Modeling Blue shift in Moonlit Scenes by Rod Cone Interaction

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Abstract

Moonlit night scenes have a tinge of blue. Earlier work to model this perceptual effect has been statistical in nature; often based on unreliable measurements of blueness in paintings of moonlit night scenes. Needless to say there is a need of a more reliable and accurate model. We present a model based on the physiological functioning of the retina and how the rod and cone cells in the retina interact in moonlight conditions to generate the perception of blue.

All model components are derived from published quantitative measurements from physiology, psychophysics, color science, and photography.

CR Categories: I.3.3 [Computer Graphics]: Picture/image generation – Display algorithms; I.4.3 [Image Processing and Computer Vision]: Enhancement – Filtering.

Keywords: Blue shift, adaptation luminance, response function.

1 Introduction

If you go outside on a purely moonlit night the surrounding appears to have a tinge of blue. This phenomenon often referred to as 'Blue Shift' is a perceptual illusion. Moonlight itself is not blue; moonlight is simply sunlight reflected off the grayish surface of the moon.

It is hard to observe blue shift in cities due to many artificial sources of light (buildings, street lights, cars etc), but it's a commonly observed phenomenon in places with low ambient light like a small village, a desert or a mountain range. This unique perceptual effect has long been romanticized by poets and artists for its beauty. Conversely many film producers use a blue filter over the lens when filming night scenes [1] to give a more natural feel. Photographers use a tungsten balanced film to register the blue shift as they perceive it. Computer animation practitioners also tend to give a cooler palette for dark scenes than light scenes [2].

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2 Earlier Work

Considering how important blue shift is to our experience and understanding of the night sky there has been surprisingly little research on it in the computer graphics community. Henrik et al [3] in their comprehensive night rendering model deal with blue shift in an empirical fashion. They crop off the scotopic regions from several paintings of night scenes and find the average chromaticity of the pixels. This average is used as a hypothetical blue. To blue shift an image they translate the image pixels towards the hypothetical blue point. The method has several draw backs and limitations as mentioned by the authors of the paper themselves. Primarily it heavily relies on the accuracy of finding a hypothetical blue or centre point towards which image pixels would be shifted. Unfortunately this is done by simply averaging out the chromaticity of scanned images of realistic paintings of moonlit scenes.

As already mentioned, blue shift is a perceptual illusion. Moonlight illuminating the scene is itself not blue; it is in fact warmer (redder) than sunlight. The only conclusion that can be drawn from this is that the illusion of blueness in moonlit nights is entirely a result of the way the retina processes moonlight. This paper investigates the physiology of the retina to understand the mechanism responsible for blue shift. And develops a model based on these findings to provide a generic, reliable and accurate way of incorporating blue shift in moonlit night scenes.

After reviewing the necessary background of retinal physiology in section 3 we give detailed derivations of the model components in section 4. In Section 5 we discuss results and performance of the model.

3 Physiological Background

The human visual system is optimized to cover a huge range of environment light intensities (10^{-4} to 10^{6} cd/m^2, about 10 $\log_{10}$ units). This is achieved by the existence of two types of photoreceptors, the *rods* and the *cones*, with different sensitivities along with several complex adaptation phenomena in the retina.

The rod cells are highly sensitive to light. Rods work best in dim light less than 10^{-1}cd/m^2. They provide achromatic vision in dark conditions known as *scotopic* vision. The cone cells on the other hand are less sensitive than the rod cells. They are active in dim to bright light (10^{-1} to 10^{6} cd/m^2). While there is only one type of rod cells, cones are of three different types. These are often referred to as L, M and S cones whose sensitivities correspond to red, green and blue portions of the spectrum respectively. In combination they allow us to perceive different colors. A consequent of cone insensitivity at low light levels is the loss of color vision. This is precisely why we perceive objects in shades of gray in a dark room (only the rods are functioning). In the light intensity range 10^{-1}cd/m^2 to 10cd/m^2 both rods and cones make significant contributions to the visual response. This is known as the *mesopic* vision. Beyond 10cd/m^2 rods are blinded by saturation and only the cones are responsible for visual stimulation. This form of vision is known as *photopic* vision.

The signals generated by the rods and cones are gauged and modulated by a series of neural circuits within the retina before they reach the visual cortex inside the brain. The 'Bipolar' cells collect signals from the photoreceptors and form the input layer of this neural circuitry. The 'Ganglion' cells are the output neurons. It is these ganglion cells that form the optic nerve carrying all visual information from the eye to higher visual centers inside the brain. There are three types of bipolar cells. 'Off-bipolar' cells and 'On-bipolar' cells process signals generated by the cone cells, while the third type often referred to as the 'Rod-bipolar' cells are designed specifically to process the rod signal.

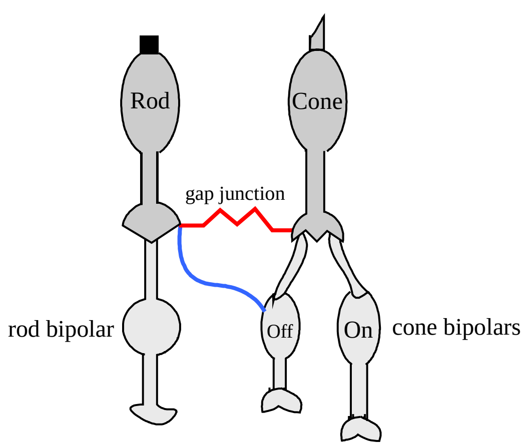

Figure 1: Rod Cone Interaction. The figure shows the two different kinds of synapses rod cells make to the cone circuitry. The red synapse (gap junctions) is active in mesopic light intensities (0.1 - 10 cd/m^2) while blue synapse is active in the narrow range of moonlight intensities (0.01 - 0.05cd/m^2).

3.1 Rod Cone Interaction

The rod to Rod-bipolar circuit serves starlight, which is so dim that over minutes no rod transduces more than one photon. This single-photon signal requires huge amplification (by the Rod-bipolar), which renders the circuit vulnerable to saturation in brighter light. Rod cells respond to this by making connections with cone circuitry, a fact commonly known as rod intrusion. Rods make two different kinds of synapses with cone circuitry depending on the intensity of light.

3.1.1 Twilight Circuit

At light intensities greater than 0.1cd/m^2 rods form gap junctions (direct electrical connections) with cone cells [4]. This circuit serves under mesopic light intensities ranging to 10cd/m^2. At light intensities greater than 10cd/m^2 rods are completely desensitized due to depletion of the photo pigment (bleaching). Thus only cones are responsible for perception of light at intensities greater than 10cd/m^2. This as already mentioned is the photopic state.

3.1.2 Moonlight Circuit

As already stated there are three types of bipolar cells: one type exclusively connected to rods (Rod-bipolar) and two types exclusively connected to cones (Off and On bipolars). Until recently, this information was generally regarded true. The anatomical connections of photoreceptors seemed well understood. Cones and rods were known to form chemical synapses on separate classes of bipolar cells [5] [6] [7]. However, latest findings suggest a direct pathway from rods to Off-bipolar cells [8] [9]. This pathway becomes active in moonlight conditions when environment light intensities are in the range of 0.01 to 0.05cd/m^2 (scotopic). Figure 1 shows this pathway as a blue line connecting the rod cell with the Off cone bipolar cell. Notice that this pathway is different from the direct gap junction between the rod and cone cells shown with a red jagged line (Twilight Circuit). Only 20% of the rods manage to contact a cone bipolar cell in this fashion. Therefore it can be argued that approximately 20% of the rod signal is registered in the cone circuitry in moonlight conditions.

3.2 Blue Shift Hypothesis

It should be noted that the perception of blue color or any color for that matter in a purely moonlit environment is surprising, considering that the light intensity (typically 0.03cd/m^2 [10]) is below the detection threshold for cone cells. Therefore if the cones are not being stimulated how do we perceive the blueness in the environment? Surely rod cells (active under low light conditions) play a role in this phenomenon. The rod to Off-bipolar circuit (moonlight circuit) is of interest to us because it becomes active only in moonlight intensities when we also perceive the blue shift. But this alone does not completely explain why we perceive a bluish tinge rather than any other color.

We therefore propose the hypothesis that rod cells in moonlight intensities synapse only onto Off-bipolar cells serving the *S-cones* (blue cones). The L and M cones remain unaffected by rods in moonlight.

The implication of this hypothesis is that the rod signal is only registered in the S-cone circuitry. This rod signal reaches the visual cortex through neural pathways designated to S-cones. The same does not happen for the L or M cones, their contribution to visual sensation in moonlight conditions remains nil. Compared with the L or M cone signal the rod signal reaching the visual cortex through S-cone pathways is significant. The brain processes this as an increase in the S-cone stimulation resulting in our illusionary perception of blue in the moonlit scene.

There is a wealth of psychophysical data to corroborate the hypothesis that rod cells influence the short wavelength (S) cones. Roger Knight et al. [11] assess the influence of rod cells on hue discrimination using the Farnsworth–Munsell 100-hue test. They report a direct effect of rod signals on S-cone mediated chromatic discrimination. Franklin et al. [12] showed that 530 and 440nm flashes that were too dim to drive either the rods or the S-cones to threshold could be mixed together to produce a threshold response (visual stimulation). They conclude that the two flashes excited the rods and S-cones separately, while the effect of these excitations summed at some locus in the visual pathway. Also studies of blue cone monochromacy support complete linear summation of the activity of rod and S-cone cells [13] [14] [15]. Trezona [16] discussed several reasons to believe that rods contribute to the blue perceptual mechanism, and speculated that the rods may share underlying neural channels with the short-wavelength cones. More recently Mears and Condo et al. [17] report the functional transformation of rod cells into S-cone cells in the absence of protein Nrl (neural retina leucine). The primary function of Nrl is to regulate rhodopsin (photopigment in rod cells) transcription but the study suggests the absence of Nrl in rod cells sparks a cellular transformation. The rod cells transform into functional S-cones. This special property of the rod cells further elucidates the close affinity of the rod and S-cone cells.

Using the physiological evidence of the moonlight circuit and the psychophysical evidence to support our hypothesis of rod influence on S-cones we now proceed to develop a mathematical model for the blue shift mechanism.

4 Deriving the Operator

This section provides a complete description of our blue shift operator. Figure 2 shows an overview of the operator. The operator takes as input RGB values of an image taken at arbitrary lighting conditions. If the input data is in the range of moonlight intensities (intensity between 0.01 and 0.05cd/m^2) the operator calculates the amount of rod influence on cones to produce the corresponding blue shift.

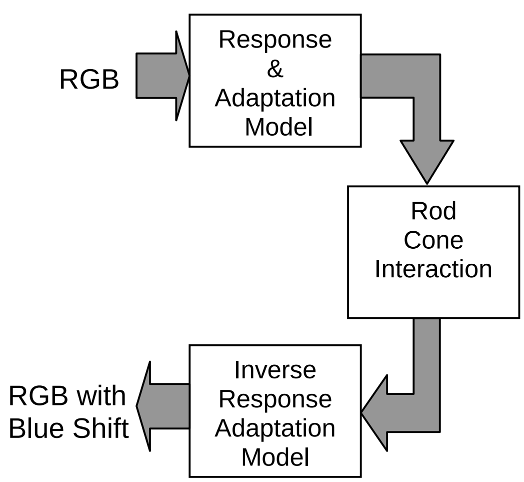

Figure 2: Block Diagram of our Blue Shift Operator. The response and adaptation model creates retina like rod responses to the input image. These rod responses are fed into the rod-cone interaction operator which calculates the cone responses. Finally using the cone responses we determine the hue of the blue shift image.

4.1 Response and Adaptation Model

The rod and cone cells are responsive only within a range of intensities that is very narrow if compared against the entire range of vision. Adaptation processes dynamically adjust these narrow response functions to conform better to the available light. Direct cellular measurements of response functions for cone, rod [5] closely follow:

$$R = R_{\max}\left[\frac{I^n}{I^n + a}\right] \qquad (1)$$

an S-shaped curve (plotting R against *logI*, see Figure 3) where ***I*** is light intensity, R is neural response ($0 < R < R_{\max}$), a is a constant defined relative to $R_{\max}$, and n is a sensitivity control parameter similar to gamma for video, film, and CRTs. (for a detailed description refer to [18])

Hunt in his intricate mathematical model [19] of human color vision essentially uses Equation 1 to estimate rod and cone responses to a viewed image. Hunt's basic response function is:

$$R(I) = 40\left[\frac{I^{0.73}}{(I^{0.73} + 2)}\right] \qquad (2)$$

As before *R(I)* is the photoreceptor response to intensity *I*. Hunt sets R_{max} in Equation 1 to 40 and uses 0.73 as the sensitivity control *n*.

He adds to Equation 2 adaptation parameters ***F*** and ***B***. These two parameters separately mimic the fast neural adaptation (bipolar, ganglion and horizontal cells) and the much slower process of photopigment bleaching and regeneration in rods and cones. Equation 2 becomes:

$$R(I) = B.f(F.I) \qquad (3)$$

where the function *f(I)* is of the form:

$$f(I) = 40\left[\frac{I^{0.73}}{I^{0.73} + 2}\right]$$

For rods F and B are given by:

$$F_{rod} = 3800 j^2\left[\frac{5I_A}{2.26}\right] + 0.2(1-j^2)^4\left[\frac{5I_A}{2.26}\right]^{1/6}, \quad B_{rod} = \frac{0.04}{0.04 + I_A}$$

where $j = \dfrac{1}{5.10^5 I_A + 1}$ and I_A is the adaptation intensity.

These two parameters have the effect of shifting the response curve to the right and reducing the amplitude respectively as the adaptation intensity increases (see Figure 3).

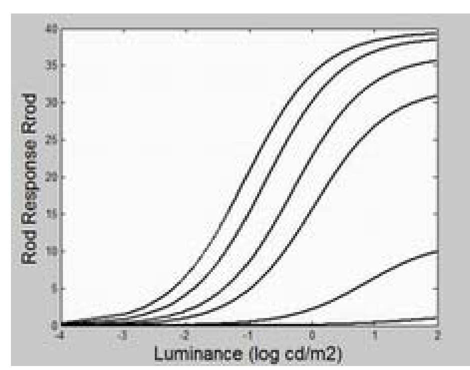

Figure 3: Model of Rod Response. These plots of R_{rod} *vs.* log*I* were drawn with fixed adaptation intensity amounts I_A = 0.0005, 0.001, 0.01, 0.1, 1, 10 cd/m^2 (from left to right). Note as the adaptation intensity increases the response curve shrinks and shifts to the right. This is due to the factors B_{rod} and F_{rod} respectively.

Our adaptation and response model acts as an idealized, film-like eye with uniform resolution. For each scene pixel, our model uses Equation 3 to compute the rod response signal. The operator begins by converting the scene RGB to luminance values (CIE standard Y', Y) labeled I_{rod} . I_A is set to 0.03cd/m^2 which is the illuminating light intensity in full moon[13]. Finally the pixel intensity values I_{rod} are fed into Equation 3 to generate rod response values R_{rod} . The cone responses R_l , R_m , R_s (for L, M and S cones respectively) are zero since cones are insensitive in moonlight.

4.2 Rod Cone Interaction

As discussed in Section 3 the cones are not excited in moonlight conditions. Instead 20% of the rod signal manages to reach the visual cortex through the S-cone pathways. To simulate this we add 20% of the rod signal to the S-cone signal. So that the final S-cone response is given by:

$$R_s = R_s + 0.2R_{rod} .$$

Note, R_l and R_m remain zero as they are unaffected by the rod cells (refer to section 3.2).

4.3 Inverse Response and Adaptation

The inverse response and adaptation operator generates a display image from the rod and cone responses. The operator essentially determines hue information from cone responses and combines it with the scene intensity values I_{rod} to generate the final image. To find the hue information we start by calculating the radiation intensities I_l , I_m , I_s corresponding to the cone responses R_l , R_m , R_s respectively. This is done by feeding the cone responses as input to the inverse of Equation 3.

Hunt converts the cone radiation intensities to tristimulus values by multiplying by the following matrix:

$$M = \begin{bmatrix} 1.9102 & -1.1121 & 0.2019 \\ 0.3710 & 0.6291 & 0 \\ 0 & 0 & 1.0000 \end{bmatrix}$$

We follow his lead and find the X, Y and Z tristimulus values corresponding to the cone radiation intensities.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = M. \begin{bmatrix} I_l \\ I_m \\ I_s \end{bmatrix}$$

The *x, y* chromaticity coordinates for each pixel can now be calculated from the X, Y and Z tristimulus values. These contain the color information for the blue shift image. To display the final blue shift image, for each pixel its hue is defined by the *x, y* chromaticity coordinates and lightness values are obtained from the scene intensity values I_{rod} .

5 Results

The two pictures across the title of this paper show the performance of our blue shift operator. The picture on the left is a photograph of a full moon night taken on normal daylight film with exposure time in the excess of five minutes. Notice the absence of blue shift, infact the picture seems very much like dawn time. That is because the illuminating light (moonlight) is not blue in reality. As already discussed it is merely sunlight reflected of the surface of moon. Therefore the camera registers the scene as it would under normal day light conditions albeit very dim due to the low intensity of light. The picture on the right is the result of our blue shift operator. The operator has accurately produced blue shift to simulate how we would perceive the moonlit scene. Notice the loss of color information, the image is monochromatic with a tinge of blue. This is in accordance with our knowledge of the cone system. The cones are not excited in low light levels of the full moon hence no perception of color. The tinge of blue perceived is due to rod influence on the S-cones. The last page of this paper shows some more results of our blue shift operator on different moonlit night scenes.

6 Conclusion and Remarks

Blue shift is a perceptual phenomenon that has its roots in the complex and intricate designs in our retina. This paper has delved into modeling various properties of the retina to develop a precise and physiologically accurate method of producing blue shift in night scenes. The method has its limitations. Our hypothesis that rod cells influence only S-cones in moonlight conditions is based on psychophysical studies testing rod influence on hue perception. Unfortunately direct physiological evidence to support or negate the hypothesis is not yet available. The model does not cater for the loss of visual detail perceived at scotopic levels. This phenomenon is very crucial to our understanding and perception of a night scene. An acuity loss operator similar to the ones used by Ferwerda et al. [20] and Henrik Jensen et al. [3] could serve this purpose.

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