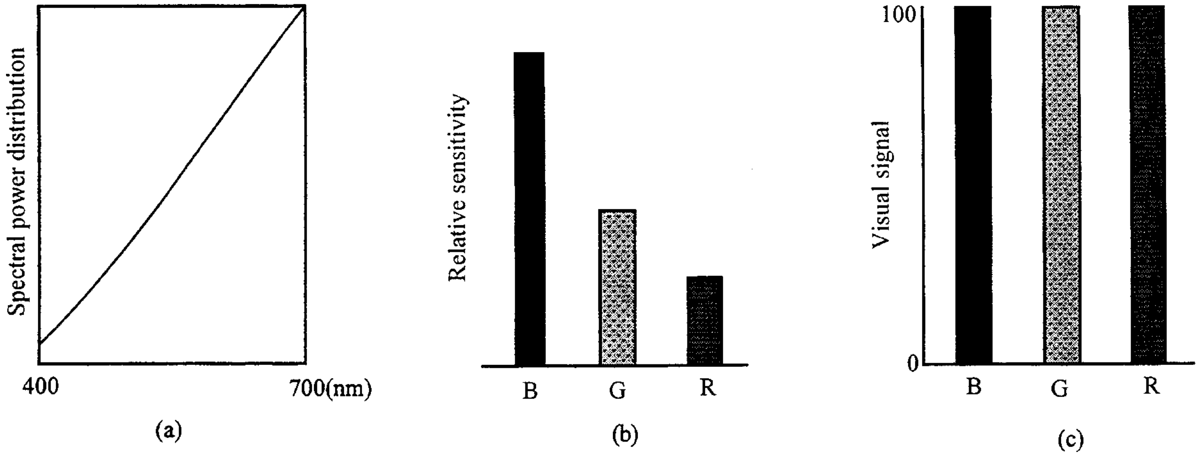

Figure 2. Chromatic adaptation under relative feedback control loop. (a) spectral power distribution of light source A, (b) relative sensitivities of the three types of cone photoreceptors, (c) visual signals of the three types of cone photoreceptors.

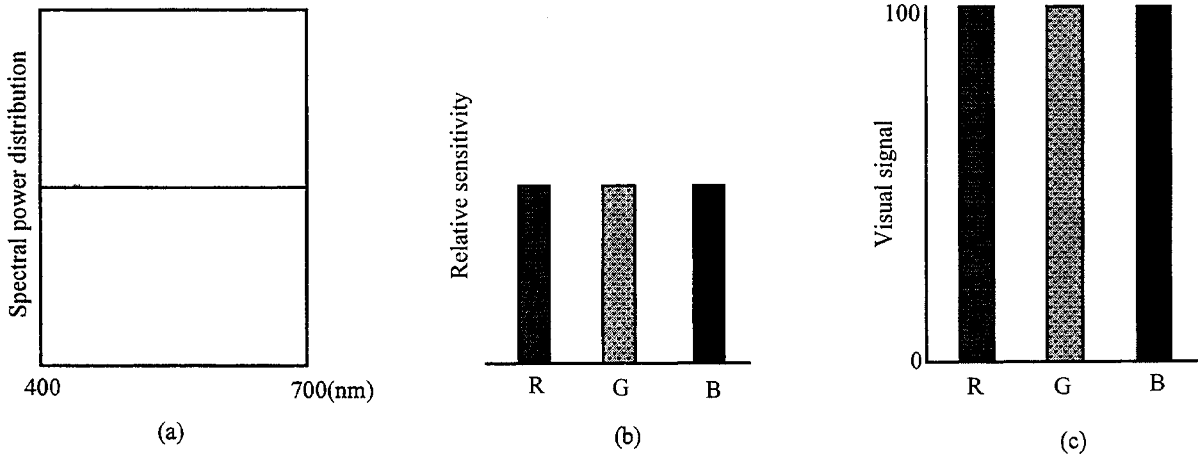

Figure 3. Chromatic adaptation under light source E. (a) spectral power distribution of light thesource, (b) relative sensitivities of the three types of cone photoreceptors, (c) visual signals of the three types of cone photoreceptors.

that of the light source. In the visible range, light source A has much more red light than blue light (see Figure 2a). Under RNFC, the red cone photoreceptor has a low sensitivity, the blue one has a high sensitivity, and the green one has a medium sensitivity (see Figure 2b). High power distribution of light source A in red region and low sensitivity of the red cone photoreceptors produce the same amount of visual signals as that produced by the low power distribution in blue region and high sensitivity of the blue cone photoreceptors. The medium power distribution in green region and medium sensitivity of the green cone photoreceptor also produces the same amount of visual signals. (see Figure 2c) All three visual signals are assumed at 100. Since the visual signals of the three cone photoreceptors are the same, they cancel each other at the following zone.[23] Therefore, the visual surroundings appears neutral.

Figure 3 shows another chromatic adaptation example under light source E. This light source has equal power distribution in the visible region (see Figure 3a). Since the spectral power distribution is equal in the visible region, the relative sensitivities of the three types of cone photoreceptors are all equal (see Figure 3b). The visual signals are also equal (see Figure 3c). The above discussions about the chromatic adaptation are an ideal assumption. The relation between light intensity and the sensitivity is not linear. The amounts of the visual signals may be not equal to cause a neutral sensation. However, the basic explanations about visual adaptation are still hold.

The visual system may not fully adapt to the visual surroundings under RNFC, if the color of the visual surroundings is too saturate. In this situation, the three visual signals are at their maximum possible equality under RNFC. Figure 4 shows an example of partial chromatic adaptation. In Figure 4 the visual surroundings are illuminated by a highly saturated yellow light source. Since the light source has a very little blue light (see Figure 4a), the relative sensitivity of the blue cone photoreceptors is at its maximum. The sensitivities of the red and green cone photoreceptors are normal (see Figure 4b). The visual signals of the red and green cone photoreceptors are 100. Although the sensitivity of the blue cone photoreceptors is at its maximum, the visual signals is still below 100 due to the much lower blue light distribution in the visual surroundings (see Figure 4c). The yellowish appearance of the visual surroundings corresponds to the blue visual signal below 100.

Land and McCann[8] conducted a color constancy experiment. They used three light sources to illuminate an arrangement of colored papers which was called a color Mondrian scene. When one of the three light sources gradually reduced, the colors in the scene appeared unchanged. Under the systematic color vision model, RNFD adjusts the relative sensitivities of the three kinds of cone photoreceptors to adapt to the chromatic change of light source for keeping chromatic adaptation. For example, with the decrease of the blue light source, the sensitivity of the blue cone photoreceptors increase, the end result is that the blue visual signal stays the same. There fore, the color sensation of the scene appears the same.

The visual system cannot chromatically adapt to the visual surroundings, if the blue light source is tuned off. In this case, the blue cone photoreceptors reach their maximum sensitivity (also see Figure 4). The blue cone photoreceptors absorbing a very small amount of blue light from the green light source and even from the red light source still create a faily strong blue visual signal. The blue colors in the scene still appear blue, although they may appear less saturated.

4. Color Vision Algorithm

Many algorithms have been introduced to predict and calculate visual color, such as the von Kries coefficient law, Hurvich and Jameson's hue cancellation of the opponent-colors theory,[25-27] the retinex algorithms of retinex theory,[7,8] and many more. Based on the systematic color vision model, the visual signals depend on the sensitivities of the three kinds of cone photoreceptors, the absorbed light, and chromatic adaptation. The product of sensitivity and absorbed light represents the visual signals. For the quantitative analysis purpose, this product is defined as the visual excitation:

$$E = S\Gamma \tag{1}$$

where S is the sensitivity of a cone photoerceptor, and Γ is absorbed light. If equation (1) is multiplied by Γ_v/Γ_v, it changes to:

$$E = S\Gamma_V\Gamma/\Gamma_V \tag{2}$$

where Γ_V is the absorbed light form the visual surroundings, Γ/Γ_V corresponds to the von Kries coefficient law, and $S\Gamma_V$ can be defined as a relative sensitivity. This leads to the following equations for the visual excitations of the three types of cone photoreceptors:

$$\begin{aligned} E_R &= S_R\Gamma_R/\Gamma_{VR} \\ E_G &= S_G\Gamma_G/\Gamma_{VG} \\ E_B &= S_B\Gamma_B/\Gamma_{VB} \end{aligned} \tag{3}$$

where E_R, E_G, and E_B are the red, green, and blue visual excitations, S_R, S_G, and S_B are the relative sensitivities of the three types of cone photoreceptors, Γ_R, Γ_G, and Γ_B are the light absorbed by the three types of cone photoreceptors, and Γ_{VR}, Γ_{VG}, and Γ_{VB} are the light absorbed by the three kinds of cone photoreceptors from the visual surroundings. Since under full chromatic adaptation the visual signal is assumed as 100, the three relative sensitivities are also at 100. When the visual system can not sustain full chromatic adaptation to the visual surroundings, then one or two values of the relative sensitivities are smaller than 100.

The general form of the equations (3) can be rewritten as:

$$\begin{aligned} E_R &= \frac{S_R\int P(\lambda)R(\lambda)\Phi_R(\lambda)d\lambda}{\int P(\lambda)\Phi_R(\lambda)d\lambda} \\ E_G &= \frac{S_G\int P(\lambda)R(\lambda)\Phi_G(\lambda)d\lambda}{\int P(\lambda)\Phi_G(\lambda)d\lambda} \\ E_B &= \frac{S_B\int P(\lambda)R(\lambda)\Phi_B(\lambda)d\lambda}{\int P(\lambda)\Phi_B(\lambda)d\lambda} \end{aligned} \tag{4}$$

where $P(\lambda)$ is the relative power distribution of the light source, $R(\lambda)$ is the spectral reflectance of the observed color, and $\Phi_R(\lambda)$, $\Phi_G(\lambda)$, and $\Phi_B(\lambda)$ are the spectral sensitivities of the red, green, and blue cone photoreceptors.

In the second zone, the visual signals of the three kinds of cone photoreceptor are coded in both antagonistic and nonantagonistic processes. The red and green visual signals are coded as the yellow signal by the nonantagonistic process-

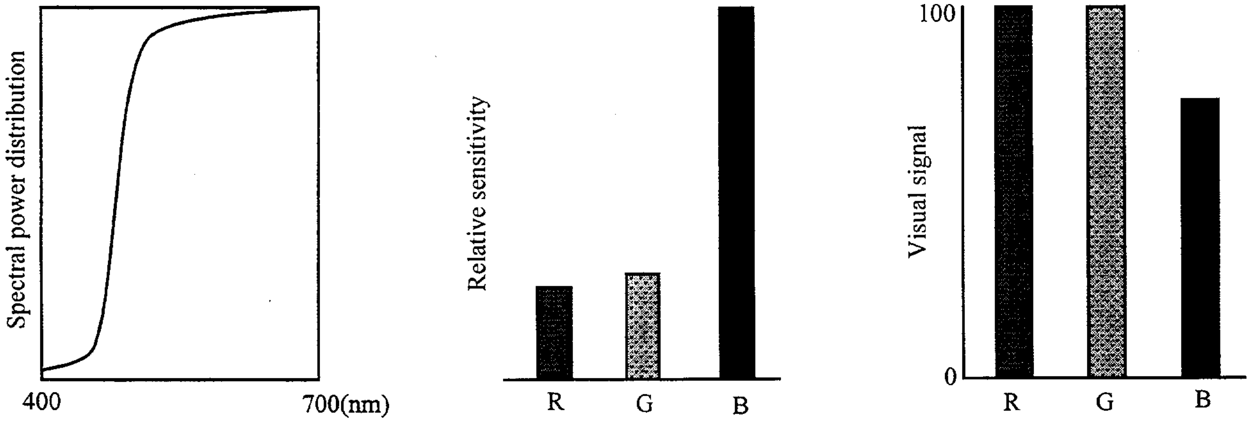

Figure 4. Partial chromatic adaptation under a yellow light source. (a) spectral power distribution of the yellow light source, (b) relative sensitivities of the three types of cone photoreceptors, (c) visual signals of the three types of cone photoreceptors.

ing. In figure 4, Y(R+G) represents the nonantagonistic process. The results of the antagonistic process can be represented by the following equations:

$$C(R,G) = f(E_R - E_G) \\ C(Y,B) = f(E_Y - E_B) \tag{5}$$

where C(R, G) and C(Y, B) represent the red-green and yellow-blue visual signals, and E_R, E_G, E_Y, and E_B, are the red, green, yellow, and blue visual excitations, respectively. The two chromatic visual signals are functions of the visual excitations.

The achromatic signal is processed separately from the chromatic signals. Brightness visual signal can be represented by the following equation:

$$L = f(E_R, E_G, E_B) \tag{6}$$

where E_R, E_G, E_B are the three visual excitations.

Equations (5) and (6) represent the theoretical color calculation algorithm of the systematic color vision model. Since the response of the three types of cone photoreceptors is approximately a cube-root function,[28] this algorithm can be changed to:

$$C(R,G) = f(E_R^{1/3} - E_G^{1/3}) \\ C(Y,B) = f(E_Y^{1/3} - E_B^{1/3}) \\ L = f(E_R^{1/3}, E_G^{1/3}, E_B^{1/3}) \tag{7}$$

Equations (7) are a general form of the color calculation algorithm for the systematic color vision model. We can obtain some approximative functions for the algorithm by experiment. These approximative functions can be used to predict color vision phenomena as well as the color perceptions of objects.

5. Color Calculations

The CIELAB color space is the one most used to calculate color for electronic imaging. A simplified form of equations (7) is:

$$C_{RG} = m(E_R^{1/3} - E_G^{1/3}) \\ C_{YB} = n(E_Y^{1/3} - E_B^{1/3}) \\ L = pE_G^{1/3} + p' \tag{8}$$

where m, n, p; and p, are constants, and C_{RG}, C_{YB}, and L are red-green, yellow-blue, and brightness coordinates. Equations (8) are similar to the CIELAB equations. For calculation purposes, the visual excitation E_Y is replaced by E_G. The above equations can be further changed to CIELAB form:

$$C_{RG} = 500(E'^{1/3}_R - E'^{1/3}_G) \\ C_{YB} = 200(E'^{1/3}_G - E'^{1/3}_B) \\ L = 116E'^{1/3}_G - 16 \tag{9}$$

where E'_R, E'_G, and E'_B are:

$$E'_R = \frac{\int P(\lambda)R(\lambda)\Phi_R(\lambda)d\lambda}{\int P(\lambda)\Phi_R(\lambda)d\lambda}$$

$$E'_G = \frac{\int P(\lambda)R(\lambda)\Phi_G(\lambda)d\lambda}{\int P(\lambda)\Phi_G(\lambda)d\lambda}$$

$$E'_B = \frac{\int P(\lambda)R(\lambda)\Phi_B(\lambda)d\lambda}{\int P(\lambda)\Phi_B(\lambda)d\lambda}$$

The color algorithm of equations (9) contain two modifications to equation (7): first, E_Y is replaced by E_G in C_{YB} calculation, second, only E_G contributes to brightness. This algorithm uses the spectral sensitivity functions of the three types of cone photoreceptors to calculated color, but CIELAB uses the color matching functions.

A recent study showed that using CIELAB to calculate color may cause abnormal hue change.[20] This abnormal hue change can be corrected by using this color calculation algorithm. The abnormal hue change is caused by using the color matching functions to calculate color. This result is not surprising since color perception depends on the spectral sensitivity functions, but the color matching functions are derived from color matching experiments. The spectral sensitivity functions of the cone photoreceptors and the color-matching functions are fundamentally different. The spectral sensitivity functions of the cone photoreceptors represent the color perception of the visual system, but the color matching functions do not.

6. Applications to Electronic Imaging

One application of the color algorithm is for color calculation and color modeling of an electronic imaging system. An input device of an electronic imaging system, such as a three CCD color camera, captures an image and generates three primary R, G, and B signals. The three excitations are R/R_n. G/G_n, and B/B_n, where R_n, G_n, and B_n are the three primary signals of a standard white object. Therefore, equations (9) can be directly used to calculate the colors of the image. For an output device the three primaries can be directly calculated by the inverse operation of the equations (9).

By using the color algorithm, the color modeling of a color imaging system is much simple. The tristimulus values XYZ are not needed. All the transformations can be easily performed by using matrix algebra, which will improve color modeling accuracy. This color algorithm provides a potential means for achieving the device-independent color imaging.

7. Discussions

Negative feedback control exists in any stable system, whether a very simple transistor amplifier or a very complex physiological system. The human visual system is such a system. Negative feedback control of the visual system plays a very important role in color vision processing. In any comprehensive color vision model, the negative feedback control should be taken into consideration. The systematic color vision model is such a comprehensive model. This model is based on the hypothesis of the systematic negative feedback control of visual system and the previous color vision theories. Under SNFC, the three kinds of cone photoreceptors have three independent sensitivities. They function like the retinexes of Land's theory. In the second zone, the three independent visual signals are coded into two chromatic signals and an achromatic signal. These visual signals are processed through the subsequent zones.

The retinex theory and the zone theory do not contradict each another. By the hypothesis of the SNFC, the zone theory and the retinex theory are integrated into the systematic color vision model. This color vision model can explain any of the color vision phenomena explained by previous color vision theories. Detailed explanations of various color vision phenomena have been given by using this color vision model.[18]

Based on the basic properties of the visual signals processing, this model uses a term visual excitation to represent the visual signals for color calculation. The visual excitation is defined as the product of the sensitivity of a cone photoreceptor and the light absorbed by the cone photoreceptor. This visual excitation definition corresponds to the von Kries coefficient law.

Equations (9) is are derived from the color vision algorithm. The equations (9) is a color calculation algorithm which are similar to the CIELAB equations. This color algorithm uses the spectral sensitivity functions to calculated colors, but the CIELAB equations use the color matching functions. Abnormal hue angle change can be avoided by using this color algorithm to calculate color. For practical calculation purposes, E_Y changes to E_G for calculate the C_{YB}. By using E_Y to calculate C_{YB}, we may end up with a more uniform color space. The two pairs of colors, red-green and yellow-blue, will be more symmetrical in this color space.

This color algorithm can be used for color calculation and color modeling of an electronic imaging system. If the spectral responses of the three primary colors of a device in an imaging system are built according to the spectral sensitivity functions of the cone photoreceptors, the colors can be directly calculated by this color algorithm. By using this color algorithm, color modeling can be accuracy and simple.

8. Conclusions

The zone theory and Land's theory of color vision naturally merge into the systematic color vision model by the hypothesis of systematic negative feedback control. This color vision model is a comprehensive model which can explain all color vision phenomena. The visual excitation, the product of sensitivity and absorbed light, is defined for quantitative analysis of the visual processing. The color calculation algorithm is derived from visual signal processing and the von Kries coefficient law. This algorithm represents the color perception of the human visual system.

Color calculation and color modeling for an electronic imaging system by the color calculation algorithm are both simple and accurate. This color calculation algorithm may result in device-independent color imaging.

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