Simulating HDR Visual Perception on Arbitrary Displays

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Abstract: High Dynamic Range (HDR) display techniques deliver a more realistic visual experience than Standard Dynamic Range (SDR). Consequently, HDR content has become increasingly prevalent over the past decade. However, due to the relatively high cost of HDR displays, SDR screens remain predominant among most users. Reproducing the visual perception of HDR content on arbitrary (mostly SDR with limited luminance ranges) displays is challenging. To address this issue, we leverage the color appearance model (CAM). We first quantify the CAM-based visual perception of both HDR image and background. Then we derived both the dimmed images within the accessible luminance range by inverse CAM. The dimmed image with the dimmed background around can reproduce the lightness perception according to the post adaptation phenomenon. The code is released at this repository.
Keywords: HDR reproducing, arbitrary display, color appearance model

1. Introduction

Emerging High Dynamic Range (HDR) display techniques significantly enhance the realism and immersion of visual content by expanding the image's dynamic range (increasing it from approximately 1,000:1 in traditional Standard Dynamic Range (SDR) to 10,000:1 or higher) [1]. HDR's key advantage lies in reproducing richer details and more realistic lighting on screens, thereby delivering higher fidelity to the natural human visual experience. HDR has expanded from its initial applications in computer graphics rendering to diverse fields including photography, gaming, film production, and medical imaging, providing creators with more powerful visual expression tools.

However, despite the rapid growth of HDR content over the past decade, its widespread adoption in the consumer electronics sector faces significant challenges. Though HDR display device shipments are growing rapidly, SDR devices still dominate the market. This is primarily because HDR display technology demands higher hardware specifications, including high peak brightness (typically requiring 1000 nits or more), wide color gamut coverage, and precise per-pixel luminance control [2]. These requirements lead to substantially higher costs for HDR devices compared to traditional SDR devices, limiting their rapid penetration into the mass market. However, the lower dynamic range of SDR screens makes it very difficult to experience the visual gains HDR offers over SDR.

In response to this challenge, this work presents an HDR reproducing technique based on a Color Appearance Model (CAM) [3]. This method simulates the visual lightness improvements HDR offers over SDR when viewed on an SDR screen. Unlike simply lowering luminance, this technique works in the JzAzBz [4] domain and aims to reproduce this lightness enhancement. It quantifies the differences in visual appearance between SDR and HDR content. We design a viewing background based on the post adaptation phenomenon [3]. Then, applying color appearance reproduction theory, the technique lowers the brightness of both SDR and HDR content within the luminance range of the SDR display. Inspired by color appearance theory, this method can successfully reproduce the visual brightness enhancement of HDR over SDR on standard SDR displays.

2. Method

A straightforward approach to reproducing the perception of HDR images on a limited-brightness SDR screen is to lower the brightness under the max luminance of the SDR screen, as shown in Fig. 1.

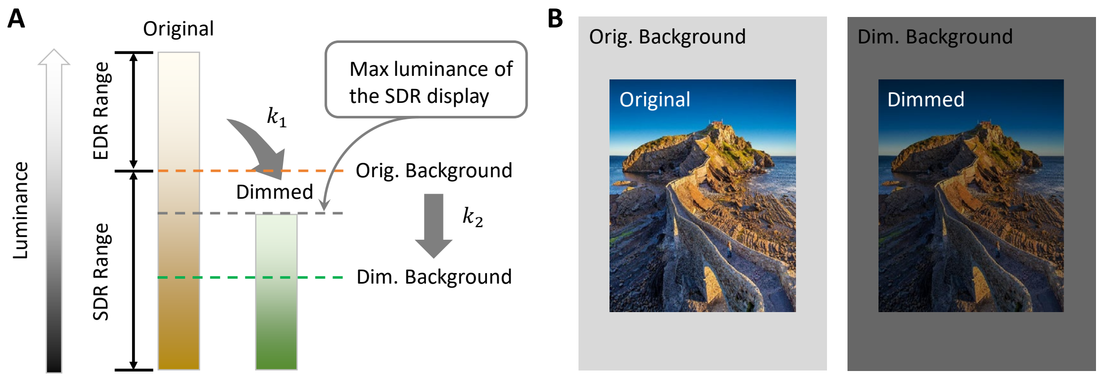

Fig. 1. Dimming the SDR and HDR content to reproduce the SDR-HDR comparison on an SDR display. EDR stands for the extended dynamic range beyond the SDR range.

Let L_o and L_d denote the linear luminance maps of original HDR and dimmed image, respectively, where $L_d = L_o / k_1$. Additionally, L_d must falls within the displayable range D, i.e., $L_d \leq D$. To reproduce the appearance of the image, the background should be also dimmed, making post adaptation, $B_d = B_o/k_2$, where B_o and B_d are the luminance of original and dimmed background images. We note that usually $k_1 \neq k_2$. This is attribute to the nonlinear cone response of the human visual system [3, 4].

CAMs provide effective tools to quantify visual perception in terms of luminance. In this section, we leverage CAM to model the visual brightness difference between the original and dimmed images and reproduce this difference within the SDR screen's accessible luminance range.

To quantify visual perception in a larger HDR display range, we take advantage of JzAzBz-CAM. As illustrated in Fig. 2, JzAzBz-CAM transforms an XYZ stimulus to visual perceptions: lightness (J), chroma (C), and hue (h). The JzAzBz domain can be regarded as a uniform color space (UCS) [5]. Thus, maintaining the ratio between the J values of image and background can reproduce the visual lightness perception after dimming.

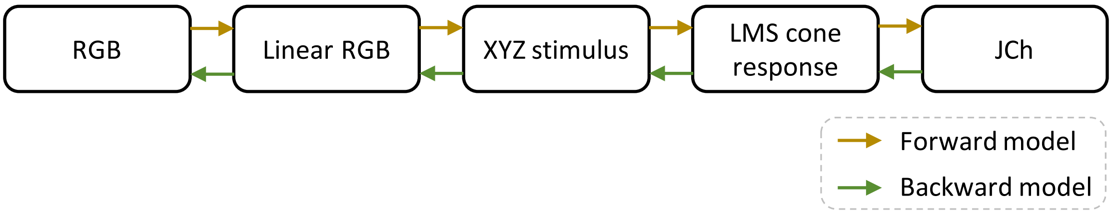

Fig. 2. We first transform the RGB signal to the linear RGB signal and then calculate the XYZ stimulus. CAM can quantify the visual perception JCh of the XYZ stimulus by the LMS cone response.

Using JzAzBz-CAM, we quantify the human visual perception of lightness for both images, and then reproduce the visual lightness gain within the limited luminance range. We quantify the lightness enhancement E of original image over the original background as follows:

$$E = J_{Lo}/J_{Bo}\,, \tag{1}$$

where J_{Lo} and J_{Bo} stand for the CAM lightness of L_o and B_o respectively. To maintain this lightness enhancement for the dimmed image, we have

$$E = J_{Ld}/J_{Bd}\,, \tag{2}$$

where J_{Ld} and J_{Bd} stand for the CAM lightness of L_d and B_d respectively. Thus, we have

$$J_{Bd} = J_{Ld} \times J_{Bo}/J_{Lo}\,. \tag{3}$$

When J_{Bd} is obtained, we can calculate B_d using the inverse JzAzBz-CAM. To simplify the processing workflow, we use the J value of the brightest pixels rather than performing pixel-wise calculations. We can employ the dimmed background to form a new lightness adaption.

3. Result

In this section, we conducted a series of simulations to validate the reported method. The default Opto-Electronic Transfer Function (OETF) and Electro-Optic Transfer Function (EOTF) for both SDR content and screens are based on 8-bit Gamma 2.2. The OETF/EOTF of HDR content follows the ITU-R BT.2020 recommendation [6], ranging from 0 to 10000 nits with a diffusion white of 203 nits. We assume that the background

L_o is the diffusion white. We considered four prevalent SDR display luminance ranges $D \in \{100, 200, 300, 400\}$ nits and force $L_d = D$ to simplify the issue.

We first calculated the dimming factor k_2 and the gray level of B_d w.r.t L_o under various SDR display luminance ranges D, as shown in Fig. 3. We can see from the figure that the curves of k_2 differ from linear scaling. The k_2 curves corresponding to different D values exhibit significant differences; larger D values correspond to greater k_2.

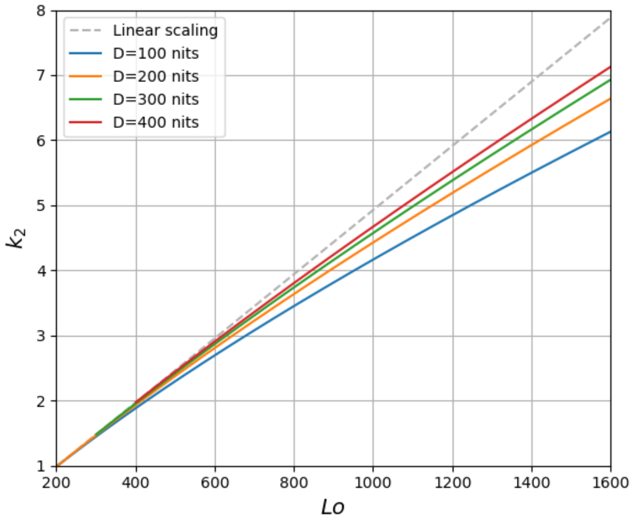

Fig. 3. The factor k_2 w.r.t L_o under various SDR display luminance ranges D.

Existing HDR image processing methods face challenges in visually presenting and comparing HDR images in academic publications and other common applications. Our approach presents a way to reproduce the perception of HDR content in SDR-compatible formats. We first calculate J_{Bd} based on J_{Lo}, then with J_{Bd} fixed, separately derived J_{Lo} values for other images. Both SDR and HDR images are dimmed while preserving the perceptual lightness relationship between them. Figure 4 shows the simulated results.

Fig. 4. The simulated SDR and HDR images. The maximum luminance of HDR image is 557 nits with the diffusion white is set as 203 nits. $D = 100$ nits.

4. Conclusion

This paper has presented a novel method for simulating the perceptual benefits of HDR content on SDR displays using JzAzBz-CAM. By leveraging light adaptation and color appearance theory, our approach maintains the relative lightness enhancement of HDR over SDR even within the limited luminance range of standard displays. This technique offers a practical solution for visualizing HDR improvements in contexts where only SDR hardware is available, such as in academic publications or consumer applications.

Reference

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