Maximum Entropy Spectral Modeling Approach to Mesopic Tone Mapping

Mehdi Rezagholizadeh, James J. Clark
Center for Intelligent Machines, McGill University, Montreal, Quebec, Canada

Abstract

Tone mapping algorithms should be informed by accurate color appearance models (CAM) in order that the perceptual fidelity of the rendering is maintained by the tone mapping transformations. Current tone mapping techniques, however, suffer from a lack of good color appearance models for mesopic conditions. There are only a few currently available appearance models suited to the mesopic range, none of which perform very well. In this paper, we evaluate some of the most prominent models available for mesopic and scotopic vision and, in particular, we focus on the iCAM06 model as one of the best-known tone reproduction techniques. We introduce a spectral-based color appearance model for mesopic conditions which can be incorporated in tone reproduction methods. Based on the maximum entropy spectral modeling approach of Clark and Skaff [1], this is a powerful color appearance model which can predict the color appearance under mesopic conditions as well as under photopic conditions. Our model incorporates the CIE system for mesopic photometry, leading to increased accuracy of color appearance model. At low (mesopic) light levels two factors come into play as compared with high light level (photopic) spectral modeling. The first is that image noise becomes significant. The Clark and Skaff model treats the noise as an inherent part of the modeling process, and an estimate of the noise level sets the tradeoff between the consistency of the solution with the measurements and the spectral smoothing imposed by the maximum entropy constraint. The second factor in mesopic vision is that both the rod and the cone systems are active, requiring a modification to the sensor model. The relative contribution of the rod and cone systems is dependent on the overall light level in this regime, and our approach is adaptive in this sense. We present several experiments comparing the performance of our tone mapping approach with that of the existing methods, showing that the proposed method works very well in this regard, and also demonstrates the potential of our model to become a part of wide-range tone mapping systems.

Introduction

Our visual system is able to deal with huge absolute levels of light from bright sunny day to star lit scenes; moreover, our eye can perceive high dynamic range of luminance (around 4 orders of magnitude) simultaneously without losing clarity. Now, it is known that our eyes have different sensitivities under different lighting conditions, less sensitive in bright scenes comparing to dark ones. Adjusting the sensitivity is done partly by changing the pupil size and the rest are compensated by the cone and rod photoreceptors undergo adaptation mechanisms.

However, cameras can not handle high dynamic range scenes as easy as our eyes do. Problems arise with capturing scenes of this kind where the image sensor face with over and under exposed regions in the images. One possible solution to avoid this problem is introduced by Debevec and Malik [2] who suggest imaging with multiple exposures and then propose a technique for combining them together. Currently available CCD or CMOS image sensors are capable of capturing wide range of luminance; however, most of existing displays are not able to display more than two orders of magnitude. Hence, most of the cameras deliver an 8-bit image which can fit to the available dynamic range of displays. Therefore, we can expect that displays be incapable of rendering high dynamic range (HDR) images known as HDR display problem. Tone mapping is a solution to this problem trying to map the high dynamic range image intensities to the low dynamic range display outputs in a way that reproduced image perceptually matches the original scene. Several tone mapping techniques have been proposed, among them we can refer to multi-scale model of Pattanaik et al. [3], perceptually based tone mapping of Irawan et al. [4], and iCAM06 tone reproduction technique [5]. A complete review of the available tone mapping operators can be found in [6].

Current tone mapping techniques and color appearance models (CAM) are trying to solve different problems; however, as Erik Reinhard states in [7], these two are two sides of the same coin (i.e. tone reproduction algorithms and color appearance models should unify to predict the correct appearance of images with a wide range of intensities). In the CAM side, abundant number of models are available such as: the Nayatani et al. model, the Hunt model, RLAB model, CIECAM97 and CIECAM02 models; most of which are explained in details in [8]. However, none of them are appropriate to be used in tone mapping algorithms, and among them, works that focus on the mesopic vision appearance is not too much. We can say that the currunt tone mapping techniques suffer from a lack of suitable color appearance model for mesopic vision. In this work, we are going to discuss some of the well-known mesopic vision models currently available in the literature. Then, we propose a spectral model accounting for the rod-cone interaction in the mesopic conditions. All of the mentioned models in this work are implemented, evaluated and compared to each other. One of the main purposes of this study is to illustrate the weaknesses and strengths of mostly known mesopic models and analysing their similarities or distinctnesses. Furthermore, this work aims at investigating the quality of tone mapping techniques (especially iCAM06) in reproducing mesopic scenes. We hope that the proposed spectral color appearance modeling for mesopic vision proposed in this work opens a way towards filling the gaps between the tone reproduction techniques and the color appearance models.

Models for Mesopic Vison: *Physiological Background*

Our visual system consists of several layers working in parallel to transport the light's excitation to the visual cortex in the brain being responsible for interpreting the visual inputs to the eye, so-called visual perception. The light falls on the retina and stimulates four types of photoreceptors: the rods and long, medium and short wavelength sensitive cones. The output of a rod cell is connected to the rod bipolar cell and the cone photoreceptor is connected to the on-bipolar and off-bipolar cells. The outputs of the bipolar cells are then transmitted to the ganglion cells which form the optic nerve. There are three types of ganglion cells working in parallel which constitute the parvocellular pathway (PC pathway) corresponding to the red/green opponency, magnocellular pathway (MC pathway) corresponding to achromatic signal , and koniocellular pathway (KC pathway) corresponding to the blue/yellow opponency [9]. These three pathways are carrying the visual information to the higher levels in the visual system. In the photopic condition, rod cells totally bleach and only cones are sensitive to the lights greater than 5 cd/m^2. In the mesopic conditions, a gap junction forms between rod and cone bipolar cells [10]. Hence, rods may contribute to all three pathways through the gap junction. In the scotopic condition, since the light level is under the cone sensitivity threshold, there is no cone contribution to the pathways. However, rod photoreceptors are very sensitive to light such that they can capture even a single photon in a dark situation and amplify it to a perceivable response. It is worth mentioning that cones are able to signal capturing of single photons either, but they are noisier than rods.

Modeling Blue Shift in Moonlit Scenes

The first algorithm we are considering is proposed by Khan and Pattanaik [10]. Their work aims at modeling the 'Blue Shift' in the dark scenes. Recent findings show that rod cells contribute to off-bipolar cells during the scotopic condition by forming chemical synapses. Based on this theory, to explain the blue shift, authors hypothesize that these synapses are just established between the rod and short type cones. They propose taking the following steps to calculate the RGB response with blue shift.

1. Given the RGB response, the scotopic luminance values, I_{rod}, are obtained and the adaptation intensity is set to 0.03 cd/m^2.
2. For each pixel, the scotopic luminance is plugged in to the Hunt model introduced for predicting the photoreceptor response to the light intensity I and the rod response values R_{rod} is calculated.
3. Cone response values, R_l, R_m, R_s, are assumed zero, since cone cells do not respond in the scotopic condition.
4. The final scotopic image is obtained by adding 20% of the rod response to the S-cone signal and then projecting the result back into the initial RGB space.

$$R_s = R_s + 0.2R_{rod} \tag{1}$$

The way that the authors address the blue shift turns out to be adding some blue to the initial image and the output of this algorithm does not look natural and realistic.

Cao Model of Mesopic Vision

Cao et al. proposed a model for mesopic vision based on the experiments they have conducted [11]. The results imply that the rod contributions to the PC, MC, and KC pathways linearly relate to rod contrast. The model is fitted to the experimental data to obtain the parameters. Kirk and O'Brien established a perceptually based tone mapping method accounting for mesopic conditions based on the Cao model [12]. Cao model can be summarized in three fundamental steps. (We keep the same notations as [12]).

1. Rod responses are involved in setting three regulators: g_L, g_M, and g_S.

$$\begin{aligned} g_L &= 1/(1+0.33(q_L+\kappa_1 q_{rod}))^2 \\ g_M &= 1/(1+0.33(q_M+\kappa_1 q_{rod}))^2 \\ g_S &= 1/(1+0.33(q_S+\kappa_2 q_{rod}))^2 \end{aligned} \tag{2}$$

where κ_1 is a coefficient which adjust the correct proportion of rod to cone response, q_i, $i \in \{L,S,M\}$ represent the cone responses, and q_{rod} indicates rod responses. These three regulators will determine the amount of the color shift in the opponent color model.

2. Regulators and rod response determine the amount of shift in each opponent channel using the following formulas:

$$\begin{aligned} \Delta o_{R/G} &= x\kappa_1(\rho_1 \frac{g_M}{m_{max}} - \rho_2 \frac{g_L}{l_{max}})q_{rod} \\ \Delta o_{B/Y} &= y(\rho_3 \frac{g_S}{s_max} - \rho_4 W)q_{rod} \\ \Delta o_{Luminance} &= zWq_{rod} \\ W &= (\alpha \frac{g_L}{l_{max}} + (1-\alpha)\frac{g_M}{m_{max}}) \end{aligned} \tag{3}$$

where x, y, and z are free tuning coefficients; $l_{max} = 0.637$, $m_{max} = 0.392$, and $s_{max} = 1.606$ are the maximum values of cone fundamentals [12]; and ρ and α are fitting parameters set as: $\rho_1 = 1.111$, $\rho_2 = 0.939$, $\rho_3 = 0.4$, $\rho_4 = 0.15$ and $\alpha = 0.619$. W is a positive value which can be used as a measure of mesopic level where $W = 0$ indicates the fully photopic condition. It is worth mentioning that the color shifts are nonlinear functions of g_is but linear functions of rod response.

3. The shifted cone responses which have accounted for mesopic color appearance effects are introduced as a linear combination of cone responses and calculated color opponent shift components.

$$\begin{aligned} \hat{q} &= [q_L\ q_M\ q_S]^T + \Delta\hat{q} \\ \Delta\hat{q} &= A^{-1}\Delta o \end{aligned} \tag{4}$$

where A is the transformation matrix between the opponent color space and the corresponding shifted cone response.

$$\begin{aligned} o_{R/G} &= \hat{q}_M - \hat{q}_L \\ o_{B/Y} &= \hat{q}_S - (\hat{q}_L - \hat{q}_M) \\ o_{Luminance} &= \hat{q}_L + \hat{q}_M \end{aligned} \tag{5}$$

iCAM06 Tone Compression Model for Mesopic Vision

As we mentioned before, iCAM06 tone mapping technique accounts for mesopic conditions by including the rod response in its tone compression operator [5]. Keeping the same notation as the original article, we can summarize the model as follows.

1. The chromatic adapted image is input to the tone compression unit and in the first step, this input image is converted to

the Hunt-Pointer-Estevez space. Then the cone responses are obtained using the cone response functions introduced by Hunt.

$$\begin{aligned}
R'_a &= \frac{400(F_L R'/Y_w)^p}{27.13+(F_L R'/Y_w)^p}+0.1 \\
G'_a &= \frac{400(F_L G'/Y_w)^p}{27.13+(F_L G'/Y_w)^p}+0.1 \\
B'_a &= \frac{400(F_L G'/Y_w)^p}{27.13+(F_L G'/Y_w)^p}+0.1 \\
F_L &= 0.2k^4(5L_A)+0.1(1-K^4)^2(5L_A)^{1/3} \\
k &= 1/(5L_A+1)
\end{aligned} \tag{6}$$

2. The adapted rod response is calculated using the Hunt model.

$$\begin{aligned}
A_s &= 3.05B_s[\frac{400(F_{LS}S/S_w)^p}{27.13+(F_{LS}S/S_w)^p}]+0.3 \\
F_{LS} &= 3800j^2(5L_{AS}/2.26)+0.2(1-j^2)^4(5L_{AS}/2.26)^{1/6} \\
L_{AS} &= 2.26L_A \\
j &= 0.00001/[(5L_{AS}/2.26)+0.00001] \\
B_S &= \frac{0.5}{1+0.3[(5L_{AS}/2.26)(S/S_w)]^{0.3}}+\frac{0.5}{1+5[5L_{AS}/2.26]}
\end{aligned} \tag{7}$$

3. The tone compression output is computed as a linear combination of cone responses and the rod response. It is assumed that rod cells contribute to all cone responses with the same weights.

$$RGB_{TC} = RGB'_a + A_s \tag{8}$$

Shin Color Appearance Model for Mesopic Vision

Shin et al. proposed a modified version of Boynton two-stage model with fitting parameters to account for the rod intrusion in the mesopic vision [13]. The parameters of the model is obtained as a function of illuminance based on the asymmetric color matching experimental data. In the experiment, the observer is presented with a Munsell color chip under the mesopic condition in the real world and is asked to match the appearance of that patch with the simulated image reproduced by this model in the CRT display under photopic condition. The model is introduced in the following.

1. The XYZ image is input to the model and is converted to the LMS space in the first step.

2. The LMS signals are plugged into the opponent channel equations of the Boynton's two stage model:

$$\begin{aligned}
A(E) &= \alpha(E)K_w((L_p+M_p)/(L_p+M_p)_w)+\beta(E)K'_w(Y'/Y'_w)^\gamma \\
r/g(E) &= l(E)(L_p-2M_p)+\alpha(E)Y' \\
b/y(E) &= m(E)(L_p+M_p-S_p)+b(E)Y'
\end{aligned} \tag{9}$$

where $A(E), r/g(E),$ and $b/y(E)$ are achromatic, red/green and blue/yellow opponent responses respectively; indices p and w indicate "photopic" and white point"; Y' represents the scotopic luminance; $\alpha(E), \beta(E), l(E), a(E), m(E),$ and $b(E)$ are the fitting parameters indicating the relative contribution of the rod response to the opponent channels; and K_w and K'_w are the maximum response of the the luminance channel at photopic and scotopic conditions.

3. Then, $A(E), r/g(E),$ and $b/y(E)$ are back transformed to the XYZ space and then to the RGB space.

Our Contribution: Spectral Model of Mesopic Vision

Clark et. al. proposed a spectral model for color perception in [1] based on which we introduce a model for mesopic vision. We try to summarize the basic equations in the following. Assuming that our measurement is given by:

$$r = \beta \int_\Lambda f(\lambda)p(\lambda)d\lambda + \nu \tag{10}$$

where $f(\lambda)$ is the spectral profile of the imaging device, the $p(\lambda)$ is the spectral power distribution and Λ specifies the visible light spectrum range. Then, the normalized response will be:

$$\eta = \int_\Lambda f(\lambda)p(\lambda)d\lambda + \frac{\nu}{\beta}. \tag{11}$$

The response is normalized such that $\int p(\lambda) = 1$. It has been shown that the maximum entropy estimation of the spectral power distribution, $\hat{p}(\lambda)$, belongs to the exponential family:

$$\hat{p}(\lambda) = exp(< f(\lambda), \theta > -\psi(\theta)) \tag{12}$$

where $<>$ defines the dot product of vectors $f(\lambda)$ and θ; additionally, $\psi(\theta)$ is a normalization function to ensure that $\int \hat{p}(\lambda) = 1$. Then the normalized measurement estimation can be obtained using the following formula:

$$\hat{\eta} = \int_\Lambda f(\lambda)\hat{p}(\lambda)d\lambda. \tag{13}$$

It is worth mentioning that θ and η are dual coordinate system for the exponential family and they relates to each other as follows [14].

$$\hat{\eta} = \frac{\partial \psi(\theta)}{\partial \theta} \tag{14}$$

where A is a positive definite matrix. Corresponding θ to our noisy measurement can be obtained by solving an optimization problem:

$$\hat{\theta} = \underset{\theta}{\operatorname{argmin}}\{(\hat{\eta}-\eta)^T A(\hat{\eta}-\eta) - \gamma H(\theta)\} \tag{15}$$

In the case of modeling the human visual system, the term $f(\lambda)$ will refer to the cone spectral sensitivity. However, as we mentioned before, the model for the mesopic condition will be slightly different.

We should modify the above model to make it appropriate for mesopic vision. During the mesopic condition, the cone and rod cells are both responsible for our vision. Hence we can modify the initial equation to fit the new situation:

$$r = \beta_1 \int_\Lambda f_c(\lambda)p(\lambda)d\lambda + \beta_2 \int_\Lambda W f_r(\lambda)p(\lambda)d\lambda + \nu \tag{16}$$

Where W is a diagonal matrix which specifies the relative weight of rod output to each cone response. If we simplify the above equation, we end up getting the following relation:

$$r = \beta_1 \int_\Lambda [f_c(\lambda) + \xi W f_r(\lambda)]p(\lambda)d\lambda + \nu \tag{17}$$

where $\xi = \frac{\beta_2}{\beta_1}$. So, we can say that replacing $f(\lambda)$ with $f_{mes}(\lambda) = f_c(\lambda) + \xi W f_r(\lambda)$ will give us the spectral model for mesopic vision. It is worth mentioning that ξ may vary with the luminance level. However, there is still one point unclear that how the γ and ξ should be defined. We address this problem using the CIE system for the mesopic photometry presented in the following subsection.

CIE System for Mesopic Photometery

CIE have recently recommended a new photometry system which incorporates the transition of the eye spectral sensitivity as a function of the luminance level in mesopic lighting conditions [15]. The normalized mesopic eye spectral sensitivity,V_{mes}, and mesopic luminance, L_{mes}, is given by:

$$M(m)V_{mes}(\lambda) = mV(\lambda) + (1-m)V'(\lambda) \quad 0 \leq m \leq 1$$
$$L_{mes} = \frac{683}{V_{mes}(\lambda_0)} \int_{\Lambda} V_{mes}(\lambda) L_e(\lambda) d\lambda \tag{18}$$

where m is a mesopic measure varying in the range [0 1], $m = 0$ corresponds to the fully scotopic ($L_{mes} \leq 0.005\ cd/m^2$) and $m = 1$ corresponds to the fully photopic ($L_{mes} \geq 5\ cd/m^2$); λ_0 is equal to 555 nm; L_e is the spectral radiance in $W.m^{-2}.sr^{-1}.nm^{-1}$; and, $M(m)$ is a normalizing function leading the maximum of V_{mes} to be equal to 1. Given the scotopic and photopic luminance values, the mesopic luminance can be calculated using an iterative approach:

$$m(0) = 0.5$$
$$L_{mes}(n) = \frac{m(n-1)L_p + (1-m(n-1))L_s V'(\lambda_0)}{m(n-1) + (1-m(n-1))V'(\lambda_0)} \tag{19}$$
$$m(n) = 0.767 + 0.3334 \log(L_{mes}(n)) \quad 0 \leq m(n) \leq 1$$

where n indicates the number of iteration, and $V'(\lambda) = 683/1699$. Taking advantage of the CIE system, we can adjust the parameters of the spectral color appearance modeling by introducing an adapting factor as a function of the mesopic measure, m. We can define the γ and ξ as follows.

$$\gamma = (1-m) \times c$$
$$\xi(m) = \frac{e^{1-m} - 1}{e - 1} \tag{20}$$

where c is a constant term serving for tuning purposes. Therefore, the CIE system for mesopic photometry can be exploited in the color appearance models underlying mesopic conditions; however, to find the mesopic luminance the major limitation is that the photopic and scotopic luminance values should be given.

Results and Discussion

In this section, we consider the experiments conducted to compare different models and discuss the obtained results. In this regard, we have designed a software including all the aforementioned models together with the proposed spectral color appearance model. Using the software, we can simulate the Munsell patches surrounded with a white background viewed under different light levels from scotopic conditions to the fully photopic situations. The aim of this system is to provide a unique environment in which we can compare the output of different mesopic models in various light intensities simultaneously. We take advantage of CIE system for mesopic condition to calculate the mesopic factor and mesopic luminance value. The parameters of different models are chosen based on the recommended settings in the original articles. The parameters of the spectral model is specified as: $W = \text{diag}([3\ 3\ 5])$ and $c = 2$. The standard D65 illuminant is selected to render the white point. We should note that in implementing iCAM06, the surround adjustment and colorfulness adjustment is disabled, because they do not correspond to the mesopic color appearance performance of this model. A snapshot of the implemented system is shown in Fig. 1. The upper left patch is the reference color chip indicates our perception in the fully photopic conditions. However, the rest color patches depict the chromaticity of the patch under mesopic vision displayed in the photopic condition (i.e. the intensity of white point is mapped to 255.)

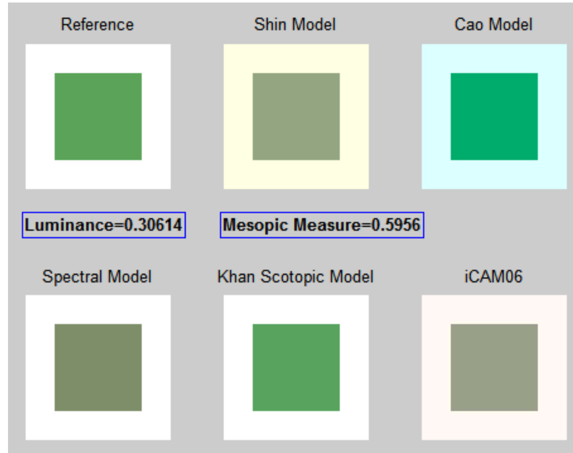

Figure 1: A snapshot of the designed system

In the first experiment, general performance of different methods is compared relative to each other for a single Musell patch, called "10gyV60C10". Models are evaluated under 14 luminance values ranging from 0.002 to 1000 cd/m^2. Fig. 2 shows the considered light intensities and the corresponding mesopic measure. The chromaticity of the perceived color patch under different light intensities for each model is shown in Fig. 3. The output chromaticity values of the iCAM06, Cao and Khan model vary along a line; because these models assume that the rod response has a linear contribution to the color perception phenomena. It should be noted that the Cao model produces the negative chromaticity values in the far end of the mesopic region and scotopic region which are not feasible. As we go further through the mesopic region, the outputs chromaticity of iCAM06, Shin and spectral models tend more towards the achromatic perception, however, Khan model leads to bluish perception. Moreover, it is worth mentioning that the iCAM06 model does not converge to the same color perception as the rest of mesopic models in the fully photopic condition. This fact is due to a weak tone compression technique involved in this method.

Table 1 tabulates the mean mutual color difference computed for all the model pairs using the CIELAB color difference formula. The aims of using Table 1 are twofold: first, to compare different models with each other and second, to prove the feasibility of our model. About the first target, we can say that Shin,

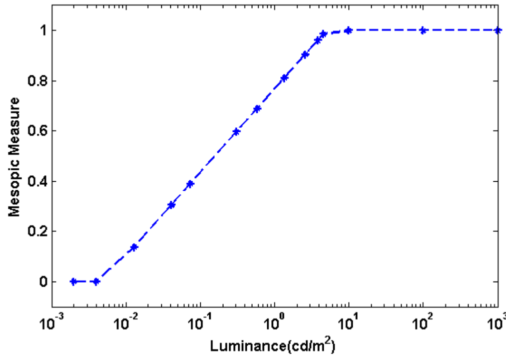

Figure 2: Luminance values and the corresponding mesopic measure considered in this experiment

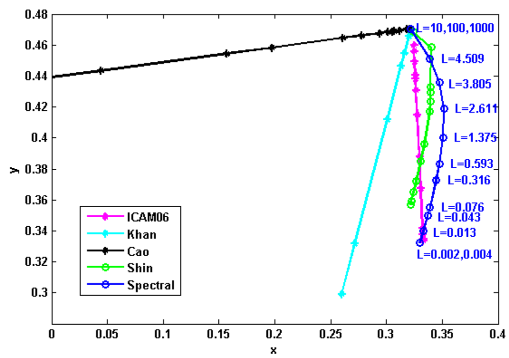

Figure 3: Output of different models for a Munsell patch under different luminance levels. Although all models should lead to the roughly same chromaticity at low intensities they show various performances.

iCAM06, and spectral model are fairly close to each other. Additionally, based on the fact that Cao generates invalid chromaticity responses and Khan model does not include the mesopic vision, we may expect large color differences between the mentioned algorithms and the Shin, spectral and iCAM06 models which are intuitively or experimentally logical. If we accept that Shin model, which is verified using experimental data, as our reference; we can say that spectral model does fairly well in terms of modeling mesopic vision. The most significant difference between both spectral and Shin models and the iCAM model is that the formers treat the rod response in a nonlinear way while the latter assumes a linear contribution of the rod response to the mesopic vision. Bear in mind that the linear assumption holds for Cao and Khan models either.

Table 1: Mean mutual color differences of the mesopic models under given luminance values

	Shin	Spectral	iCAM	Cao	Khan
Shin	0	**9.14**	**10.15**	256.33	24.75
Spectral	**9.14**	0	**15.78**	254.48	21.64
iCAM	**10.15**	**15.78**	0	254.07	24.53
Cao	256.33	254.48	254.07	0	240.07
Khan	24.75	21.64	24.53	240.07	0

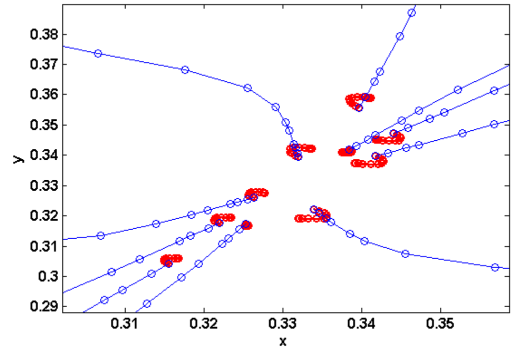

Figure 4: Investigating the effect of adaptation term in the spectral model: Red circles indicate the output of spectral model when $\gamma = 2$ and no adaptation term is used, while blue circles depict the spectral model with the same adjustment as the first experiment.

In the second experiment, we have done the same evaluation process as the first experiment over a set of chosen Munsell patches (as Shin suggested in [13]) covering various hue angles; however, we have confined ourself to the three models which are producing closer outputs. The list of the Munsell color patches involved in this experiment can be found in Fig. 5. First, we investigate the effect of selecting the mesopic measure as an adaptive factor in the spectral model. Fig. 4 shows the case in which a spectral model without using the mesopic measure in the γ adjustment is compared with the spectral model introduced in the prior experiment. This figure shows that without using the mesopic measure, this model can not deal with the photopic situations satisfactorily and reproduced colors appear very desaturated. Mean mutual color differences are calculated for the three selected models where the spectral is substituted with the non-adaptive version (see Table 2). The results imply that the non-adaptive spectral model distances from the other two models: iCAM and Shin.

Table 2: Mean mutual color differences calculated when the spectral model does not include the adaptive term as a function of the mesopic measure

	Shin	Spectral	iCAM
Shin	0	**17.91**	**10.62**
Spectral (no adaptation)	**17.91**	0	**23.24**
iCAM	**10.62**	**23.24**	0

Second, we compare the performance of the three selected mesopic models dealing with 10 different patches under 14 different light intensities shown in Fig. 2. Fig. 5 depicts the result. Bear in mind that in the scotopic range, our work and the iCAM06 model give rise to, more or less, similar achromatic perception; however, the Shin model tends towards a greenish percept in that condition.

Conclusion

In this work we discussed different mesopic color appearance models and tried study them from different points of views: generality, feasibility, and performance. Additionally, we tried

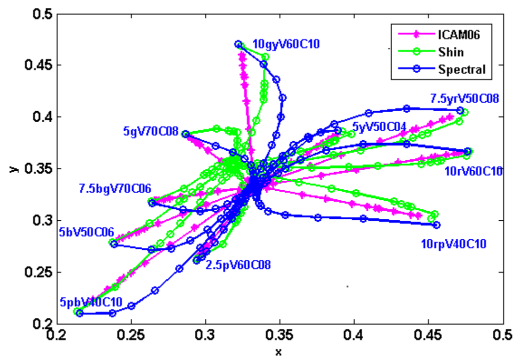

Figure 5: The output of iCAM, Shin and Spectral model for 10 different color patches under various luminance values are shown.

to evaluate one of the most well-known tone reproduction methods, iCAM06, in terms of the mesopic color reproduction quality. We tried to answer the question that to what extent the employed rod response in the iCAM06 give rise to realistic perception and to what extent the mesopic model involved in that tone mapping technique is correct based on the existing color appearance models for mesopic conditions. However, before answering those questions, we should realize that to what degree the current experimental data is reliable. If we assume that the Shin experiments are fully correct, then apparently, we should accept the fact that rod cells contribute to the cone cells in a nonlinear way. In the other hand, the Cao model suggest a linear contribution from the rod cells to the mesopic vision. However, our work showed that the Cao model bring about the infeasible chromaticity values near the scotopic region, which puts this model under question. Moreover, the Khan scotopic model is not generalizable to the mesopic and photopic situations and results of this model turn out to be unrealistic. Now, we can go back to our posed question and judge the iCAM06 model based on the results we obtained in this paper. This model is closer to Shin and spectral models rather than Khan or Cao models. However, iCAM06 has some clear flaws like: iCAM06 tone compression operator assumes that the equally weighted rod response is added to the entire cone responses and in a linear way which both turn out to be untrue. As we saw, the proposed spectral mesopic model works very close to the iCAM06 and Shin models. Our model is inspired from current theories on the mesopic vision, is intuitive, works under scotopic and photopic situations as well as the mesopic region. The spectral model is one of the first works which takes advantage of the recently proposed CIE system for the mesopic vision. Likewise, the spectral model gives us an estimated power spectrum for the fallen light on the photoreceptor which can be exploited for obtaining the scotopic luminance value. Obtaining the scotopic luminance is necessary for the most color appearance models which involves rod-cone interaction; however, without knowing the power spectrum of the illuminant, computing the exact amount of this quantity is not possible. Hunt proposed an approximate formula calculating the scotopic luminance of illuminants based on their photopic luminance values [16]. It is shown that for the equi-energy stimulus, $L_s = 2.26L$, where L and L_s are the photopic and scotopic luminance respectively. Although, in the real world, we never face to the perfect equi-energy stimulus, most of the non-spectral models for mesopic vision rely on this approximate formula to get the scotopic luminance. Finally, using the spectral method, we can handle the noise effect in the images which is the subject of interest in many color image processing applications. The successful results of experiments indicated that the spectral model has a high potential to become a part of current tone mapping techniques.

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