A Color Adjustment Method for HDR Display of Video Content Received Over Wireless Multimedia Networks

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***Abstract*— Bandwidth limitations in wireless networks may be prohibitive for transmitting High Dynamic Range (HDR) video content to end users to take advantage of the capabilities of HDR displays. Instead, the Standard Dynamic Range (SDR) version of the content may be transmitted, which is inverse tone mapped to the visually rich HDR format at the receiver end. One of the challenges in this approach is that the mapping process causes color shifts. Failing to address this color change, degrades the overall visual quality of the generated HDR video. In this paper, we propose a perception-based color adjustment method that is capable of preserving the hue of colors and produces HDR colors that closely follow their SDR counterparts, while causing negligible luminance change. Performance evaluations show that our method outperforms existing state-of-the-art color adjustment methods.**

Keywords*— *high dynamic range, color adjustment, inverse tone mapping

I. INTRODUCTION

Advances in capturing and displaying technologies have drastically improved the visual quality of video content, making the High Dynamic Range (HDR) technology an unprecedented market success. However, bandwidth limitations in existing wireless networks may not always allow delivery of the perceptually rich High Dynamic Range (HDR) video content to playback devices. In these cases, transmission of Standard Dynamic Range (SDR) video is preferred, which is followed by inverse tone mapping at the receiver that converts it back to the HDR format. This process may introduce visual artifacts, among which color shift is the most challenging. The cause for this shift comes from the fact that inverse Tone Mapping Operators (iTMOs) are applied only on the luminance channel of the SDR frame and once the HDR luminance channel is generated, color adjustment methods must be employed to form the color channels. The latter is an important step in the inverse tone mapping process, as one of the objectives is to generate HDR colors that closely follow their SDR counterparts and thus preserve the artistic intent of the original SDR content. However, maintaining the color accuracy between the input SDR and the generated HDR frames is a challenge because of the expansion of brightness levels from SDR to HDR [1], [2].

In this paper, we propose a perception-based color adjustment method that aims at eliminating the color shifts caused by iTMOs. By performing the color adjustment in the perceptual domain, our proposed method prevents hue shifts and keeps luminance changes to imperceptible levels, generating HDR colors that closely follow their SDR counterparts. Our subjective evaluations demonstrate that our proposed color adjustment method outperforms all other state-of-the-art methods in terms of maintaining the color accuracy between input SDR and generated HDR frames.

The rest of this paper is organized as follows: Section II describes common color adjustment methods, presents our proposed color adjustment method and analyses its performance compared to existing methods. Section III presents our evaluations and discusses the results and Section IV concludes our paper.

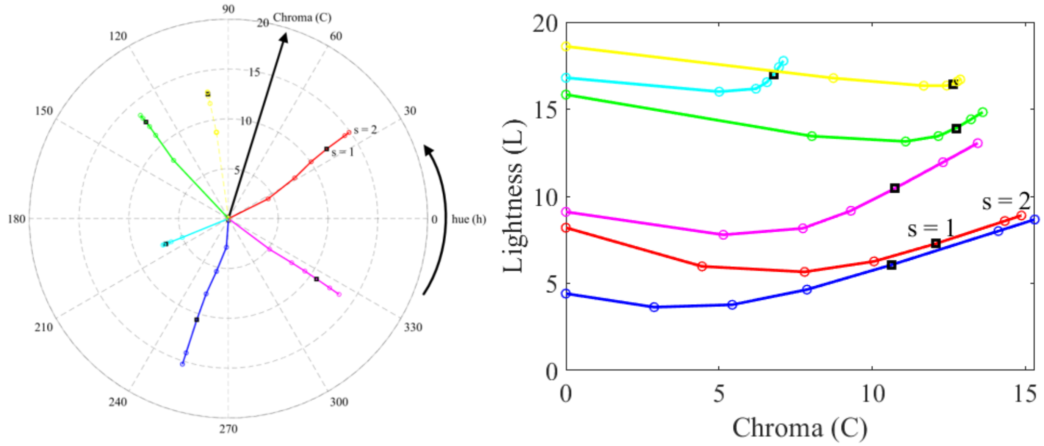
II. RELATED WORK AND PROPOSED METHOD

One of the most widely used approaches for color adjustment in SDR to HDR mapping is proposed by Schlick et al. in [1]. This method performs the color adjustment in the light domain and the *RGB* color space, as follows:

$$C_{HDR} = \left(\frac{C_{SDR}}{L_{SDR}} \right)^{s} L_{HDR} \tag{1}$$

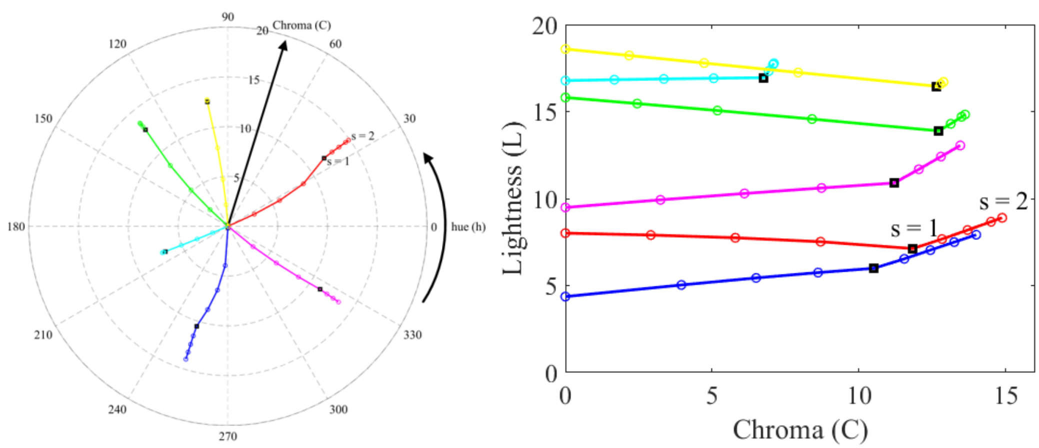
where C_{HDR} denotes one of the color channels (red, green, or blue) of the generated HDR frame, C_{SDR} represents the same color channel in the input SDR frame, L_{HDR} and L_{SDR} are the HDR and SDR luminance channels, respectively and s is a saturation factor which is greater than zero.

The performance of this method is shown in Fig. 1, with Fig. 1(a) showing the changes in hue (h) with respect to Chroma (C) as the saturation factor s varies for six basic



(a) (b)

Fig. 1. Changes in hue (h) and Lightness (L) with respect to Chroma (C) for six basic colors as we change the saturation factor s from zero to two for Schlick et al.'s method. (a) and (b) demonstrate the changes in h and L with respect to C for six basic colors, respectively. The points where s = 1 are marked with black squares.



(a) (b)

Fig. 2. Changes in hue (h) and Lightness (L) with respect to Chroma (C) for six basic colors as we change the saturation factor s from zero to two for Mantiuk et al.'s method. (a) and (b) demonstrate the changes in h and L with respect to C for six basic colors, respectively. The points where s = 1 are marked with black squares.

colors. As it can be seen, changing s results in changes in the hue of colors, especially for red and blue. Fig. 1(b) presents the changes in Lightness (L) with respect to Chroma (C) as we change saturation factor s. We observe that the overall brightness of colors first decreases and then starts to increase as s increases.

Another color adjustment approach is proposed by Mantiuk et al. [2], which also performs the adjustment in the light domain and the RGB color space but the main aim here is to limit the resulting luminance changes, as follows:

$$C_{HDR} = \left(\left(\frac{C_{SDR}}{L_{SDR}} - 1 \right) s + 1 \right) L_{HDR} \tag{2}$$

Similar to the previous case, Fig. 2(a) shows the changes in hue (h) for six basic colors with respect to Chroma (C) as the saturation factor s changes. We observe that changing s results in changes in the hue of colors, especially for red and blue. However, as seen in Fig. 2(b), the overall lightness of colors has a near-constant behavior for different values of s.

To address the issue of hue shift caused by Mantiuk et al.'s and Schlick et al.'s methods, we introduce a method that performs color adjustment in the perceptual domain. This is an essential step, as our eyes do not see light in a linear way [3], with sensitivity in perceiving brightness changes directly dependent on the overall ambient brightness. More specifically, our eyes are more sensitive to brightness variations in dark areas than they are to normal and bright ones. The introduction of HDR led to

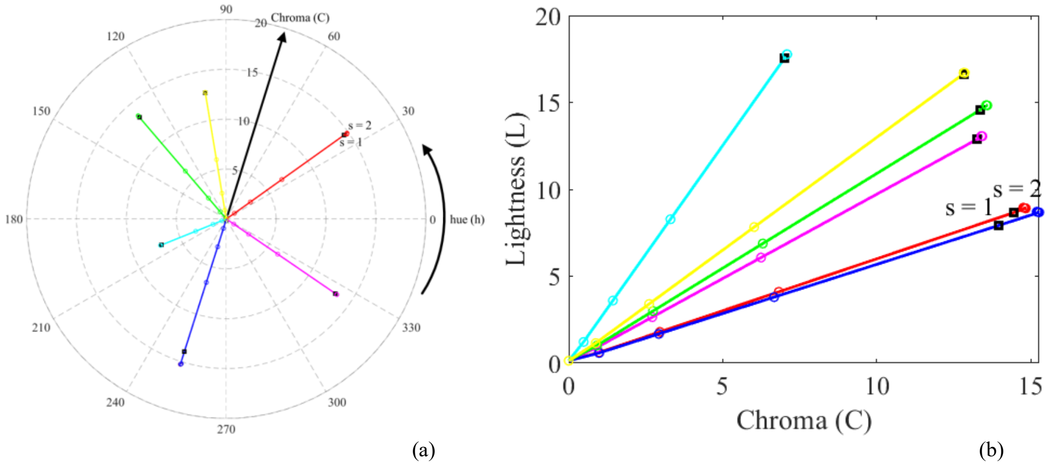
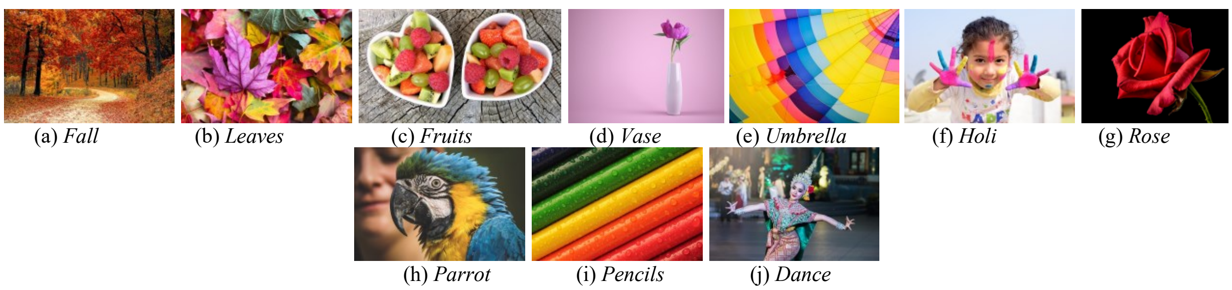


Fig. 3. Changes in hue (h) and Lightness (L) with respect to Chroma (C) for six basic colors as we change the saturation factor s from zero to two for our proposed color adjustment method. (a) and (b) demonstrate the changes in h and L with respect to C for six basic colors, respectively. The points where $s = 1$ are marked with black squares.



(a) *Fall* (b) *Leaves* (c) *Fruits* (d) *Vase* (e) *Umbrella* (f) *Holi* (g) *Rose* (h) *Parrot* (i) *Pencils* (j) *Dance*

Fig. 4. A subset of our 400 SDR frames dataset randomly taken from [5].

the design of a Perceptual Quantizer (PQ) [4] that takes advantage of the properties of the Human Visual System (HVS) and optimizes the distribution of light values, converting physically linear values to perceptually linear ones. Perceptual linearity indicates that any change in light intensity at any brightness level is perceived equally by our eyes. Based on the above, we propose to perform the color adjustment in the PQ domain as follows:

$$C_{HDR,PQ} = s\frac{L_{HDR,PQ}}{L_{SDR,PQ}}C_{SDR,PQ} \tag{3}$$

where $C_{HDR,PQ}$ denotes one of the color channels (red, green, or blue) of the generated HDR frame in the PQ domain and $C_{SDR,PQ}$ represents the same color channel in the SDR frame in the PQ domain. $L_{HDR,PQ}$, and $L_{SDR,PQ}$ are the HDR and SDR luminance channels in the PQ domain, respectively and s is a saturation factor which is greater than zero.

The hue and lightness performance of our proposed color adjustment method are shown in Fig. 3. We observe that comparing Figs. 1(a), 2(a), and 3(a) demonstrates that our method preserves the hue of colors irrespective of the changes in s as opposed to Schlick et al.'s and Mantiuk et al.'s methods. Comparison of Figures 1(b), 2(b), and 3(b) shows that Mantiuk et al.'s method is limiting the changes in color Lightness (L) compared to our proposed and Schlick et al.'s methods, with our method showing a linear behavior.

III. Experimental Evaluations

The next step is to evaluate how our method affects the overall luminance of the final HDR output. To this end, we first have to identify a suitable value for the saturation factor s that yields the smallest change in the HDR luminance channel for our color adjustment method. Therefore, we conducted an experiment where we randomly selected 400 SDR frames from [5] and generated their corresponding HDR frames using the latest iTMO described in [6] coupled with the proposed color adjustment method, at three different saturation factors: 1) $s = 0.8$, 2) $s = 1$, and 3) $s = 1.2$, which result in 400×3 = 1200 pairs of SDR and HDR frames. Our dataset included a broad range of color hues and saturation levels representing human faces, indoor, and outdoor scenes. Fig. 4 shows a small subset of our dataset that includes *Fall*, *Leaves*, *Fruits*, *Vase*, *Umbrella*, *Holi*, *Rose*, *Parrot*, *Pencils*, and *Dance*. For each SDR and HDR pair in our dataset of 400 frames, we compute the absolute difference between the luminance channel of the generated HDR

Table I.

Mean, SD, and 95% CI of the average ΔL for different values of the saturation factor in our proposed color adjustment method

	ΔL		
	$s = 0.8$	$s = 1$	$s = 1.2$
Mean	0.0889	0.0080	0.0761
SD	0.0363	0.0131	0.0351
95% CI	[0.0853,0.0925]	[0.0067,0.0093]	[0.0727,0.0795]

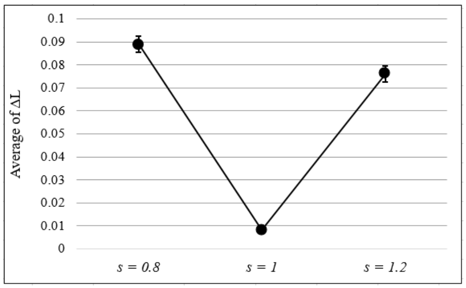


Fig. 5. Average of ΔL along with its 95% CI over our dataset of 400 SDR frames for three different values of s.

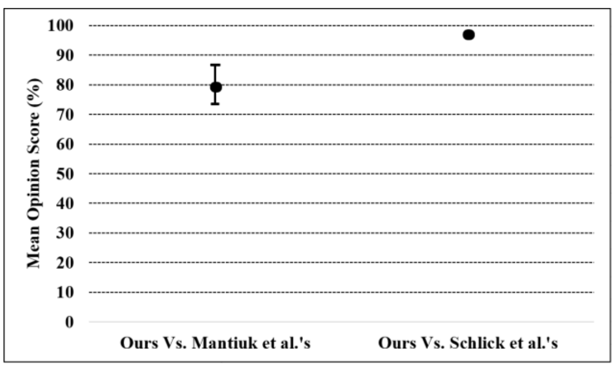


Fig. 6. Preference scores of the subjects in mean opinion score (MOS) when comparing the color accuracy of our proposed color adjustment method over that of Mantiuk et al.'s and Schlick et al.'s methods coupled with Kim et al.'s iTMO.

frame before and after applying color adjustment. An efficient color adjustment method should not affect the overall HDR luminance ($\Delta L \approx 0$). Table I presents the mean, standard deviation (SD) and the 95% confidence interval (CI) for the average values of ΔL for each pair of SDR and HDR frames in our dataset and for the three different saturation factors. We observe that when $s = 1$, our method yields on average the lowest change in ΔL. Fig. 5 is a graphical representation of these results.

Using the saturation factor $s = 1$ for our color adjustment method, we subjectively evaluated its performance against Mantiuk et al.'s and Schlick et al.'s color adjustment methods. To generated the HDR frames, we applied each color adjustment method to two of the latest iTMOs: Kim et al.'s [6] and Luzardo et al.'s [7] methods.

Subjects were asked to compare the HDR frames generated and choose the one that they thought was closer to the original SDR frame in terms of its colors. For this test, we used the same 400 SDR frames chosen from [5] covering a wide range of color hues and saturation levels representing human faces, indoor, and outdoor scenes. Eighteen subjects (4 females and 14 males) between the ages of twenty-three and thirty-four participated in our test. All subjects were screened for color blindness and visual acuity using the Ishihara and Snellen charts, respectively. Prior to the test, subject were familiarized with the test procedure through a training session. The original SDR frames were shown on a Sony BVM-X300 professional monitor [8], while the HDR frames were shown on another identical Sony BVM-X300 professional monitor in a side-by-side manner, using a 14-pixel wide black stripe between them. Each SDR-HDR pair was shown for 10 seconds on each display.

During the test, subjects were asked to choose one of the two HDR frames ("A" or "B") that they think its colors more closely represent the ones in the original SDR frame. Subjects were also provided with the "equal" choice in case the colors in both HDR frames appeared equally close to the ones in the original SDR frame.

The position of HDR frames were randomly switched between the left and right side of the display to remove any effect caused by any variations of brightness across the display. Analysis of the results followed the process described in [9]. We used the outlier detection methodology in [9] and found two outliers and excluded their results from our analysis. Fig. 6 shows the percentage of how many times, on average, subjects decided that the colors generated by our proposed color adjustment method more closely represent the ones in the original SDR frame over those of the other two methods using Kim et al.'s iTMO [6]. As it can be observed, on average, our method outperforms Mantiuk's by 76%, and Schlick's by 96% of the times in terms of how closely the colors of the output HDR frame represent the ones in the original SDR frame.

To prove that the performance of our proposed color adjustment method is independent of the iTMO used, we used Luzardo et al.'s iTMO [7] and repeated the same subjective test, generating HDR frames using our proposed color adjustment method, Mantiuk et al.'s and Schlick et al.'s methods. Fig. 7 shows the percentage of how many times, on average, subjects decided that the colors generated by our proposed color adjustment method more closely represent the ones in the original SDR frame over those of the other two methods using Luzardo et al.'s iTMO [7]. We observe that, on average, our method outperforms Mantiuk's by 79%, and Schlick's by 86% of the times in terms of how closely the colors of the output HDR frame represent the ones in the original SDR frame.

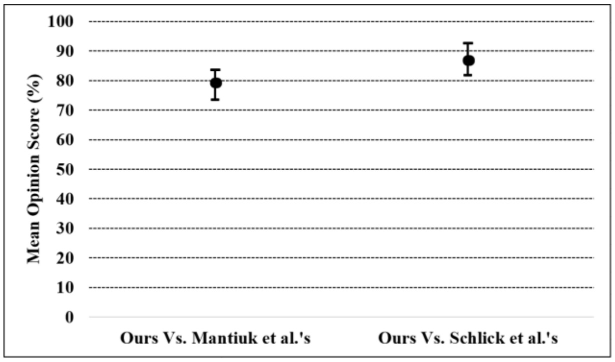


Fig. 7. Preference scores of the subjects in mean opinion score (MOS) when comparing the color accuracy of our proposed color adjustment method over that of Mantiuk et al.'s and Schlick et al.'s methods coupled with Luzardo et al.'s iTMO.

IV. CONCLUSIONS

In this paper, we addressed the issue of color shift in SDR to HDR mapping. Such mapping may take place at the display device, which due to wireless bandwidth limitations receives SDR content and converts it to HDR format to take advantage of the HDR capabilities of the display. We proposed a perception-based color adjustment method that, unlike other methods, preserves the hue of the colors while causing negligible changes in luminance irrespective of the iTMO used. Subjective evaluations demonstrated that our proposed color adjustment method, outperforms existing state-of-the-art methods and can generate HDR colors that closely follow their SDR counterparts irrespective of the iTMO used. Preliminary evaluations have shown that our color adjustment method works equally well on tone mapping applications.

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