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Color correction for tone mapping

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Abstract

Tone mapping algorithms offer sophisticated methods for mapping a real-world luminance range to the luminance range of the output medium but they often cause changes in color appearance. In this work we conduct a series of subjective appearance matching experiments to measure the change in image colorfulness after contrast compression and enhancement. The results indicate that the relation between contrast compression and the color saturation correction that matches color appearance is non-linear and smaller color correction is required for small change of contrast. We demonstrate that the relation cannot be fully explained by color appearance models. We propose color correction formulas that can be used with existing tone mapping algorithms. We extend existing global and local tone mapping operators and show that the proposed color correction formulas can preserve original image colors after tone scale manipulation.

Categories and Subject Descriptors (according to ACM CCS): Computer Graphics [I.3.3]: Picture/Image Generation—Display algorithms;

1. Introduction

While many tone mapping algorithms offer sophisticated methods for mapping a real-world luminance range to the luminance range of the output medium, they often cause changes in color appearance. The most common tone manipulation is luminance compression, which usually causes darker tones to appear brighter and distorts contrast relationships. Figure 1B shows an HDR image after compressing luminance contrast by a factor of 0.3 while preserving pixel chrominance values (in terms of the CIE xy chromatic coordinates). When compared to the non-compressed image (exposure adjustment + sRGB display model) in Figure 1A, the colors are strongly over-saturated. If, instead of compressing luminance, all three color channels (red, green and blue) are compressed, the resulting image is under-saturated, as shown in Figure 1C. To address this problem, tone mapping algorithms often employ an ad-hoc color desaturation step, which improves the results, but gives no guarantee that the color appearance is preserved and requires manual parameter adjustment for each tone-mapped image (Figure 1D).

The goal of this work is to quantify and model the correction in color saturation that needs to be made after tone mapping. We do not rely on the predictions of the existing appearance models but instead conduct a subjective appearance matching in which we measure the necessary color correction. Given a tone-curve in the luminance domain, we want to find new chrominance values such that the resulting image closely matches the appearance of the image with no tone modification. However, unlike other approaches [PFFG98,PTYG00,FJ04,AR06,KJF07], we do not want to compensate for the difference in viewing conditions between a display and the real-world scene, such as adapting luminance, chromatic adaptation (white balancing) or color appearance effects due to the difference in absolute luminance levels. The color-corrected images should preserve the appearance of the reference image with unmodified contrast shown on the same display. For HDR scenes the reference image is the best exposure displayed after accounting for a display function (display model). We also do not study the aspect of color preference, although it is known that more saturated colors are preferred in reproduction [FdB97]. These assumptions are necessary to isolate different effects, which would otherwise obscure the experimental results.

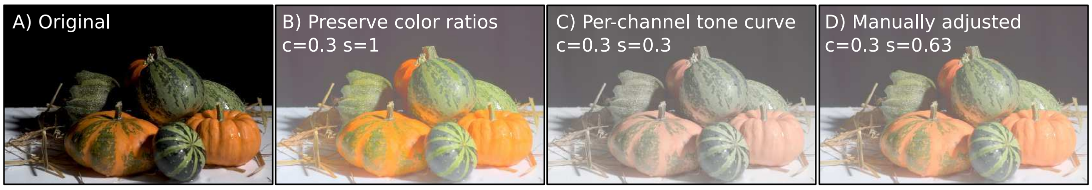

Figure 1: *An original image A) compared with three images after contrast compression. Two common color correction methods B) and C) are compared with manual color adjustment D). Existing color correction methods cannot adjust colors for large contrast compression.*

This paper offers the following contributions:

- Color reproduction properties of the color correction methods commonly used in tone mapping are analyzed in Section 3.
- We measure the necessary color correction in an experimental study and derive a color correction model in Section 4.
- We demonstrate that color appearance models cannot fully explain experimentally measured color correction in Section 5.
- In an additional experiment we measure the color correction in the CIELAB color space [Col86] (Section 6) and then discuss the limitations of this method in Section 7.
- Local and global tone mapping operators are extended to include the proposed color correction in Section 8.

2. Related work

Color reproduction on devices of limited color gamut have been well studied in the context of gamut mapping [ML01, GSS*07]. However, gamut-mapping differs from our problem in three major aspects: Firstly, gamut mapping attempts to modify both luminance (lightness) and chrominance (chroma) to preserve color appearance. In our case, the luminance modification (tone-curve) is given by the tone mapping operator and we are allowed to modify only chrominance. Secondly, gamut mapping considers mostly mapping colors from one device to another of comparable dynamic range. Therefore, the contrast compression used in gamut mapping is much smaller than that applied for tone mapping, which needs to compress the dynamic range found in the real-world to the fraction of that range that is available on an output device. Finally, gamut mapping operates on display-referred images, which have been already tone-mapped by a camera, while tone mapping operates on scene-referred images.

Color appearance studies have revealed many factors that influence our color perception. The apparent colorfulness of uniform color patches has been found to vary with the luminance (Hunt effect) [Hun52], image size [NB06] and the color of the surround [BM97]. The apparent lightness or brightness of heterochromatic patches depends on chromacity (Helmholtz&Kohlrausch effect) [Nay97] and apparent hue depends on luminance (Abney effect) [ANK87]. Calabria and Fairchild [CF03] found that the perceived contrast of complex images decreases with reduced chroma and the relation is sigmoidal. The sigmoidal relation does not hold for achromatic images, which are perceived to have higher contrast than images at 20% chroma level.

Most of the work on color reproduction in tone mapping is focused on preserving color appearance of the real-world scene, as it is perceived by the human eye, on a computer screen [PFFG98, PTYG00, FJ04, AR06, KJF07]. Pattanaik et al. introduce a complex model of human color vision, incorporating separate pathways for rod and cone vision, opponent color processing, and gain control for both luminance and contrast signals [PFFG98]. Later work [PTYG00] focuses on the aspects of temporal adaptation, uses the photoreceptor model instead of the luminance gain control, and employs a simplified appearance model based on Hunt's model. The early iCAM color appearance model [FJ04] achieves contrast compression by applying a spatially varying power function to the three color channels in the LMS color space. The newer iCAM06 model [KJF07] replaces the power function with the photoreceptor response model and considers separately scotopic and photopic signals. It also accounts for perceived contrast change with adapting luminance level due to the Stevens effect [SS63] and with surround luminance due to the Bartleson-Breneman effect [BB67], and compensates for increased colorfulness with luminance due to the Hunt effect [Hun52]. While these papers describe self-contained tone-mappers that address color appearance issues, Akyüz and Reinhard [AR06] propose a color processing framework that could be adapted to any tone mapping that preserves the ratios between color channels. Their method transforms an HDR image using a forward and then backward CIECAM'02 color appearance model [MFH*02], and then the resulting luminance map is replaced with the result of a tone mapping operator.

The above tone mapping operators account for the color differences that are the result of different luminance and chromatic adaptation between a real-world scene and display viewing conditions. However, none of these approaches considered the change in color appearance that is caused by the tone mapping curve itself, which is the subject of our study.

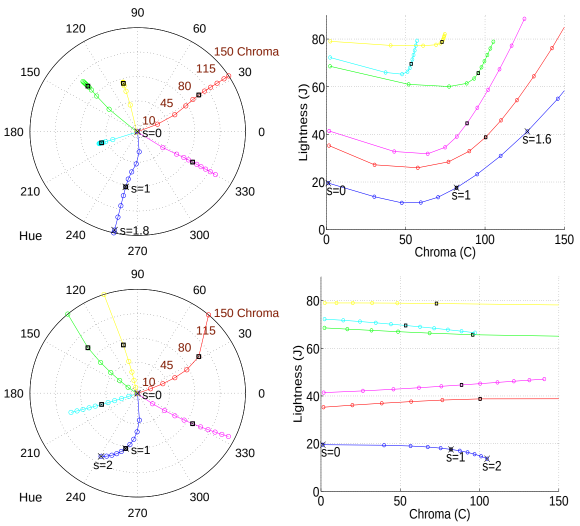

Figure 2: *CIECAM02 prediction of hue, chroma and lightness for the non-linear (two plots at the top, Equation 2) and luminance preserving (two plots at the bottom, Equation 3) color correction formulas. The lines depict the change of perceptual attributes for six basic colors (red, magenta, blue, cyan, green and yellow) of different luminance when the saturation factor s varies from 0 to 2. The initial points ($s = 1$) are marked with black squares. The non-linear formula (Equation 2) strongly distorts lightness, but better preserves hues than the luminance preserving formula (Equation 3).*

3. Color correction in tone mapping

The common approach to color treatment in tone mapping, introduced by Schlick [Sch94], is preserving color ratios:

$$C_{out} = \frac{C_{in}}{L_{in}} L_{out}, \tag{1}$$

where C denotes one of the color channels (red, green, or blue), L is pixel luminance and *in*/*out* subscripts denote pixels before and after tone mapping. All values are given in linearized (not gamma-corrected) color space. Later papers on tone mapping, employing stronger contrast compression, observed that the resulting images are over-saturated, as shown in Figure 1B, and suggested an *ad-hoc* formula [TT99]:

$$C_{out} = \left(\frac{C_{in}}{L_{in}}\right)^s L_{out}\ , \tag{2}$$

where s controls color saturation. The drawback of the above equation is that it alters the resulting luminance for $s \neq 1$ and for colors different from gray, that is $k_R R_{out} + k_G G_{out} + k_B B_{out} \neq L_{out}$, where $k_{R,G,B}$ are the linear factors used to compute luminance for a given color space. This formula can alter the luminance by as much as factor of 3 for highly color saturated pixels, which is an undesirable side effect. Therefore, we introduce and examine in this paper another formula, which preserves luminance and involves only linear interpolation between chromatic and corresponding achromatic colors:

$$C_{out} = \left(\left(\frac{C_{in}}{L_{in}} - 1\right) s + 1\right) L_{out}\ . \tag{3}$$

The difference between the color correction formulas from Equations 2 and 3 is best shown on the plots of hue, chroma and lightness as predicted by the CIECAM02 color appearance model, shown in Figure 2. The change in color correction factor s for the non-linear formula from Equation 2 modifies not only chroma, but also the lightness of the colors. The luminance preserving formula from Equation 3 can prevent such lightness shift, but leads to stronger hue shift, especially for red and blue colors. Therefore the choice of one formula over another may depend on whether preserving hue or luminance is more important for a particular application.

Another approach to color treatment is to apply the same tone-mapping curve to all three color channels. It can be shown however that this is equivalent to Equation 2 if the color correction factor s is equal to the contrast compression factor c, and the tone curve has the form:

$$L_{out} = (L_{in}\, b)^c\ , \tag{4}$$

where b is the brightness (exposure) adjustment that normalizes for maximum display brightness ($L_{out} = 1$ for the peak display luminance).

If the tone-curve is an arbitrary function, applying the same tone-curve to all color channels is not equivalent to Equation 2 under $s = c$, but the results are very close. In case of local tone mapping operators, the three color channels usually cannot be modified simultaneously. Therefore, those operators must rely on color transfer formulas, such as Equation 2 or 3. The assumption that $s = c$, or altering the three color channels simultaneously, works well for small contrast compression, but leads to images with faded colors for smaller c, as shown in Figure 1C.

The Equations 2 and 3 above offer a convenient way of correcting colors in the RGB color space, but they require manual adjustment of the parameter s. The main goal of this work is to estimate the parameter s given a luminance-specific tone-curve.

The RGB color space used in this paper assumes the sRGB color primaries and D65 white point. The RGB trichromatic values are linear with respect to radiance (not gamma-corrected). All results included in the paper and in the supplementary materials are transformed to the sRGB color space ($\gamma = 2.2$).

4. Experiment 1: color matching for tone mapping

We conducted a subjective study in order to investigate how much color correction is required to compensate for the contrast compression.

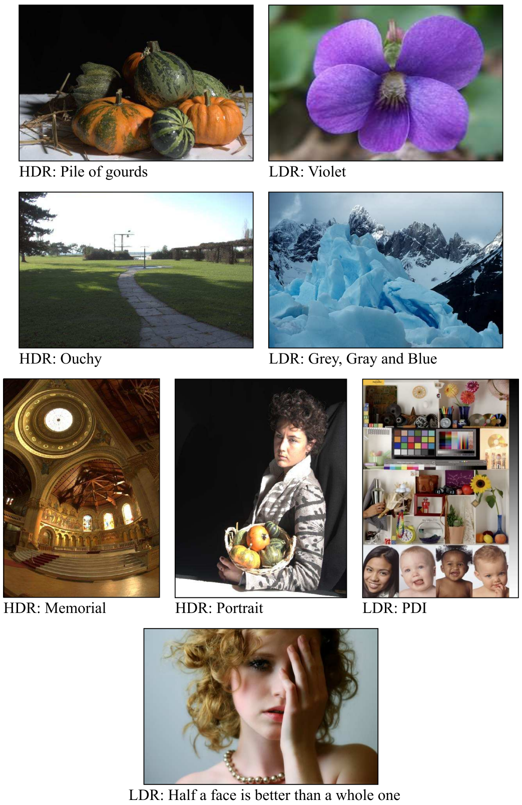

Figure 3: *HDR and LDR images used in the experiments.*

4.1. Participants

The experiment was split into two parts to test both non-linear (Equation 2) and luminance preserving (Equation 3) color correction formulas. Eight participants (3 females and 5 males) finished the first part and ten (2 females and 8 males) the second part. Their age was between 23 and 38 years, with average of 32 years. They had normal or corrected to normal visual acuity. Six participants had basic expertise in imaging, and the remaining four were not experienced in computer graphics. None of them was aware of the technical details of the experiment. All participants had correct color vision and only three of them shared both parts.

4.2. Stimuli

We used 8 natural images in the experiment (shown in Figure 3). They encompass a broad range of color hues and saturations appearing in photographs presenting human faces, close-ups, indoor and outdoor scenes. To test both scene- and output-referred images, 4 HDR and 4 LDR images were used.

The images were displayed on a 26” LCD display (NEC SpectraView 2690, with screen size 55x33.5 cm, resolution 1920x1200 pixels, minimum and maximum luminance levels 0.7 and 300 cd/m^2 respectively). We used the native NEC 2690 settings for color primaries and white point, which were close to the sRGB model. The display response for red, green and blue color channels was carefully measured using the Minolta CS-100A colorimeter and then used as a lookup table in the display model and inverse display model. The experiment was conducted under dim illumination (60 lux).

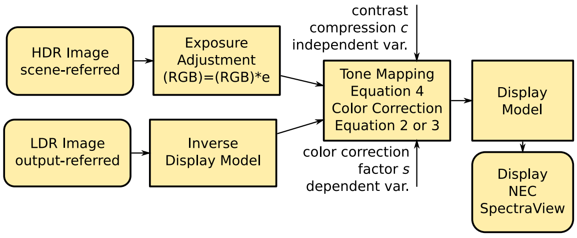

Figure 4: *Tone mapping and color correction used in the experiments.*

Figure 4 illustrates the image processing applied to LDR and HDR images before showing them on the display. Image contrast was modified using Equation 4 and contrast factor c varied from 0.1 to 1.6. Color saturation factor s was adjusted by a participant and colors were corrected using either Equation 2 or 3. Contrast compression and color correction were performed in the linear domain after applying an inverse display model to the LDR images. The exposure of individual HDR images was adjusted to the level that gave the best visualization of unmodified HDR images on the monitor.

Contrast compression and color correction cause a strong luminance increase for small values of c and high values of s, which leads to out-of-gamut colors and problems with subjective comparison of colorfulness due to the hue shift caused by color clipping. To avoid out-of-gamut colors we decided to reduce the luminance of the input images to 33% (100 cd/m^2) of the peak luminance of the display, which also makes the peak luminance closer to the typical settings of an office display.

4.3. Experimental procedure

Figure 6 shows a screen-shot from the experiment. Participants were asked to adjust the overall colorfulness of the left image to make it appear as close as possible to that of the reference image but slightly and visibly lower. Likewise, the right image should be adjusted to be perceived as slightly but visibly more colorful. Then, the matching colorfulness is assumed to be the mean of both left and right target images. As we verified in a pilot study, this method gives less inter- and intra-subject variations than direct color matching of images with the same number of comparisons. Differences in colorfulness are difficult to discriminate and direct matching results a random point from the distribution with a large

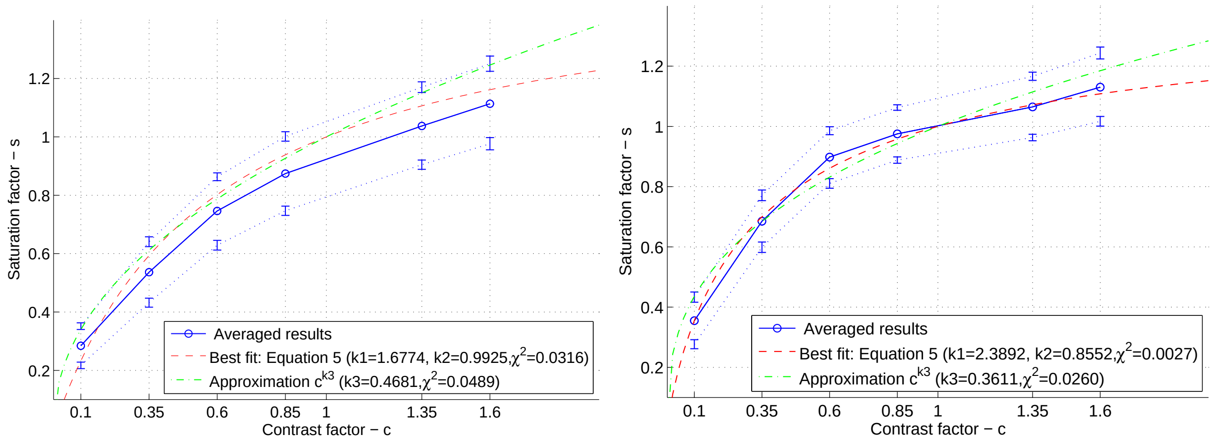

Figure 5: *Result of matching colors between image with altered contrast and an original image. Left: for non-linear color correction, right: for luminance preserving correction. The solid lines show averaged results and the dotted lines indicate the saturation factor for images 1 JND more and less saturated, and the continuous line is their mean. Error bars show the standard error of mean. The red line shows the best fitting model.*

Figure 6: *Screenshot from the experiment. In the center is the linearly mapped reference image. Left and right are two tone mapped images adjusted by a participant. Background color is set to neutral grey.*

standard error. By measuring ± 1 just noticeable difference (JND) and taking the average, we obtain a point that is more likely to lie close to the mean of the distribution.

For each color correction formula, participants matched image colors in a total of 48 tests, one for each of the 8 images and 6 compression levels (c=0.1, 0.35, 0.6, 0.85, 1.35, and 1.6). The whole experimental procedure took approximately 30 minutes for a single participant. Before actual experiment, each participant conducted a short pilot experiment in which he/she was explained how to interpret the "overall image colorfulness".

4.4. Results

Figure 5 shows averaged results for both color correction formulas. The plots indicate moderate contrast correction for small contrast modification (slope<1) and much stronger correction for strong contrast compression. The interpolated line for the non-linear color correction formula (left plot) do not cross the point $s(1) = 1$, which could be explained by the measurement error and lack of data near that point.

To check the statistical significance of other factors, we conducted several Analysis of Variance (ANOVA) tests. We found no statistical difference between LDR and HDR images ($F(1,863) = 0.1$ for the test of 2 LDR/HDR $\times$ 6 contrast levels $\times$ 2 contrast correction formulas), which suggests that the relation holds for both output-referred and scene-referred images. There is a significant effect of gender ($F(1,863) = 12.13$; $p < 0.01$ for 2 (gender) $\times$ 6 (contrast) $\times$ 2 (formula) test), with females choosing slightly less saturated images. We found also an effect of expertise in imaging ($F(1,863) = 9.53$; $p < 0.01$ for 2 (expert) $\times$ 6 (contrast) $\times$ 2 (formula) test), with those participants who work professionally with images selecting a slightly higher s factor.

The relation between c and s can be approximated with a power function $s(c) = c^{k_3}$, but the function is not plausible at extrapolated values for $c > 1.6$ and the fit is poor (see plots in Figure 5). Therefore, we use instead a sigmoid function:

$$s(c) = \frac{(1+k_1)\, c^{k_2}}{1+k_1\, c^{k_2}}. \tag{5}$$

The function has been selected, so that it does not change color saturation if contrast is left unchanged ($s = 1$ for $c = 1$) and eliminates all color information when an image has no contrast ($s = 0$ for $c = 0$). The parameters for the best least-square fit are shown on the plots.

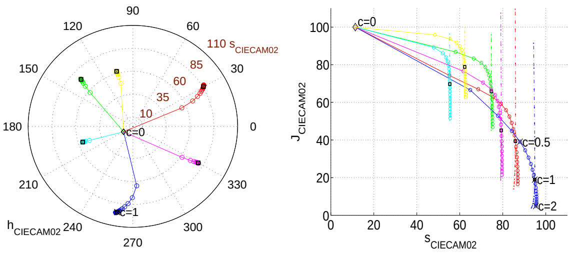

Figure 7: *CIECAM02 prediction (hue, saturation, lightness) for color change due to contrast modification ($c \in [0,2]$), while color correction s =model prediction (solid lines, circles) or $s = 1$ (dotted lines). Plots for non-linear color correction formula. The notation is the same as in Figure 2. The black squares indicate initial color coordinates ($c = 1$). Corrected colors are not linearly related to any perceptual attribute.*

5. Color appearance models and color correction

The results of Experiment 1 demonstrated that the desirable color saturation level is related to contrast compression in a complex and non-linear way. Color appearance models attempt to predict non-linearities in the visual system and provide a set of perceptual attribute predictors, such as colorfulness, chroma and saturation, which should be linearly related to our color perception. In this section we test whether an appearance model can explain the non-linear relation we found in our experiment. We want to find which perceptual attribute should be preserved after contrast compression to achieve the best color match with an original image.

We choose six basic colors of different hue, saturation and lightness, distort them by compressing contrast ($c \in [0,2]$) with respect to a reference white, and process them with both color correction formulas (Equations 2 and 3) using the color correction factor s given by the models found in the experiment (Equation 5). The resulting colors are transformed to the space of perceptual attribute predictors of hue, lightness, chroma, saturation and colorfulness, using of one of the popular appearance models: CIELAB, CIELUV [Col86], CIECAM02 [MFH*02] and iCAM [FJ04].

From all perceptual attributes, the CIECAM02 saturation was the most consistent across contrast variation and was selected for the plot in Figure 7. The remaining plots can be found in the supplementary materials. Even though the CIECAM02 saturation was the most consistent, solid lines in Figure 7 indicate a non-linear relation between CIECAM02 saturation and contrast compression. Therefore, preserving CIECAM02 saturation or altering it according to a simple linear rule cannot correct colors when contrast is compressed. This shows that none of the perceptual attributes in any of the considered appearance models can explain our experimental data.

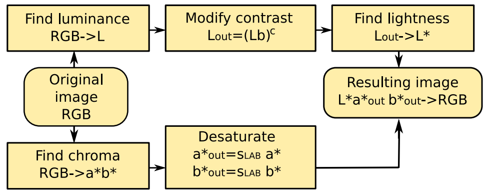

Figure 8: *To correct colors in the CIELAB color space, CIELAB chroma from the original image is corrected by the factor s_{LAB} and combined with the lightness L^* from the tone-mapped image.*

6. Experiment 2: Color correction in CIELAB

In Section 3 we discussed the limitations of the simple color correction formulas in the RGB color space, which either preserve lightness but distort hue, or better, preserve hue but distort lightness. Perhaps if colors are corrected in the space of perceptual attributes, along the axis of chroma or colorfulness (along the radius on the hue/chroma plots in Figure 7), the color correction will be simpler and the resulting images will give a better match to the originals. We test this hypothesis in the following experiment.

Both CIELAB and CIELUV models can be easily adapted to our color correction scheme. Luminance can be modified using a contrast altering formula (Equation 4) while CIELAB or CIELUV chroma is preserved or modified along the chroma axis. The framework for color correction in the CIELAB color space is shown in Figure 8. A similar color correction procedure cannot be found for CIECAM02. Because of the interactions between chrominance and luminance that are modeled in CIECAM02, there can be no chromatic coordinates that would result in exactly the same colorfulness and hue values after altering luminance. It is only possible to find a least-squares approximation of the original colorfulness, but this would be too expensive computationally for any practical application. Therefore, we restrict our considerations to the CIELAB color space.

Experiment 2 has the same goal and procedure as Experiment 1, but this time we limit the number of participants to 4 and apply color correction in the CIELAB color space, as shown in Figure 8. The results of the experiment are shown in Figure 9. For small contrast modifications ($0.6 < c < 1.6$) the color correction is almost unnecessary ($s_{LAB} \approx 1$). Therefore, preserving chroma in the CIELAB space for small contrast changes should produce desirable results. This is consistent with common practice in gamut mapping where color operations are usually performed in the lightness / chroma space. However, for strong contrast compression ($c < 0.6$) colors need to be desaturated, similarly to the RGB color correction formulas.

Figure 10 illustrates the s_{LAB} color correction in the CIECAM02 hue, saturation and lightness coordinates using

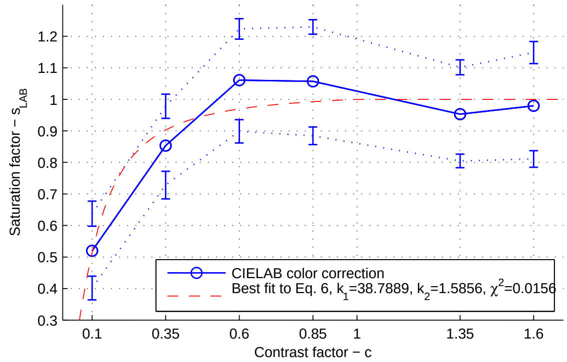

Figure 9: *Result of matching image colors using color correction in the CIELAB color space. The notation is the same as for Figure 5.*

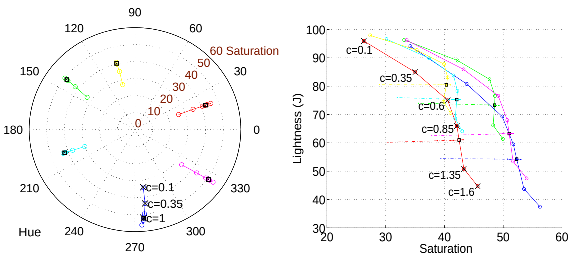

Figure 10: *CIECAM02 prediction for color correction in the CIELAB space (Figure 8). a^* and b^* components were modified based on s_{LAB} from Figure 9. The notation is the same as in Figure 7, except that the dotted lines in the right plot show color change for $c = 1$ and $s_{LAB} \in [0,2]$ (same characteristic as shown in Figure 2).*

the same notation as the plots in Figure 7 for the RGB color correction formulas. The color correction in CIELAB better preserves hue and lightness (compare dotted lines in Figure 10 with Figure 2). The trend is similar to that in Figure 7. This confirms the observation that although saturation is the attribute that requires the least correction after contrast modification, it cannot explain stronger desaturation for contrast compression $c < 0.6$.

7. Are color appearance models suitable for tone mapping?

The results of Experiment 2 suggest that the CIELAB chroma predictor can better preserve the color appearance after contrast modification, and therefore seems to be an attractive alternative to color correction in the RGB color space (Equations 2 and 3). The CIELAB color space as well as CIECAM02 or CIELUV, however, cannot be easily used for high dynamic range scenes. The major difficulty is accurate estimation of the reference white color, both in terms of

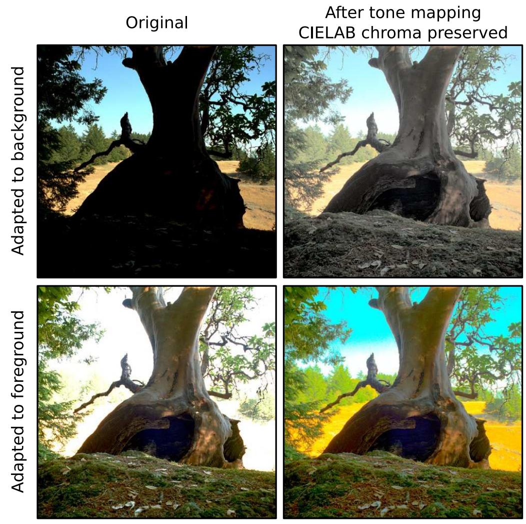

Figure 11: *High dynamic range image before and after tone-mapping [MDK08] while preserving CIELAB chroma. The resulting colors strongly depend on the selection of the absolute white point for the CIELAB transformation.*

chrominance and absolute luminance. Figure 11 shows that different selection of a reference white leads to completely different colors in tone mapped images. In the top row we assumed the reference white appropriate for the background and in the bottom row we assumed the reference white appropriate for the foreground. Automatic estimation of a reference white on the pixel level is a difficult problem, and although some methods exist [KMS05], they may lead to unreliable estimation. At the same time, CIELAB predictions completely fail if a reference white is poorly estimated. Therefore, a fully automatic color correction in the CIELAB color space is currently a viable alternative only for low dynamic range scenes.

Another important observation is that the goal of most appearance models is different than the goal of our experiment and of most tone mapping operators. Appearance models try to predict *perceived* colors accounting for all limitations of the visual system, such as poor color vision under low light. In our study and in most tone mapping operators, the goal is to preserve *photographic* colors, which are the colors that could be expected under optimal camera exposure settings. Those photographic colors do not turn pale under low light and are closer to the *memory colors* of a particular object [BT02].

8. Application in tone mapping

In this section we demonstrate how the relation between contrast compression and desired color correction, which we

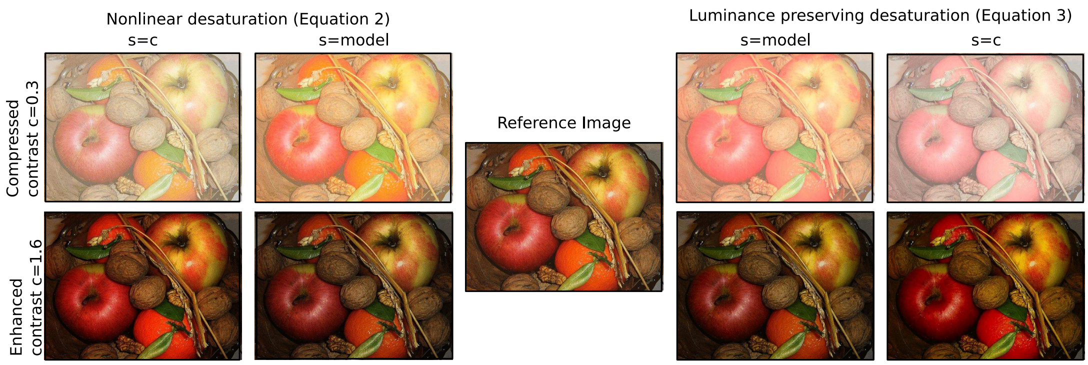

Figure 12: *Result of four color correction methods for contrast compression (top) and enhancement (bottom).*

found in the subjective study, can be used to extend global and local tone mapping operators.

Probably the most common tone operation is contrast compression and enhancement using a power function (Equation 4). Figure 12 shows an example from a large test set we used for validation (the full test set can be found in the supplementary materials). The figure contains images after contrast compression and enhancement, whose colors were corrected using both color correction formulas (Equations 2 and 3), and the color correction factor was either assumed to be equal to the contrast compression factor ($s = c$) or was computed from our experimental models (Equation 5). The assumption $s = c$ produces satisfactory results for many images. However, this example shows over-saturated images for contrast enhancement and images that are too washed-out for contrast compression. The contrast-compressed images that were color corrected with the model (1st row, 2nd and 4th column) may look slightly unnatural due to strong saturation, but the goal of our color correction is the best match to the reference rather than the most natural look or the preference. Another important observation is that the luminance preserving formula (right side) often results in a hue shift for red colors, as discussed in Section 3 and shown in Figure 7.

The tone mapping based on the bilateral filtering [DD02] can be easily extended to include the proposed color correction formulas. The operator uniformly reduces the contrast of the base layer (low pass + edges) while preserving details (high frequencies). The amount of compression in the logarithmic domain is equivalent to the contrast compression factor c. The original algorithm does not perform any desaturation and employs Equation 1. This produces good results when the operator is run with the default parameters but results in over-saturated colors for strong contrast compression, as shown in Figure 13. We employ the non-linear color correction formula (Equation 2) with the experimental model (Equation 5) to fix the over-saturated colors.

The color correction formulas proposed in this paper can be applied not only to the simplified operator (Equation 4) with a known contrast compression factor c, but to any tone mapping function. The contrast factor can be approximated by the slope of the tone curve on the log − log plot, which is given by the derivative of the tone-curve in the logarithmic space. Denoting $\widehat{L} = \log_{10}(L)$, c is given by:

$$\begin{aligned} \widehat{L}_{out} &:= tmo(\widehat{L}_{in}) \\ c(L_{in}) &= \frac{d}{d\widehat{L}} tmo(\widehat{L}_{in}) \end{aligned} \qquad (6)$$

A similar approach was used in [PTYG00] to relate the saturation factor s to the local contrast compression. The function $c(L_{in})$ gives us an estimate of contrast compression for each tone level, which we can use in combination with any c-s relation model (Equation 5) and with any color correction formula (e.g. Equations 2 and 3).

We modify the display adaptive tone mapping operator [MDK08] to include our color correction formula (Equation 5). The original algorithm employs Equation 2 to compensate for color difference, in which the parameter s has to be manually adjusted. The first column of Figure 14 shows that for the same color correction factor ($s = 0.3$) color correction need to be readjusted when tone mapping for displays of different dynamic range. The proposed color correction model can compensate for these differences and automatically readjust color correction factor s.

Full size results for over 40 LDR and HDR images can be found in the supplementary materials.

9. Discussion

The considerations of this paper seem to be limited only to global tone mapping operators, which affect only low frequencies. We conducted a pilot study in which we investigated the effect of a local operation, unsharp masking, on the colorfulness of images. Figure 15 shows an image that has enhanced (left) or reduced (right) details (top) and global contrast (bottom). The image clearly indicates that sharpening has little effect on perceived image colorfulness. Since

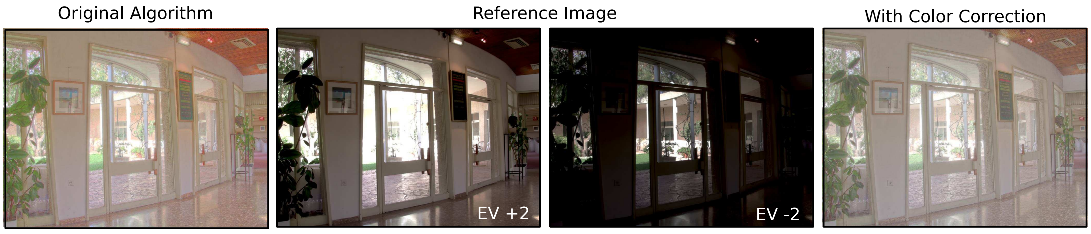

Figure 13: *The result of the “bilateral” tone mapping [DD02] with strong contrast compression, original algorithm compared to the algorithm with color correction.*

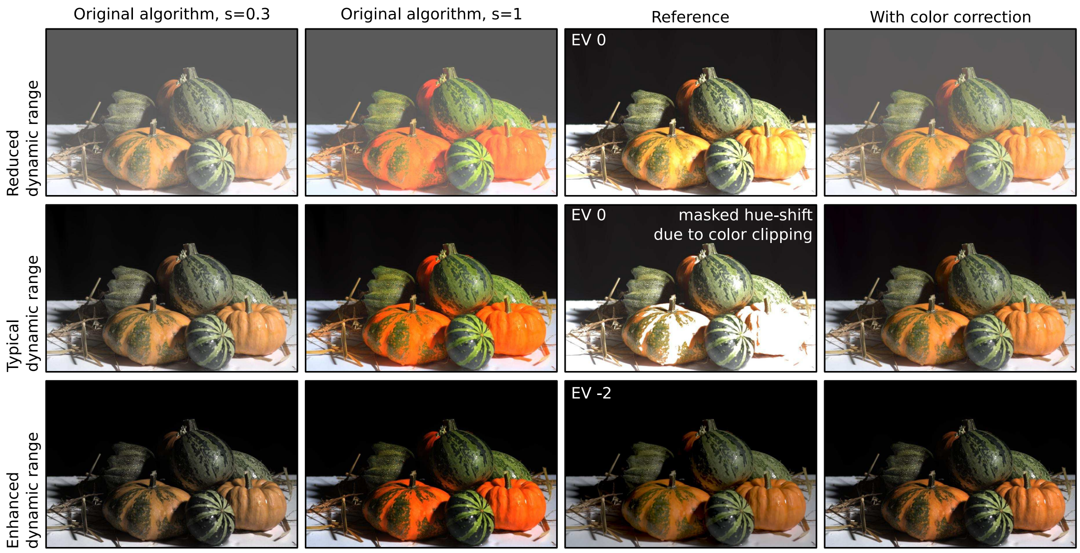

Figure 14: *The result of the “display adaptive” tone mapping [MDK08] for a display of reduced, typical and extended dynamic range (from top to bottom row). The original algorithm with a constant color correction factor ($s = 0.3$ and $s = 1$) is compared to result of the proposed color correction. The yellow color that can be seen in the reference image (top row) is an artifact of color clipping and is not visible when clipped colors are masked (center row) or exposure is reduced (bottom row).*

sharpening is often the main component of local tone mapping operators, our color correction method is also valid for those operators.

To better isolate the effect of contrast compression on image colorfulness, all the experiments were designed to minimize clipping of colors that exceeded the display color gamut. We did not use the full dynamic range of the display to reserve margins for highly saturated colors and we did not consider very strong contrast enhancement. We also allowed for colors that would not be available on an sRGB display with a peak luminance of 100 cd/m^2. We conducted a pilot study in which we did not observe any difference in measurement if we clipped colors to the limited sRGB color gamut or if we used all the available gamut of our display. Further studies, however, should investigate the effect of color clipping on the necessary contrast correction, especially for large contrast enhancements.

10. Conclusions and Future Work

Tone mapping inevitably results in an image distortion which affects both tone and color reproduction. In this work we analyze how such color distortions can be reduced.

The main contributions of this paper are two models predicting desirable color correction given contrast distortion due to tone mapping. The models are used with simple and computationally inexpensive color correction formulas, which are applicable for global tone mapping operators and give good practical results for local operators. We found that the non-linear color correction formula strongly distorts lightness but introduces less hue distortion than the luminance preserving formula, and is therefore more suitable for tone mapping. We experimented with color appearance models, which can potentially produce less hue and chroma distortions, but are less suitable for high dynamic range images

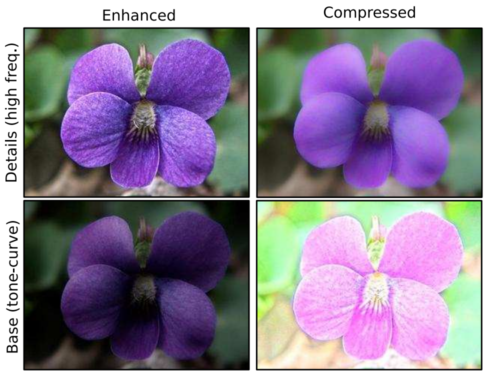

Figure 15: *Enhancement (left) and compression (right) of details (high frequencies) has little effect on colorfulness (top row) as compared to global contrast modification (bottom row).*

because of problems with reference white estimates and different rendering intents.

Our results suggest that the image colorfulness is affected by overall image contrast, defined as a slope of a tone-curve on the log-log plot (gamma) and is not influenced by sharpenning. Such overall contrast, however, is difficult to define for local tone-mapping operators that introduce strong discontinuities on the tone curve. Further studies are needed to isolate a set of factors that influence colorfulness after local tone-mapping operations.

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