Perception-Based Rendering: Eyes Wide Bleached

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Abstract

Perception issues are a key factor in rendering Vision-Realistic images. This paper develops a novel spectral sensitive model of the Human Visual System (HVS) in order to simulate the bleaching effect in retinal photopigments. First, the Stiles-Crawford effect is taken into account to determine the pupil size of the adapted eye and to compute the directional sensitivity of the photoreceptors in the retina. After that, the percentage of bleached pigment based on the incident retinal illuminance is calculated to simulate the loss of spectral sensitivity of the human observer seeing the scene.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Display algorithms–Viewing algorithms

1. Introduction

The Human Visual System (HVS) is our best render engine and the only one that can explain some of the visual phenomena that we can experience.

The eye usually undergoes a loss of spectral sensitivity when it is subjected to high or moderate levels of luminance. This effect is commonly named bleaching and the visual effect is a distortion of the perceived colors. The retina is a compound of photoreceptors called rods and cones. Rods are very sensitive under low lighting conditions whereas cones are active in photopic luminance levels. The cones are referred to as long-, middle- and short-wavelength-sensitive (L, M and S), according to the part of the visible spectrum to which they are most sensitive.

When the light bleaches the pigment in a photoreceptor (a proteine called rhodopsin), its density decreases. The loss of concentration in the photopigment makes the absorption of light diminishes and the range of spectral sensitivity becomes narrower around the wavelength peaks. In the rods, the effects of bleaching on spectral sensitivity are insignificant; instead, very small changes on its pigment density provoke very large adaptive changes in rod sensitivity. On the contrary, in cones, the effects of bleaching on pigment concentration can have large effects on spectral sensitivity and may need to be taken into account when evaluating chromatic adaptation and color matching.

2. Overview

In the process of searching for previous work done in the simulation of the bleaching effect in computer graphics, the authors have detected a lack of defined models. Only a recent work by [GSAM04] has been explicitly proposed. The simulation of the bleaching model for these latter authors has been defined as an ad-hoc model for the effective visual-rendering of sunsets. Therefore, only the red range of the spectrum is taken into account to determine the bleaching factor in L-cones.

Our model studies in depth the full spectral sensitivity of the three kinds of cones and also deals with other related internal stimuli in the HVS as the directional sensitivity of photoreceptors (Stiles-Crawford effect [SC33]), the pupil size in light adaptation and the light absorption in the cristalline lens. The sensitive model proposed here works on spectral physically-based rendered images, and uses image-based techniques proposed by [BHK*03] combined with view data of the scene.

3. Our sensitive model

3.1. Bleaching the photopigments

The percentage of photopigment bleached after a given exposure time and a retinal iluminance has been described in [Alp71]. This time-dependant function describes how the steady level of bleaching is reached more rapidly as the intensity increases. But for very high intensities which produce

Photoreceptor	I_{r0}
Rods	4.4 log scotopic td
L+M-Cone	4.3 log photopic td
L-Cones	3.89 log photopic td
M-Cones	3.89 log photopic td

Table 1: *Half bleaching steady retinal illuminance (after [Rus72])*

immediate bleaching, or for long exposures, it is adequate to use the steady-state form given in Equation 1 [HA73].

$$B = \frac{I_r}{I_r + I_{r0}} \quad (1)$$

where I_r is the incident retinal illuminance hitting a given cone, I_{r0} is the steady retinal illuminance that bleaches half the pigment and B is the percentage of pigment bleached at the cone. Typical values for I_{r0} depending on the type of photoreceptor are given in Table 1. A good estimate for the half bleaching constant for the S-cones has not been obtained, since these kind of photoreceptors are vulnerable even at moderate intensities of blue light, causing long-lasting loss of sensitivity if the bleaching level reaches the 50%.

The units of retinal illuminance $I_r(\lambda)$ are expressed in trolands (td) and computed by multiplying the world luminance $L_w(\lambda)$ (cd/m^2) times the eye pupil area A_p in mm^2 (Equation 2). Therefore, the variations in pupil size are an important factor to compute the effective troland value that reaches the retina; but also the directional sensitivity on the retina (the Stiles-Crawford effect) should be taken into account as an internal stimulus in order to compute the desired effective retinal illuminance.

$$I_r(\lambda) = A_p L_w(\lambda) \quad (2)$$

3.2. The pupil size

The pupil is the main controller of the light that gets into the eye and reaches the retina. When the observer is under very low luminance conditions, the diameter of his pupil increases and can become as large as 8 mm, while at very high luminances it may be as small as 2 mm. Therefore, larger pupils admit more light. Two good relationships between pupil diameter and scene luminance were proposed by [MS44] (Equation 3) and [dGG52] (Equation 4):

$$d = 4.9 - 3\tanh[0.4(\log L_a + 1.0)] \quad (3)$$

$$\log d = 0.8558 - 4.01 \cdot 10^{-4}(\log L_a + 8.6)^3 \quad (4)$$

In these equations, d represents the pupil diameter and L_a is the luminance which the eye is adapted to. The computation of this adaptation luminance is performed averaging the pixels of the image that fall in the 2-degree foveal area of the retina.

3.3. The Stiles-Crawford effect

A ray of light entering from the center of the pupil and hitting a point P in the retina is more visually efficient than another ray entering from a different point of the pupil area and hitting the same point P in the retina. This directional sensitivity effect is commonly referred to as the Stiles-Crawford effect of the first kind and usually abreviated as SCE1.

The accepted explanation for this phenomenon is the optical directionality of the photoreceptors, which would then depend on the incidence of the beam of ligth with respect to the axis of the excited photoreceptor, and to the orientation of the molecules of the visual photopigment it contains.

Among the empirical formulae proposed, we have taken the original one introduced by [SC33] wich relates the relative directional sensitivity η with the distance r between P and P_0 (taken to be the point of entry for maximal η, usually the centre of the pupil) and a wavelength dependant parameter $p(\lambda)$. The SCE1 formula is given in Equation 5 and its classical curve is represented in Figure 1.

$$\eta(\lambda) = 10^{-p(\lambda) r^2} \quad (5)$$

where the parameter $p(\lambda)$ characterizes the magnitude of the directional effect of each kind of photoreceptor (see Figure 2).

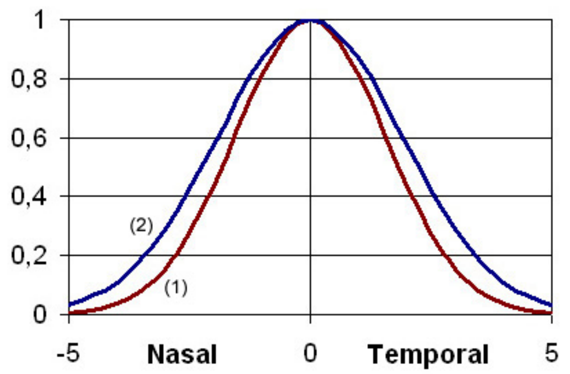

Figure 1: *SCE1 for constant $p(\lambda)$ values: 0.06 (1–Red) and 0.09 (2–Blue). The horizontal axis represents the distance r (expressed in mm) between a given point in the pupil and the point where η has its maximum value. The vertical line at zero marks the the maximal η in the centre of the pupil.*

The Stiles' curve for the parameter $p(\lambda)$ described in [Sti39] was corrected after the studies of [Mel71] on the photometry of the cristalline lens [WS82]. This optical component of the eye acts also as a prereceptoral filter, absorbing part of the light passing through. This absorption is proportional to the thickness of the lens and is greater in the shortwave range of the spectrum. Therefore, we have taken into account this corrected variation of the parameter $p(\lambda)$ showed in Figure 2.

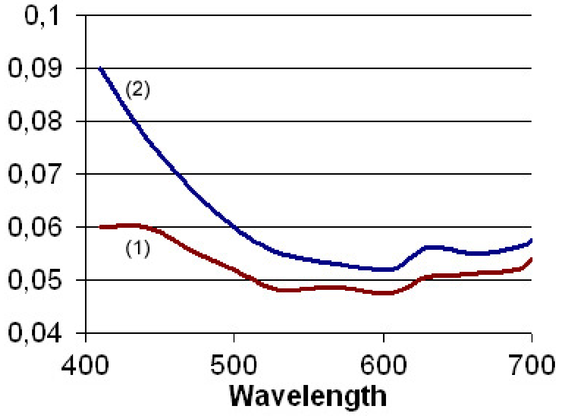

Figure 2: *Wavelength dependence of the SCE1: parameter $p(\lambda)$ after Stiles [Sti39] (1–Red) and Melleiro [Mel71] (2–Blue)*

In order to obtain the spectral illuminace perceived by the photoreceptors, the retinal illuminace calculated in Equation 2 must be weighted by the directional sensitivity η according to Equation 6:

$$I'_r(\lambda) = I_r(\lambda) \times \eta(\lambda) \quad (6)$$

3.4. Undergoing the loss of sensitivity

So far we have seen how to compute the illuminance that reaches the retina due to the pupil, the lens and the SCE1, but the human color vision depends also on the three types of cones that contains, each of which has different spectral sensitivities.

Figure 3 (Top) shows the $\bar{l}(\lambda)$, $\bar{m}(\lambda)$ and $\bar{s}(\lambda)$ 10-deg cone fundamentals proposed by [SMJ93], which are based on the CIE XYZ 1964 10-deg color matching functions [WS82]. We use these cone fundamentals to modulate the retinal illuminance $I'_r(\lambda)$ obtained in Equation 6 and compute the final perceived spectral retinal illuminance for each type of cone as it is showed in Equation 7.

$$\begin{aligned} I_r^L(\lambda) &= I'_r(\lambda) \times \bar{l}(\lambda) \\ I_r^M(\lambda) &= I'_r(\lambda) \times \bar{m}(\lambda) \\ I_r^S(\lambda) &= I'_r(\lambda) \times \bar{s}(\lambda) \end{aligned} \quad (7)$$

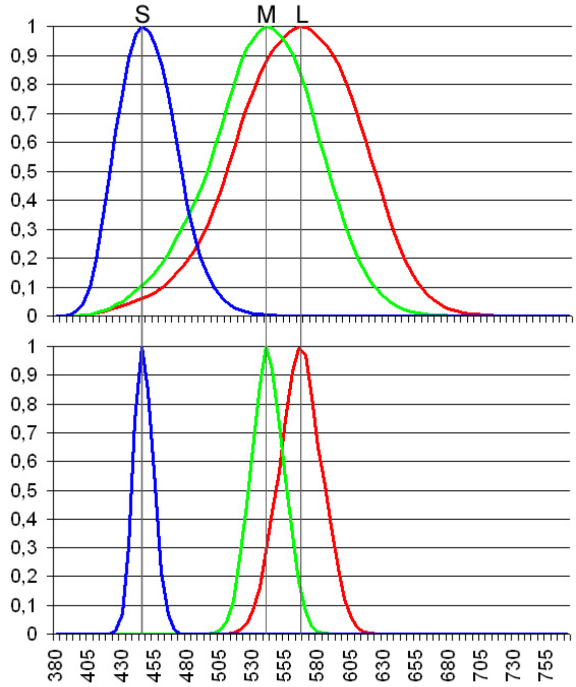

Figure 3: *Top: Spectral Sensitivities $\bar{l}(\lambda)$, $\bar{m}(\lambda)$ and $\bar{s}(\lambda)$ for L-, M- and S-Cones (Red, Green and Blue respectively). Bottom: Narrowed Spectral Sensitivities due to a 50% bleaching factor in each of the three cones. Vertical black lines point out the the spectral peak of sensitivity.*

We only have to integrate each spectral retinal illuminance over the spectrum to obtain the troland values I_r^L, I_r^M and I_r^S. Using Equation 1 and the latter troland values we obtain the percentage of pigment bleached at the L-, M- and S-cone (B_L, B_M and B_S).

The final step before performing the color matching operation is narrowing the cone fundamentals by the amount obtained in the bleaching percentages (see bottom of Figure 3) in order to simulate the bleaching of the photoreceptors. Now we can derive the color matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ from the "bleached" spectral sensitivities $\bar{l}(\lambda)$, $\bar{m}(\lambda)$ and $\bar{s}(\lambda)$ and compute the final perceived color by a bleached eye. For correctly displaying the computed spectral luminances, we use a tone reproduction operator based on [WRP97].

4. Results and conlusions

As we have stated before, our sensitive model works in image-space, performing the described steps for each pixel in the spectral image. First of all and as a global step, the adatation luminance is computed in the 2 degrees foveal area of the image in order to obtain the aperture of the pupil. This foveal area is centered around an interactively selected point.

In this way, this point will be used also as the center of the pupil in order to compute the distance of each pixel in the image for the SCE1. The last assumption in our sensitive model is that each pixel covers a package of three cones (one of each kind).

Figure 4 shows a sunset scene without our bleaching effect. As can be seen, light in the yellow-red spectral range predominates in the picture. Figure 5 shows the result of aplying our sensitive model. The foveal and the pupil centre are in the middle of the sun. The more distant a pixel is, the less noticeable the bleaching effect due to the SCE1. The predominance of the reddish light in the sky provokes more bleaching in the L-cones and that narrows the function $\bar{l}(\lambda)$. The consecuence is that the yellow-red spectral light will have more weight now in the yellow-green range of the M-cone (function $\overline{m}(\lambda)$). That is why a reddish pixel in the image is perceived by the eye as a greenish color after a long exposure time.

Figure 4: *Image reproduced without any effect*

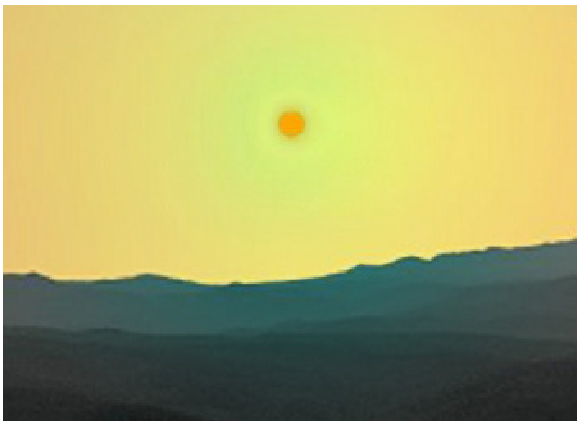

Figure 5: *Image reproduced with our sensitive model of the eye, simulating the bleaching effect*

5. Acknowledgements

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References

[Alp71] ALPERN M.: Rhodopsin kinetics in the human eye. *Journal of Physiol. 217* (1971), 447–471. 1

[BHK*03] BARSKY B. A., HORN D. R., KLEIN S. A., PANG J. A., YU M.: Camera models and optical systems used in computer graphics: Part ii, image based techniques. In *Proc. of the 2003 International Conference on Computational Science and its Applications (ICCSA'03)* (Berlin/Heideberg, 2003), Springer-Verlag, pp. 256–265. 1

[dGG52] DE GROOT S. G., GEBHARD J. W.: Pupil size as determined by adapting luminance. *Journal of the Optical Society of America 42* (1952), 492–485. 2

[GSAM04] GUTIERREZ D., SERON F. J., ANSON O., MUNOZ A.: Chasing the green flash: a global illumination solution for inhomogeneous media. In *SCCG'04: Proc. of the 20th Spring Conference on Computer graphics* (New York, NY, USA, 2004), ACM Press, pp. 97–105. 1

[HA73] HOLLINS M., ALPERN M.: Dark adaptation and visual pigment regeneration in human cones. *Journal of General Physiology 62* (1973), 430–447. 2

[Mel71] MELLEIRO J.: Light absorption ans scatter in the human lens. *Vision Research 11* (1971), 129–141. 2, 3

[MS44] MOON P., SPENCER D. E.: Visual data applied to lighting design. *Journal of the Optical Society of America 34* (1944), 605. 2

[Rus72] RUSHTON W. A. H.: *Handbook of Sensory Physiology VII/I*. New York: Springer-Verlag, 1972, ch. Visual pigments in man. 2

[SC33] STILES W. S., CRAWFORD B. H.: The luminous efficiency of rays entering the eye pupil at different points. In *Proc. Roy. Soc.* (1933), vol. 112, pp. 428–450. 1, 2

[SMJ93] STOCKMAN A., MACLEOD D. I. A., JOHNSON N. E.: Spectral sensitivities of human cones. *Journal of the Optical Society of America 10* (1993), 2491–2521. 3

[Sti39] STILES W. S.: The directional sensitivity of the retina and the spectral sensitivities of the rods and cones. In *Proc. Roy. Soc.* (1939), vol. 127, pp. 64–105. 2, 3

[WRP97] WARD G., RUSHMEIER H., PIATKO C.: A visibility matching tone reproduction operator for high dynamic range scenes. *IEEE Transactions on Visualization and Computer Graphics 3*, 4 (1997), 291–306. 3

[WS82] WYSZECKI G., STILES W. S.: *Color Science: Concepts and Methods, Quantitative Data and Formulae*. Wiley, 1982. 3