EUROGRAPHICS 2014 / E. Galin and M. Wand *Short Paper*

A Tone Reproduction Operator for All Luminance Ranges Considering Human Color Perception

Michihiro Mikamo, Bisser Raytchev, Toru Tamaki and Kazufumi Kaneda

Department of Information Engineering, Hiroshima University

Abstract

In this paper, we present a novel tone reproduction operator that is able to handle the color shift that occurs in photopic, mesopic, and scotopic vision, using a model based on a two-stage model of human color vision and psychophysical data obtained from measurements of human color perception. Since conventional methods are limited to generating images under a certain visual condition, it is difficult to apply just one operator to deal with scenes with continuous change within a wide luminance range, such as various scenes in movies. To overcome this problem, we have developed a model based on psychophysical data involving wavelength discrimination within a wide luminance range, which provides us with clues about the change of color perception. That is, the spectral sensitivity shifts toward the short wavelengths and decreases according to the adaptation light levels. By integrating the wavelength discrimination into our model, the proposed operator enables us to compute the transition of color perception under a wide range of viewing conditions.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Picture/Image Generation—Display algorithms I.4.8 [Image Processing and Computer Vision]: Scene Analysis—Color

---

1. Introduction

The range of luminance we encounter in everyday life is vast. For instance, from highlights to shadows in a scene, the dynamic range would be four orders or more. To store such a wide range of luminance, high dynamic range (HDR) images can be used [DM97]. High dynamic range imaging is an approach to render realistic scenes using HDR images. These provide relative values to physically accurate measurements, but displaying them requires to reduce the luminance range as the dynamic range between an image and a display device can differ. This problem is known as the tone reproduction problem [RSSF02].

Conventionally, researchers have been focusing on reducing the luminance range only. Nowadays, however, solving the tone reproduction problem is being recognized to involve not only reducing the dynamic range to a displayable range, but also reconstructing the color appearance to be similar to the original scene [Rei11]. In fact, some color appearance models were developed for dynamic range reduction, such as the method in [FJ02]. However, modeling human color perception from low to well-lit conditions is still considered a difficult problem because of the wide luminance range.

The blue shift, also known as the Purkinje shift, is one of the remarkable features that occur in the human visual system. It brings a change of functionality of the cones and rods in the retina. Depending on how these visual photoreceptor cells work, visual conditions can be divided into three categories: photopic, mesopic, and scotopic vision. Photopic vision is mediated by cones and color perception is accurate in well-lit scenes. As the condition shifts to scotopic vision, rods are becoming predominant and color perception decreases. Mesopic vision ranges in between those above mediated by cones and rods. Colors are perceived but in a distorted way.

We have developed a model based on psychophysical data involving wavelength discrimination that provide us with clues about the Purkinje shift. That is, the spectral sensitivity shifts toward short wavelengths and decreases according to the change of adaptation lighting levels. Our model includes those features of the spectral sensitivity that enable us to simulate the Purkinje effect occurring according to the adaptation lighting levels. Our model focuses only on the color shift in fully adapted luminance levels. Other perceptual effects, such as the change of visual acuity in scotopic vision and the time-course of adaptation, are presently not

DOI: 10.2312/egsh.20141004

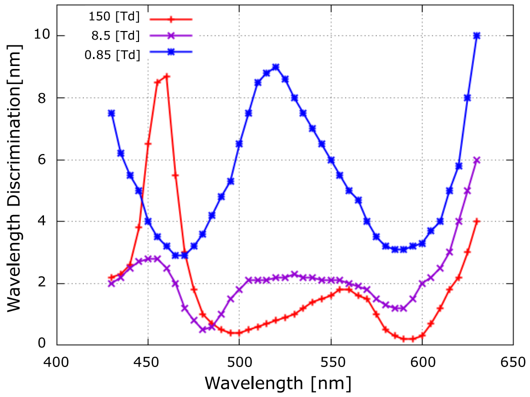

Figure 1: *Wavelength discrimination curves for three different levels of adapted retinal luminance. Adapted from [McC60].*

incorporated, though they would complement the proposed method.

2. Related Work

Several tone mapping operators have been developed to simulate the Purkinje shift. Krawczyk et al.'s method [KMS05] is based on the blue color of scotopic vision and linearly interpolates the original and the blue color using the rod response. Their main contribution is simulating visual effects in real-time from a video. Kirk and O'Brien [KO11] take advantage of experimental data of rod and cone responses directly. On the other hand, the method in [KWK09] adapts their experimental result to represent scenes with high intensity.

Existing methods deal with photopic, mesopic, and scotopic vision separately. Therefore the applications tend to be limited to still images or rendering a scene with a single visual condition. We have developed a model based on psychophysical data involving wavelength discrimination that provide us with clues about the Purkinje effect. Since wavelength discrimination covers a wide luminance range, it enables us to compute the color shift under arbitrary visual conditions.

Another feature of our method is that the model includes data that is directly related to human color perception, while the other existing methods are based on neural responses. Although they provide the evidence of cell and nerve activities, it is difficult to determine the amount of their contribution to color perception. Based on wavelength discrimination, our model makes it possible to compute color perception in photopic, mesopic, and scotopic vision.

2.1. Wavelength Discrimination

Wavelength discrimination is the threshold wavelength difference at which a human viewer can detect the difference of monochromatic lights [McC60, IT78]. Figure 1 shows wavelength discrimination curves for three different retinal illuminance levels (150, 8.5 and 0.85[Td]) [McC60]. The horizontal axis shows the wavelength of visible light. The vertical axis shows the wavelength discrimination corresponding to each wavelength. Figure 1 shows, for example, that when the retinal illuminance is 150 [Td], the wavelength discrimination is about 1 [nm] at 520 [nm], which means that we can detect the difference between 521 [nm] and 520 [nm] monochromatic light.

The inverse of the wavelength discrimination gives the spectral sensitivity. That is, the smaller wavelength discrimination becomes, the higher spectral sensitivity we have. In Figure 1, the wavelength discrimination curves exhibit the following two features related to the Purkinje shift. First, the wavelength discrimination shifts toward the short wavelengths when the adaptation retinal illuminance level decreases. Namely, the spectral sensitivity is becoming higher for the short wavelengths. Second, the wavelength discrimination is also becoming larger for all wavelengths, which means that the spectral sensitivity is decreasing.

Ingling and Tsou developed the expressions for the wavelength discrimination [IT78]. They explained that the L, M, and S cone's spectral sensitivities can be converted to an opponent color spectral sensitivity linearly:

$$o_{rg}(\lambda) = k_1 C_l(\lambda) + k_2 C_m(\lambda) + k_3 C_s(\lambda), \tag{1}$$

$$o_{yg}(\lambda) = k_4 C_l(\lambda) + k_5 C_m(\lambda) + k_6 C_s(\lambda), \tag{2}$$

where, $o_{rg}(\lambda)$, $o_{yg}(\lambda)$ are the red-green opponent and yellow-blue opponent color spectral sensitivities, respectively. $C_l(\lambda)$, $C_m(\lambda)$, and $C_s(\lambda)$ are the L, M, and S cone's spectral sensitivities, and k_1, …, k_6 are corresponding to weights. In their paper, the wavelength discrimination $\Delta W(\lambda)$ is expressed as,

$$\Delta W(\lambda) = \frac{1}{\sqrt{\left(o_{rg}(\lambda)\right)^2 + \left(o_{yb}(\lambda)\right)^2}}. \tag{3}$$

2.2. The Two-Stage Model

In Ingling and Tsou's two-stage model, the visual responses are treated in two color spaces: LMS space and opponent-color space. In the first stage, after light reaches the retina, the L, M, and S-cones respond to it and convert it into electric signals. At the second stage, the signals are converted into opponent-color responses; red-green, yellow-blue, and black-white responses [IT78].

In our work we also employ the two-stage model since it allows to include the parameter functions in the model.

3. Proposed Model

Our model is based on the two-stage model of human color vision [IT78] (see Figure 2). We assume that the input image is a spectral image that contains the absolute intensity of a scene. Our idea is simple: We compute the color of the scene using the spectral sensitivities that satisfy the wavelength

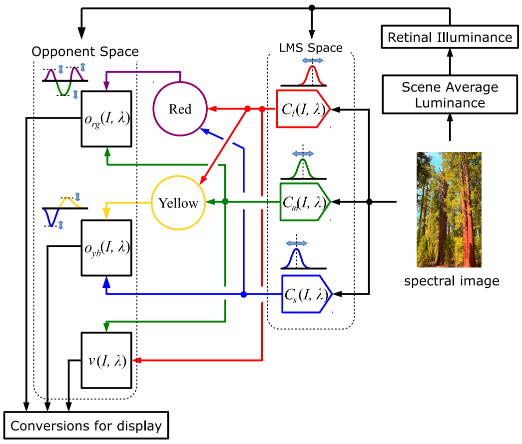

Figure 2: *The overview of our model. Our model is based on a two-stage model of human color vision [IT78].*

discrimination of the adaptation level. Since the wavelength discrimination shows the evidence of the Purkinje shift, the spectral sensitivities derived from the wavelength discrimination inherit that feature.

Using the two-stage model, we first shift the L, M, and S-cone sensitivities toward the visible wavelength. Next, their amplitudes are adjusted to fit the wavelength discrimination in the opponent color space. In order to implement this, we introduce the parameter functions. We apply them to the opponent color spectral sensitivities so that we can obtain the colors for the corresponding visual condition.

3.1. Deriving Parameter functions

Here we derive parameter functions that give the parameters to compose the wavelength discrimination in the adaptation lighting level. Those parameter functions are applied to the first and second stage of the two-stage model.

To follow the wavelength discrimination in the adapted luminance level, we modify Eqs. 1 and 2 so that they can include the shift of sensitivities:

$$o_{rg}(\lambda, I) = k_1(I)C_l(\lambda - \lambda_l(I)) + k_2(I)C_m(\lambda - \lambda_m(I)) + k_3(I)C_s(\lambda - \lambda_s(I)), \quad (4)$$

$$o_{yg}(\lambda, I) = k_4(I)C_l(\lambda - \lambda_l(I)) + k_5(I)C_m(\lambda - \lambda_m(I)) + k_6(I)C_s(\lambda - \lambda_s(I)). \quad (5)$$

In Eqs. 4 and 5 above, $\lambda_l(I)$, $\lambda_m(I)$, and $\lambda_s(I)$ allow the LMS spectral sensitivities to move horizontally, while $k_1(I)$ through $k_6(I)$ change the amplitude of the opponent color spectral sensitivities that bring vertical movement to the wavelength discrimination. These are functions of adapted retinal illuminance I.

We compute the parameter functions $k_1(I)$ through $k_6(I)$, $\lambda_l(I), \lambda_m(I)$, and $\lambda_s(I)$ by applying parameter fitting methods two times. First, we compute sets of parameters that satisfy the wavelength discrimination in known adaptation levels. Next, we follow the transition to derive the parameter functions $k_1(I)$ through $k_6(I)$, $\lambda_l(I)$, $\lambda_m(I)$, and $\lambda_s(I)$.

In the first step, we compute the sets of parameters that satisfy the wavelength discrimination of the known adaptation status in Figure 1. Solving for these from Eq. 3, Eq. 4, and Eq. 5, we obtain a system of nonlinear equations. We chose to solve the optimization problem by using Generic algorithms. After the computation, we obtain the three sets of parameters, $\{k_{1I_m} ... k_{6I_m}, \lambda_{lI_m}, \lambda_{mI_m}, \lambda_{sI_m}\}$ $(I_m = 0.85, 8.5, 150)$.

In the next step, we regard them as a function of the adapted retinal illuminance I. We approximate them using sigmoid functions, as sigmoids are commonly used to approximate non-linearities in visual perception:

$$\lambda_l(I) = -\frac{18.3}{1+7.2I^{-0.7}} - 0.9, \quad \lambda_m(I) = -\frac{44.6}{1+35.4I^{-1.2}} + 22.0,$$
$$\lambda_s(I) = \frac{43.0}{1+9.0I^{-1.50}} + 28.0,$$
$$k_1(I) = \frac{6.69}{1+2500I^{-2.65}} + 0.80, \quad k_2(I) = -\frac{6.24}{1+2500I^{-2.50}} - 0.77,$$
$$k_3(I) = \frac{0.36}{1+50.02I^{-1.50}} + 0.04, \quad k_4(I) = \frac{0.24}{1+50.04I^{-1.70}} + 0.03,$$
$$k_5(I) = \frac{0.42}{1+1.76I^{-0.02}} + 0.14, \quad k_6(I) = \frac{0.15}{1+2.80I^{-0.46}} - 0.27.$$

We apply these parameter functions to Eqs. 4 and 5 so that they satisfy the wavelength discrimination at the adapted retinal illuminance level.

3.2. Applying Parameters and Conversion for Display

Using the above mentioned parameter functions, we get the opponent color spectral sensitivities that satisfy the wavelength discrimination under the adaptation status:

$$\begin{bmatrix} v(\lambda, I) \\ o_{rg}(\lambda, I) \\ o_{yb}(\lambda, I) \end{bmatrix} = \mathrm{M}(I) \begin{bmatrix} C_l(\lambda - \lambda_l(I)) \\ C_m(\lambda - \lambda_m(I)) \\ C_s(\lambda - \lambda_s(I)) \end{bmatrix}, \quad (6)$$

where

$$\mathrm{M}(I) = \begin{bmatrix} 0.6 & 0.4 & 0.0 \\ k_1(I) & k_2(I) & k_3(I) \\ k_4(I) & k_5(I) & k_6(I) \end{bmatrix}, \quad (7)$$

and I is the adapted retinal illuminance obtained by multiplying pupil area A and average luminance of the input image $\overline{L}$ $(I = A(\overline{L}))$. $v(\lambda, I)$ is the achromatic sensitivity in the opponent-color space. Coefficients 0.6, 0.4, and 0.0 originally come from [IT78] for the lightness in opponent space. This is because, to our knowledge, the lightness perception in mesopic to scotopic is still not well-defined.

Using those spectral sensitivities, we can get tristimulus values V, O_{rg}, O_{yb} with the Purkinje shift.

$$Z = \int_{\Omega} S(\lambda) z(\lambda) d\lambda, \quad (8)$$

where Ω is the range of visible light, $Z \in \{V, O_{rg}, O_{yb}\}$, $z(\lambda) \in \{v(\lambda), o_{rg}(\lambda), o_{yb}(\lambda)\}$, and $S(\lambda)$ is the spectral distribution at each pixel.

The following two processes are required to display the result on display devices. First, we need to consider the gap in the viewing conditions - the difference between the conditions under which an image is taken and those under which the viewer sees the image. We apply the inverse matrix $\mathrm{M}^{-1}(150)$ assuming that the viewers are in photopic vision adapted in 150 [Td]. Second, a luminance range reduction is required to make the resulting image displayable. We

(a) 150[Td] (b) 8.5[Td] (c) 0.85[Td]

Figure 3: *Rendering results for the Color Checker.*

(a) 470.2 [cd/m^2] Actual scene average (b) 0.94 [cd/m^2] (c) 0.005 [cd/m^2]

Figure 4: *Results obtained using the proposed method.*

go through Yxy color space to apply a tone mapping operator as in [RSSF02]. The parameter "key" decide the brightness of the result and is automatically set using a method in [KMS05].

4. Results

We used actual spectral reflectance data of the color checker under the condition of D65 light [Mun] to test the proposed method. Figure 3 shows the results when the adapted retinal illuminance is set to (a) 150, (b) 8.5, and (c) 0.85 [Td]. The key was set to a constant to see the changes of color. Each patch is numbered so that it can be easiliy referred in the explanation of the results. Comparing (a), (b) and (c) in Figure 3, it can be seen that all colors became bluish. Especially, we can see the apparent color changes between the orange, reddish and purple patches (#7, #9, #12, #15, #17). They lost their red components and became closer to emerald green. On the other hand, the bluish patches (#8, #13, #10) remain blue. We can also see the changes of color of patch #11 and patch #12 between (b) and (c). In (b), they are close to emerald green, while they are close to cyan in (c). Those are representative features of the Purkinje shift.

Figure 4 shows some other results obtained using the proposed method. From left to right, the scenes were rendered corresponding to conditions of photopic, mesopic, and scotopic vision. The average luminance of the scenes were set to 470.2 (actual scene average), 0.94, and 0.005 [cd/m^2], respectively. The scene was taken on a the sunny day in a forest [Fai08]. As the proposed method needs spectral images as input, we used a RGB-to-spectral conversion based on the method in [Smi99]. In the photopic vision case, the colors are quite vividly. As the light level decreases, the Purkinje shift occurs, namely, the red intensities weaken, while the blue intensities become prominent.

The comparison with existing algorithms are included in the additional media.

5. Conclusion and Future Work

In this paper, we proposed a novel tone reproduction operator that is able to handle wide luminance changes from photopic, mesopic, and scotopic visions, continuously. We developed a model based on the two-stage model of human color vision and psychophysical data involving the wavelength discrimination obtained from measurements of human color perception. The data enables us to model the Purkinje shift on a wide luminance range.

We demonstrated our model both on an actual spectral distribution on the Color checker and on a complex luminance scene. On the Color checker, blue colors remain blue and reddish colors become dim.

For now, our model focused mainly on the Purkinje shift. As a future work, including other perceptual effects, such as changes of visual acuity and applying local adaptation of retinal illuminance to the color shift would be of interest.

References

[DM97] Debevec P. E., Malik J.: Recovering high dynamic range radiance maps from photographs. In *ACM SIGGRAPH 1997 papers* (1997), pp. 369–378. 1

[Fai08] Fairchild M. D.: *The HDR Photographic Survey*. MDF Publications, 2008. 4

[FJ02] Fairchild M. D., Johnson G. M.: Meet icam: A next-generation color appearance model. In *IS&TSID 10 th Color Imaging Conference* (2002), pp. 33–38. 1

[IT78] Ingling C. R., Tsou B. H.-P.: Orthogonal combination of the three visual channels. *Vision Research 17* (1978), 1075–1082. 2, 3

[KMS05] Krawczyk G., Myszkowski K., Seidel H.-P.: Perceptual effects in real-time tone mapping. In *Proceedings of the 21st spring conference on Computer graphics* (2005), SCCG '05, ACM, pp. 195–202. 2, 4

[KO11] Kirk A. G., O'Brien J. F.: Perceptually based tone mapping for low-light conditions. In *ACM SIGGRAPH 2011 papers* (2011), pp. 42:1–42:10. 2

[KWK09] Kim M. H., Weyrich T., Kautz J.: Modeling human color perception under extended luminance levels. *ACM Trans. Graph. 28*, 3 (2009), 27:1–27:9. 2

[McC60] McCree K. J.: Small-field tritanopia and the effects of voluntary fixation. *Optica Acta 7* (1960), 317–323. 2

[Mun] *Munsell Color Science Laboratory: USEFUL COLOR DATA*. http://www.cis.rit.edu/mcsl/online/cie.php. 4

[Rei11] Reinhard E.: Tone reproduction and color appearance modeling: Two sides of the same coin? *19th Color and Imaging Conference* (2011). 1

[RSSF02] Reinhard E., Stark M., Shirley P., Ferwerda J.: Photographic tone reproduction for digital images. In *ACM SIGGRAPH 2002 papers* (2002), pp. 267–276. 1, 4

[Smi99] Smits B.: An rgb-to-spectrum conversion for reflectances. *J. Graph. Tools 4*, 4 (1999), 11–22. 4