A New Photoreceptor Model of Human Visual System for HDR Natural Luminance Perception

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Abstract

The human visual system is a very complex system and the photoreceptors on the retina are mainly responsible for sensing the luminance of natural scenes. In this paper, a new model which can simulate the adaptive luminance characteristics of the human eye's photoreceptor cells is proposed. According to this model, a new tone mapping algorithm which can display high dynamic range (HDR) images on low dynamic range (LDR) display devices is presented. This technology make the final mapped image simulate the viewer's photorealistic in real scene. First, a HDR image was divided into bright, middle and dark regions, and the three corresponding response curves for each region were acquired. Then, each curve applied different weighting factors, which was obtained by counting the number of pixels within each region. Finally, the final tone mapping curve was synthesized. The proposed algorithm which does not require manually setting parameters has strong stability and it is easy to use. In a variety of experimental conditions for natural scenes, the proposed algorithm has a strong realism. The proposed algorithm was also compared with existing major tone mapping algorithm based on traditional photoreceptor model.

Keywords: Adaptive photoreceptor model, High dynamic range image, Tone mapping, Photorealistic images

1 Introduction

High dynamic range (HDR) images [1] are used to describe complete visual range of real world scenes and can show details of very dark and bright areas. HDR images can be acquired directly by hardware [2] or software methods [3]. Most of the conventional display devices such as liquid crystal display (LCD) or light-emitting diode (LED) can only support a relatively low dynamic range (LDR) which usually has only two orders of magnitude. As shown in Figure 1, these display devices will lose the brightness and dark regions for displaying HDR image directly. This situation is constrained by the hardware cost, and is difficult to change in a short term. Therefore, how to make HDR image be the most optimal LDR display device has become an increasingly important topic. It is from a HDR image tone reproduction which is called tone mapping [4].

Figure 1. "memorial" HDR image effect after linear mapping

Human visual system (HVS) can adapt from night vision threshold to strong flash with 12 magnitudes for a wide range of light intensity. This drives people to study the compression mechanism of human eye for natural luminance. Neurophysiologic studies have shown that this work is mainly completed by photoreceptors on the retina [5]. There are currently two types of photoreceptor cells: cones and rods. Rods are particularly sensitive to light intensity and can provide a dark visual perception for human at 10^{-6}~10 cd/m^2 dark light conditions. That is a colorless vision. Cones are less sensitive than rods, and can provide a color visual perception at 10^{-2} ~10^6 cd/m^2 bright light conditions [6]. Researchers have developed a photoreceptor perception model based on this characteristic [7] and a lot of tone mapping algorithms are generated based on this model [8-10].

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However, the human eye will not have such a large adaptive luminance capacity at the same time. When we are from bright place into a dark room, we almost can't see any object in the beginning, and after some time gradually returned to normal vision. On the contrary, when we are from the darkroom into the bright place, initially we will feel bright light, and own vision returned to normal state after a few minutes. The time of the human eye to adapt to the outside world is the photoreceptors' transformation time of luminance response curve.

Due to this phenomenon, this paper presents a new photoreceptor luminance perception model. The new model not only simulates the compression characteristics of photoreceptors for natural luminance but also simulates the change of visual visibility at the same time. Based on this model, a new tone mapping algorithm is proposed. First, the proposed algorithm averagely divides HDR image into bright, middle and dark regions in the logarithmic domain, and calculates response curve of each region by simulating human eye photoreceptors which adapt luminance level characteristic. Then, a weight factor for each response curve can be calculated by counting the number of pixels within each region. Finally, tone mapping curve can be acquired based on weight factors. The proposed algorithm is fully automatic, no need to set parameters manually. Because it simulates the human eye photoreceptors adaptive characteristics, so as to have a strong sense of reality. This study can facilitate the progress of other research work on the human visual system [11-13].

The rest of the paper is organized as follows. Section 2 introduces the related works. Section 3 describes the new model and corresponding algorithm in detail. Section 4 evaluates the proposed algorithm in several HDR scenes, and compares the proposed algorithms with the tone mapping algorithm based on traditional photoreceptor model. Section 5 summarizes the paper.

2 Related Work

Naka and Rushton [7] proposed an adaptation model for cones and rods. The luminance perception model can be summarized as

$$R = \frac{I^p}{I^p + \sigma^p} R_{\max} \tag{1}$$

where R is photoreceptors' response for luminance, I is the light intensity corresponding to the Y value in the XYZ color space, and σ is the semi-saturation constant. It means the intensity causeing the half-maximum response. p is the sensitivity control exponent, generally set between 0.7 and 1. Finally, R_{max} is the maximum response values of photoreceptors. From Figure 2 we can see that in the case of constant luminance background, photoreceptors' response curve showing sigmoid nonlinear characteristics. Rods and cones have similar luminance perception response curve shape, so in this paper we will no longer distinguish between rods and cones.

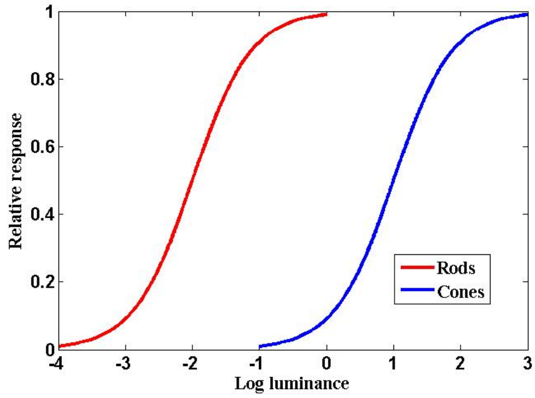


Figure 2. Photoreceptors response curve

However, when the background luminance is changed, the response curve also moves accordingly. Such changes can be modeled by semi-saturation constant σ as a function of background luminance. Thus the formula (1) can be rewritten as

$$R = \frac{I^p}{I^p + \sigma_b^p} R_{\max} \tag{2}$$

where σ_b and R_{max} are functions of the relevant background luminance I_b [14].

$$\sigma_b = k_1 \cdot I_b^m \tag{3}$$

$$R_{\max} = k_2 \cdot I_b^{-r} \tag{4}$$

where m and r are constant associated with the photoreceptor type [15]. Set sensitivity control exponent $p = 1$, and combining (2) with (3), (4)

$$R = \frac{I}{I + k_1 \cdot I_b^m} (\mathrm{k}_2 \cdot I_b^{-r}) \tag{5}$$

Formula (5) is the traditional adaptive photoreceptors model, and the model curve is shown in Figure 3.

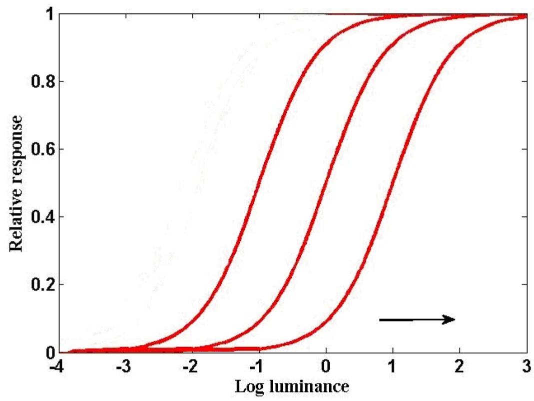


Figure 3. Traditional photoreceptors adaptive curve

From Figure 3 we can see that with the increase of the external luminance intensity, the response curve of photoreceptors shift right along the X axis (black arrows in the Figure 3). The result is the response curve can cover different dynamic ranges continuously. This model has been widely used in tone mapping technology. At present, researchers have proposed a lot of tone mapping algorithms based on this model.

Reinhard and Devlin [8] presented an S-shaped mapping curve based on the traditional photoreceptors adaptive model. The S-shaped mapping curve can adjust the luminance region and the specific shape of the response by the user control parameters. Kuang et al. [9] is an improved version of the iCAM color appearance model, also called iCAM06. iCAM can predict not only the general properties of color appearance, but also the color stimulus properties in complex space. iCAM06 used dual Filter hierarchical algorithm instead of the Gaussian low-pass filter, and used visual hyperbolic nonlinear response compression to replace simple nonlinear local gamma correction. iCAM06's tone compression curve is the traditional photoreceptor adaptive curve. The algorithm is to keep the consistency of color appearance after the tone mapping. Reinhard et al. [10] combined dynamic compression and color appearance model. They simulated the pathway that light takes from entering the eye until the computation of the neural response generated by the photoreceptors, and established a complete and complex HDR image color appearance model. They also give a local algorithm based on lightness perception. The algorithm is to match all known psychophysical color and color appearance data. And the tone mapping curve of this algorithm is also traditional.

3 Proposed New Model and Algorithm

However, as stated in the Section 1, when there is a very large dynamic range of situations in real life scenarios, this model is not accurate. For example, the shadow of a building under the hot sun, the lit flashlight at dark night, the running car in the tunnel and so on. For these HDR scenes, the human eye is not able to adapt to bright and dark regions of these scenes at the same time, when the human eye to adapt to bright area (sun, flashlights, daytime), the dark areas in the scene (building shadows, dark night, tunnel) visibility definitely decreased, and vice versa shown in Figure 4.

Traffic accidents prone to the place shown in Figure 4. The tone mapping technique proposed in this paper simulates the real perception curve of human eye for the HDR scene. Therefore, when a traffic accident occurs in the place shown in Figure 4, the HDR network surveillance camera [16] which uses the technology proposed in this paper can be very accurate to restore the situation that the driver's eyes to see, and this provides strong evidence for the responsibility identification of the traffic accident.

Figure 4. Human eye temporarily blinding in tunnel scene

3.1 New Photoreceptors Perception Model

Human eye perceive luminance in the form of a logarithmic curve [17], so we averagely divided the HDR image into three regions in the logarithmic domain, representing dark, middle and bright region. Figure 5(a) is a false color image of a memorial. Figure 5(c), Figure 5(d), Figure5(e) is a false color image of memorial's dark, middle, and bright regions.

As shown in Figure 3, the photoreceptors for different luminance level show different response curves. In order to simulate the effect of the human eye from dark areas to bright areas of adaptation, we rewrite (5) as follows:

$$L_d(\mathrm{n}) = \frac{L_w(\mathrm{n})}{L_w(\mathrm{n}) + \mathrm{k}_1(\mathrm{n}) \cdot \mathrm{L}_{wa}(\mathrm{n})^m} \cdot (\mathrm{k}_2(\mathrm{n}) \cdot \mathrm{L}_{wa}(\mathrm{n})^{-r}) + \mathrm{k}_3(\mathrm{n}), \quad \mathrm{n} = 1,2,3 \qquad \textbf{(6)}$$

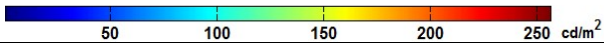
where n represents dark, middle and bright regions of HDR image. L_d is the "display" luminance for LDR image, L_w is the "world" luminance for HDR image, L_{wa} is the "adaptive" luminance for HDR image, also called background luminance. k_3 ensure that large luminance value corresponding to a large response, it can prevent the reversal of visible contrast.

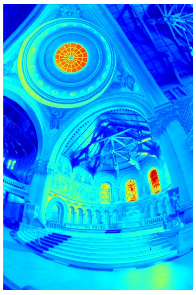
There are unknown variables $L_{wa}(n)$, $k_1(n)$, $k_2(n)$, $k_3(n)$ in (6), we calculate the value of these variables in the following.

L_{dmin}, L_{dmax} denote the minimum and maximum of LDR image. In order to fully utilize the dynamic range of the display device, normalized calculation $L_{dmin} = 0$, $L_{dmax} = 1$. $L_{wa}(n)$ represents the background luminance of each region, we use the logarithm average of the HDR image as the background luminance value approximation.

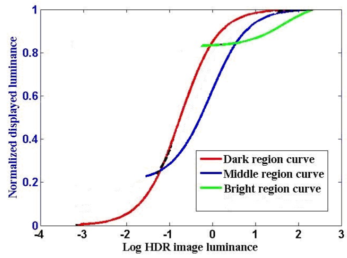
$$L_{wa}(\mathrm{n}) = \exp\left(\frac{1}{N}\sum_{i=1}^{N}\log(\mathrm{L}_w(\mathrm{n}))\right), \quad \mathrm{n} = 1,2,3 \qquad \textbf{(7)}$$

where N is the number of the HDR image pixels.



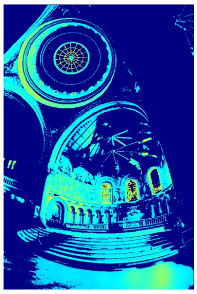


(*a*) luminance of the HDR image

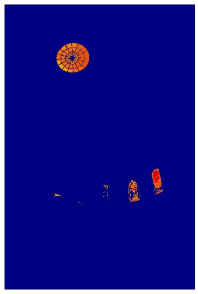


(b) Response curve for each region

(c) dark, middle, and bright regions



(d) dark, middle, and bright regions



(e) dark, middle, and bright regions

Figure 5. "memorial" HDR image regional division

$k_3(n)$ is the distance that response curve shifts in the vertical direction, because we simulate the human eye's adaptation changes from dark to bright regions, so $k_3(1) = L_{dmin} = 0$. This ensures that the dark region's response curve of the HDR image is mapped to the minimum value of the display device. Meanwhile, in order to prevent the reversal of visible contrast situation occurred, and to ensure the continuity of the final tone mapping curve, the minimum value of the mapped middle region should be equal to the mapped dark region's maximum value. $k_3(2) = L_{dmax}(1)$. Likewise, the mapped bright region's minimum value should be equal to the maximum value of the mapped middle region. $k_3(3) = L_{dmax}(2)$.

$k_1(n)$ is an exponential equation that also related to background luminance $L_{wa}(n)$. As shown in (8), α and β are empirical constants, experiment results show that $\alpha = 6$, $\beta = 0.5$ can achieve better results

$$k_1(\text{n}) = \alpha \cdot \left[\exp(\log_{10}(\text{L}_{wa}(\text{n})))\right]^{\beta}, \quad n = 1,2,3 \qquad \textbf{(8)}$$

$k_2(n)$ determines the amplitude compression of the response curve, the maximum value of the HDR image is mapped to the maximum value on the display device.

$$\frac{L_{w\max} \cdot (\text{k}_2(\text{n}) \cdot \text{L}_{wa}(\text{n})^{-r})}{L_{w\max} + k_1(\text{n}) \cdot \text{L}_{wa}(\text{n})^{m}} + k_3(\text{n}) = \text{L}_{d\max} = 1, n = 1,2,3 \ \textbf{(9)}$$

Solution of $k_2(n)$ obtained:

$$k_2(\text{n}) = \frac{(1 - \text{k}_3(\text{n})) \cdot (\text{L}_{w\max} + \text{k}_1(\text{n}) \cdot \text{L}_{wa}(\text{n})^{m})}{L_{w\max} \cdot L_{wa}(\text{n})^{-r}}, n = 1,2,3 \ \textbf{(10)}$$

Now, all variables are determined. The response curve of each region can be calculated automatically. As shown in Figure 5(b), the red, blue and green line represents the response curve of the dark, middle and bright regions separately. From Figure 5(b) we can find the new adaptive curve has more practical significance for HDR scenes, with the external luminance intensity increases, the response curve of photoreceptors not only shifted to the right along the *X* axis, at the same time the amplitude of the response curve is gradually compressed, and gradually decreased visual acuity, the trend is shifted up along the *Y* axis.

3.2 The Algorithm Based on New Model

Based on the new photoreceptors model, we proposed a new tone mapping algorithm, which can automatically make the HDR image match the dynamic range of LCD or LED display and printing device. Algorithm flow is shown in Figure 6. First, the HDR image is converted through the color space to the luminance image. Then we use the luminance threshold segmentation in the logarithmic domain. Based on new photoreceptors perception model we calculate the response curve for each sub-region. After that we calculate the weight factor for each region based on the proportion of the whole image. Finally, we synthesize image and restore the color.

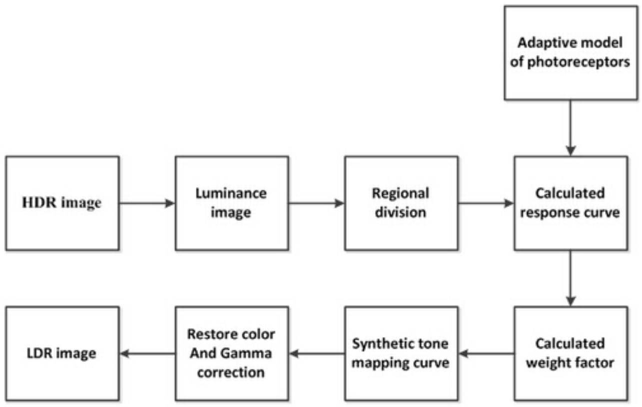


Figure 6. Block diagram of the proposed algorithm

The input HDR image is an RGB color image, but our tone mapping algorithm make dynamic range compression in the luminance domain. Therefore, the HDR image converts to the XYZ color space in (11). Y in the XYZ color space values to represent of the eye perception of luminance response.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.4124 & 0.3576 & 0.1805 \\ 0.2126 & 0.7152 & 0.0722 \\ 0.0193 & 0.1192 & 0.9505 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad \textbf{(11)}$$

Based on the new photoreceptor perception model described in Section 3.1, we have three photoreceptors' response curve for an HDR image. The three curves have different effects for the entire image. Figure 7 is a regional division histogram of "memorial" HDR image. The red, blue and green line represents the dark, middle and bright regions separately. From Figure 7 we can see dark regions > middle regions > bright regions. Obviously, if the region is bigger, the corresponding response curve's weight factor is also larger. We calculate weight factors by separately counting the number of pixels in each region.

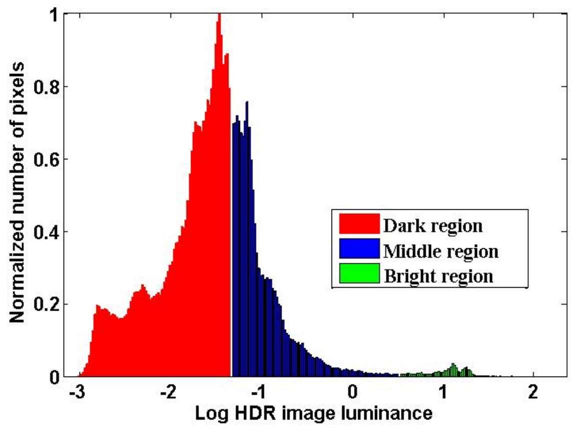


Figure 7. Histogram for each region ("memorial" HDR image)

$$w(\mathrm{n}) = \frac{num(\mathrm{n})}{N}, \quad n = 1,2,3 \quad \textbf{(12)}$$

Where *num(n)* is the number of pixels in each region, *w(n)* is a weight factor. We synthesize tone mapping curve based on weight factor.

$$L_d = \sum_{n=1}^{3} L_d(\mathrm{n}) \cdot \mathrm{w}(\mathrm{n}) \quad \textbf{(13)}$$

The proposed algorithm uses a simple transformation to restore the luminance image to the color image, which is commonly used in tone mapping algorithms.

$$C_{out} = \frac{C_{in}}{L_d} \cdot L_w \quad \textbf{(14)}$$

Where C represents a different color channels (red, green, blue). *In/out* subscript indicates the pixel values before and after the tone mapping. And the final color image should apply the gamma correction factor depending on the type of display.

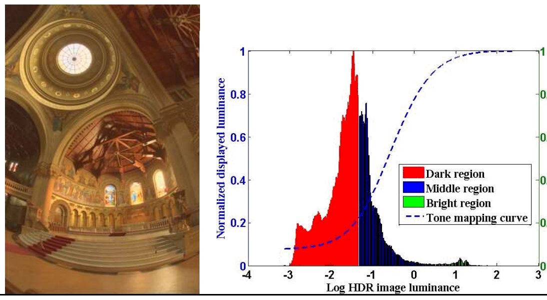
4 Results and Discussions

In order to verify the effectiveness of the algorithm, a variety of HDR images have been experimented, and results are shown in Figure 8. Each piece of test image gives the corresponding partition histogram and the final tone mapping curve.

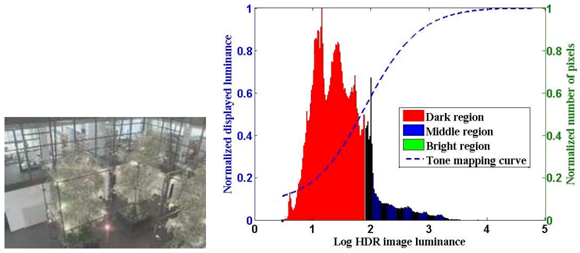
From the experimental results, we can see that, the tone mapping curve which is calculated based on the proposed algorithm can automatically adapt to various experimental reality scenes with a strong sense of reality. Due to the proposed algorithm simulated the human eye's photoreceptors response curve for the real scene. As shown in Table 1, different reality scenes' weight factors of dark, middle and bright regions are different. According to the photoreceptors' characteristics of adaptive luminance, which is for gradually increasing the luminance level, the response curve has a trend to the right and upward. We get the final tone mapping curve by combining the different regional response curves.

Table 1. Weight factor for each region

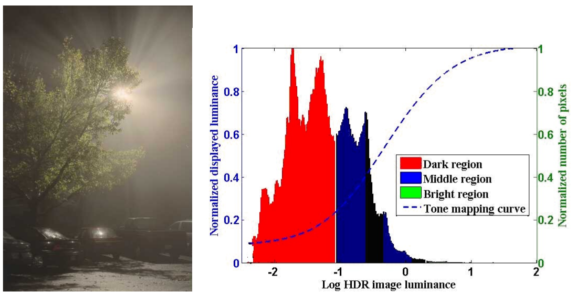
HDR image	Dark	Middle	Bright
Memorial	0.6633	0.3215	0.0152
Atrium	0.8439	0.1540	0.0021
Big Fog	0.6325	0.3639	0.0036
Cathedral1	0.0573	0.7713	0.1714
Cathedral2	0.8861	0.0920	0.0220
Cathedral3	0.8031	0.1827	0.0142
Belgium	0.0259	0.8214	0.1526
Montreal	0.5524	0.4455	0.0021



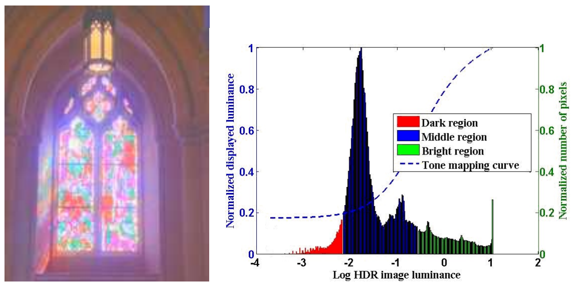
(a) Memorial



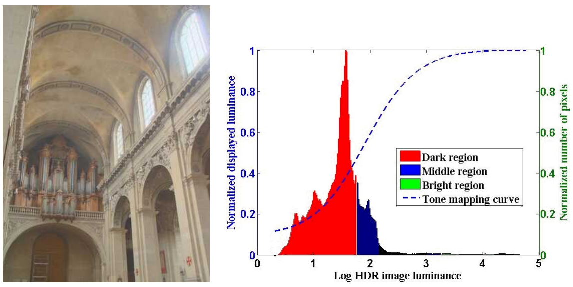
(b) Atrium



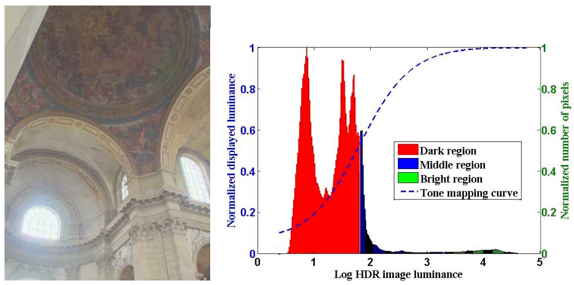
(c) Big Fog



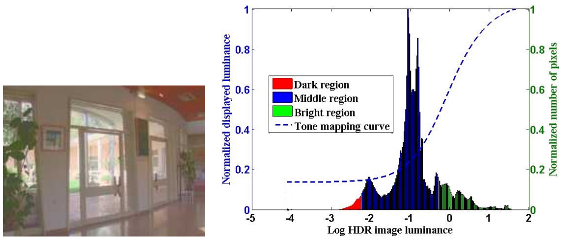
(d) Cathedral1



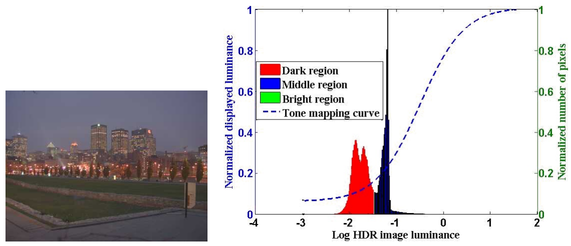
(e) Cathedral2



(f)Cathedral3



(g) Belgium



(h) Montreal

Figure 8. The images are tone mapped scenes using the model in this paper, corresponding histogram and tone mapping curve

One of the advantage of the proposed algorithm is it does not need to set any parameters manually. It is known that the less manually setting parameters, the higher stability of the algorithm, and the more widely range of applications. Table 2 shows the proposed algorithm comparing with other recent HVS-based tone mapping algorithms.

Table 2. The number of parameters set by manual

Algorithm	Number of parameters
Reinhard05 [8]	4
Mantiuk06 [18]	1
Kuang07 [9]	2
Mantiuk08 [19]	2
Reinhard12 [10]	3
Bo 13 [20]	3
The proposed	0

Our goal is to design a fully automatic tool with a strong realistic HDR image tone mapping algorithms. Figure 9 shows the proposed algorithm compares with a tone mapping algorithm which is not based on HVS model. Fattal's algorithm [21] is simple, efficient and almost can display all the details. However, as shown in Figure 9, the effectiveness of the algorithm does not match the human visual perception. The proposed algorithm is better in realistic aspect.

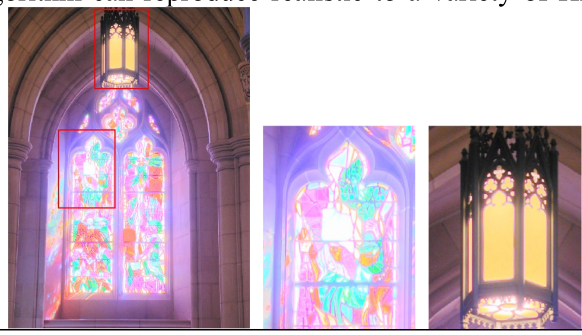
(a) Fattal's algorithm (b) the proposed algorithm

Figure 9. Compare photorealistic

Figure 10 shows the results of the proposed algorithm compares with the tone mapping algorithm based on traditional photoreceptor model [9]. As shown in the enlarged details, both algorithms maintain a high degree of detail visibility in the bright regions of the scene. But in the dark regions, the proposed algorithm is not high visibility. This is because the proposed algorithm simulates the luminance adaptation's change from the bright regions to dark regions. Through the analysis of Section 3, we can see that this situation matches the actual situation. When the human eye gradually adapts HDR scenes' bright regions, the scene of the details of dark regions will decrease visibility. In conclusion, the results of the new tone mapping algorithm are more realistic.

5 Conclusion

The aim of tone mapping algorithms is true reproduction of the human visual system to natural scene perception. In other words, it can provide an ideal image which is consistent with human visual characteristics to computer vision. We put the photoreceptor perception of luminance characteristics combined into tone mapping algorithms to provide a high quality image which is more suitable for the human eye perceives. This paper presents an automatic tone mapping algorithms based on a new photoreceptor perception model. The final mapped image has a strong sense of reality. It is important that the proposed algorithm can reproduce realistic to a variety of HDR images on LDR display device and with free manual setting parameters.



(a)

(b)

Figure 10. Comparing with the tone mapping algorithm based on traditional photoreceptor model

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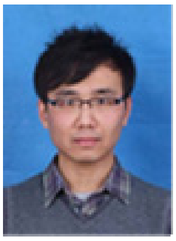
Biographies



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