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Hue Preservation using Enhanced Integrated Multi-scale Retinex for Improved Color Correction

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Abstract. *The images captured by most current digital cameras suffer from a narrow dynamic range that results in poor color fidelity and perceived image quality. Accordingly, this article proposes an enhanced integrated multi-scale Retinex (IMSR) method in a device-independent color space, namely, CIELAB, to preserve the hue and obtain a high contrast and naturalness. To achieve the desired objectives, a captured sRGB image is transformed into CIELAB color space using standard equations, then the IMSR is applied to only the L^* values, thereby preserving the balance of the color components, hue, and saturation. However, since this process causes unnatural undersaturation, a saturation adjustment is performed by applying a simple saturation compensation method, which maintains the chromatic ratio with respect to the sRGB gamut boundary according to the variation in the luminance. The adjusted CIELAB values are then transformed into sRGB using an inverse transform function. In experiments, the proposed method showed an improved visibility in both dark and bright regions, while reducing color distortion. Furthermore, in an observation preference test, the images resulting from the proposed method were perceived as having a higher visibility and naturalness. © 2011 Society for Imaging Science and Technology.*
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INTRODUCTION

Digital cameras are now widely used to take photographs. However, when digital cameras are used to shoot scenes with extreme conditions, this often give rise to highlight clipping and/or underexposure, as the sensors in most digital camera have a restricted capability with a limited dynamic range for both the high and low luminance regions of a scene. In fact, digital cameras can only sense a dynamic range of about 10^2 cd/m^2, whereas the dynamic range of a real scene is almost 10^8 cd/m^2. In contrast, the dynamic range of the human eye is almost 10^5 cd/m^2, and although this does not cover the entire dynamic range of a scene, the human visual system uses a mechanism called "lightness adaptation" to perceive the light and dark areas of a scene simultaneously.[1,2] Thus, to obtain a similar perception when looking at digital images, tone reproduction or tone mapping methods are used.

There are two types of tone reproduction technique: a TRC (spatially invariant tone reproduction curve) and TRO (spatially variant tone reproduction operator).[3] TRC methods are based on the global adaptation mechanism of human vision and work point-wise on the image data. However, while TRC methods are simple and efficient, these methods do not preserve the local contrast in the case of both light and dark regions. Meanwhile, TRO methods are based on a multi-resolution decomposition algorithm, such as Gaussian decomposition, and operate in a local way on the image data (e.g., by convolution). As a result, the local image contrast is preserved, although unwanted spatial artifacts, like as halo or banding effects, sometimes occur.

Recently, various Retinex methods, which are TRO methods, have been widely used, due to their high local contrast and visibility improvement, even given the presence of artifacts like halo effects. Jobson et al. also developed the Retinex theory into the single-scale Retinex (SSR) method and multi-scale Retinex (MSR) method as a combined form of the SSR method.[4,5] Initially, the MSR method experienced problems related to appropriate values for the parameters, chromatic unbalance, color distortion, noise, and graying out. Thus, a lot of research has been dedicated to improve these issues. A multi-scale Retinex with color restoration attempted to overcome the graying-out phenomenon in large uniform areas of an image by adopting a color restoration function to control the saturation of the final rendition.[6] However, the output does not reproduce natural tones and colors when compared with the real scene. Meanwhile, an adaptive scale-gain Retinex algorithm was introduced to prevent halo artifacts and suppress chromatic unbalance and

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noise by synthesizing both the original image and the image processed by the MSR.[7] The adaptive scale-gain Retinex method adopts a linear space without a logarithmic conversion to avoid any uncertainty for noise and the output range spreading in dark shadows. In a recent paper, an integrated multi-scale Retinex (IMSR) algorithm was introduced to improve the visibility in dark shadow areas of natural color images, while preserving a pleasing contrast without banding artifacts.[8] In this case, a Gaussian pyramid decomposition is used to reduce the computation time for generating a large-scale surround, while an integrated surround value for the luminance is applied to each channel to preserve the color balance in RGB color space. Previous research has also attempted to prevent color or chroma distortion by controlling the ratio of the RGB channels.[5–7] However, regardless of such efforts, most previous methods lead to some perceived color distortion. Based on the assumption that the input images are directly acquired in sRGB, the execution of a MSR in RGB color space does not preserve the perceived hue, that is, the hue of the original image in CIELAB color space is distorted.

In this article, we propose an enhanced IMSR method in a device-independent color space, namely CIELAB, to preserve the hue. First, a captured sRGB image is transformed into CIEXYZ color space and then converted into CIELAB color space to calculate lightness, hue, and saturation. The IMSR is then only applied to the lightness values, thereby preserving the balance of color components. Thereafter, the L^* values produced by the IMSR are mapped to displayable values by means of both a cumulative distribution function and a mapping function using hat of sRGB gamut to preserve the luminance in the high valued regions. However, since this process results in an unnatural saturation, a saturation adjustment according to the changed luminance is applied to a^* and b^* channels. These chroma values are adjusted by simple image gamut extension method for saturation compensation based on the ratio of chroma variation at sRGB gamut boundary depending on the luminance variation to achieve color naturalness. Finally, the adjusted CIELAB values are transformed into sRGB using an inverse transform function. In the experiments with real scene images, the results showed a high visibility in both dark and bright regions, and natural colors without any hue distortion. Furthermore, in the case of an observer preference test, most observers perceived for the images of the proposed method as more natural than previous results.

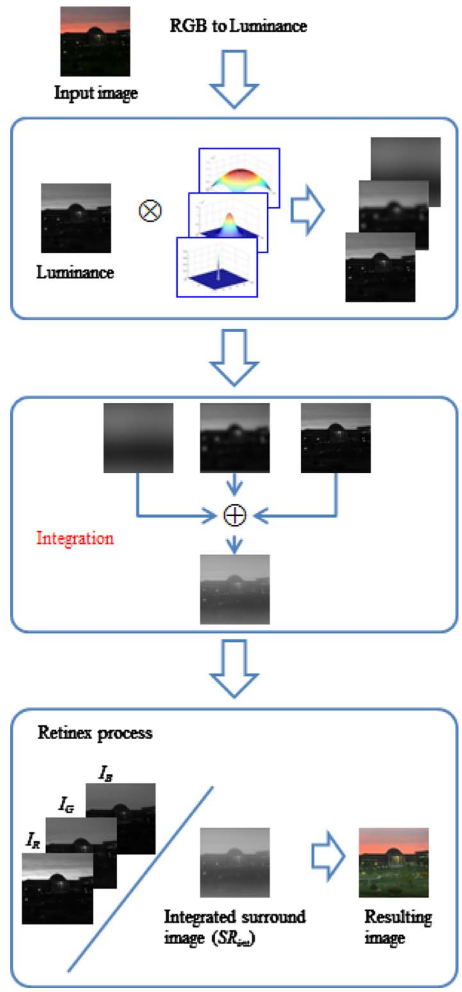

Figure 1. Flowchart for IMSR using integrated surround.

PREVIOUS INTEGRATED MULTI-SCALE RETINEX METHOD

The IMSR method proposed by Wang[8] is based on the adaptive scale-gain Retinex developed by Kotera et al.[7] with certain differences. First, the IMSR adopts a linear space without a logarithmic conversion to avoid any uncertainty for noise and the output range spreading in dark shadows. Second, the IMSR only uses the luminance channel to form the surround image, and then applies this result to each color channel to maintain the color balance. As such, the main difference is the use of an integrated multi-scale luminance surround from multiple luminance surround images using Gaussian filters with a different standard deviation. In order words, instead of the weighting sum of multiple SSRs, in MSR method, the IMSR integrates $m=1\sim M$ different surround images SR_m into a single surround image SR_{merge} with adaptive weight parameters $w(\sigma_m)$. The whole process is illustrated in Figure 1.

Preserving the color balance is achieved by using the luminance image $Y(x,y)$ and applying the integrated surround images SR_{merge} to each channel in the IMSR. The following equation describes the IMSR process,

$$IR_{merge}(x,y) = \alpha \frac{I_i(x,y)}{SR_{merge}(x,y)}, \quad (1)$$

where I is the input RGB image, IR_{merge} is the image calculated by the Retinex, i is the index indicating the RGB channel, α is the gain coefficient, and SR_{merge} is the integrated surround image. SR_{merge} is calculated by integrating the different surround images $SR_{merge}(x,y)$ with different adaptive weights $w(\sigma_m)$ as follows:

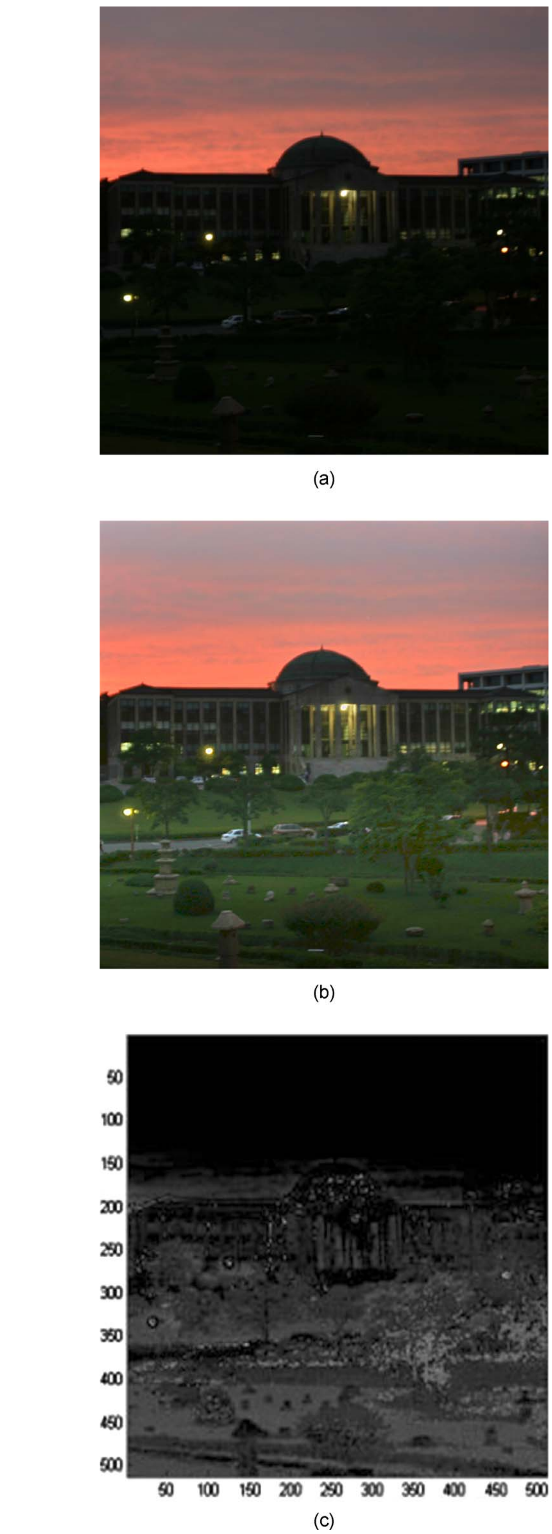

Figure 2. Result of IMSR and hue difference in CIELAB. (a) is the original image, (b) is the resulting image by IMSR, and (c) is the hue difference between the original and resulting image.

$$SR_{merge}(x,y) = \sum_{m=1}^{M} w(\sigma_m) SR_m(x,y,\sigma_m). \qquad (2)$$

Also, Eq. (3) shows the calculation of the surround images performed by convolution between the luminance Y images using Gaussian filters $G_m(x, y)$ with a different standard deviation σ_m.

$$SR_m(x,y,\sigma_m) = G_m(x,y) \otimes Y(x,y), \qquad (3)$$

$$G_m(x,y) = K_m \exp(-(x^2+y^2)/\sigma_m^2), \qquad (4)$$

$$\sum_{m=1}^{M} w(\sigma_m) = 1, \qquad (5)$$

$$\int\int G_m(x,y)dxdy. \qquad (6)$$

The setting of the optimum gain coefficient α and weights w are difficult without the original image. Thus, Wang proposed the Trial and Error method based on human vision to obtain the optimum parameters.[8] A test scene "color block" under nonuniform illumination in the experiments is captured by a digital camera, and then the camera image is modified using ADOBE PHOTOSHOP™ by trial and error method until it is seen approximately matched to the visual scene. The modified image is taken as a target image. To find the optimum parameters, the color differences ΔE^*_{ab} between the visual target image and the processed images are evaluated in CIELAB color space. As such, the optimum gain coefficients and weights, used in this study, were based on those data determined for the IMSR.

For the IMSR results shown in Figure 2, there is less banding than with the MSR. Also, the visibility and contrast are increased with the naturalness of the colors. Nonetheless, although this algorithm can preserve the color balance in RGB color space, the perceived hue is not preserved. Thus, if the original image is a sRGB image, the perceived hue can be thought as the hue value in CIELAB color space. In the Fig. 2(c), the hue difference mainly occurred on the dark area in the original image.

PROPOSED TONE REPRODUCTION METHOD

As mentioned above, the main objective of the proposed method is to preserve the perceived hue, and the process is explained in Figure 3. To consider the hue values, the proposed method adopts CIELAB color space. Therefore, the first process is the transformation of the sRGB values into CIELAB values. Then, only the lightness values are enhanced using the IMSR. However, normalization is a problem in the last IMSR process. Usually, the maximum value of lightness is applied to each channel as the denominator, yet this dulls the lightness values in bright regions. Therefore, to deal with this problem, the information of a cumulative distribution function (cdf) using enhanced lightness values is applied. Next, the values of the sRGB gamut are clipped to the sRGB gamut boundary using a proposed mapping function based on sRGB gamut hat, resulting in a lightness-enhanced image. However, the dark regions in the original image look like a black-and-white image, as they have low saturation values, therefore, the enhanced regions still have low satura-

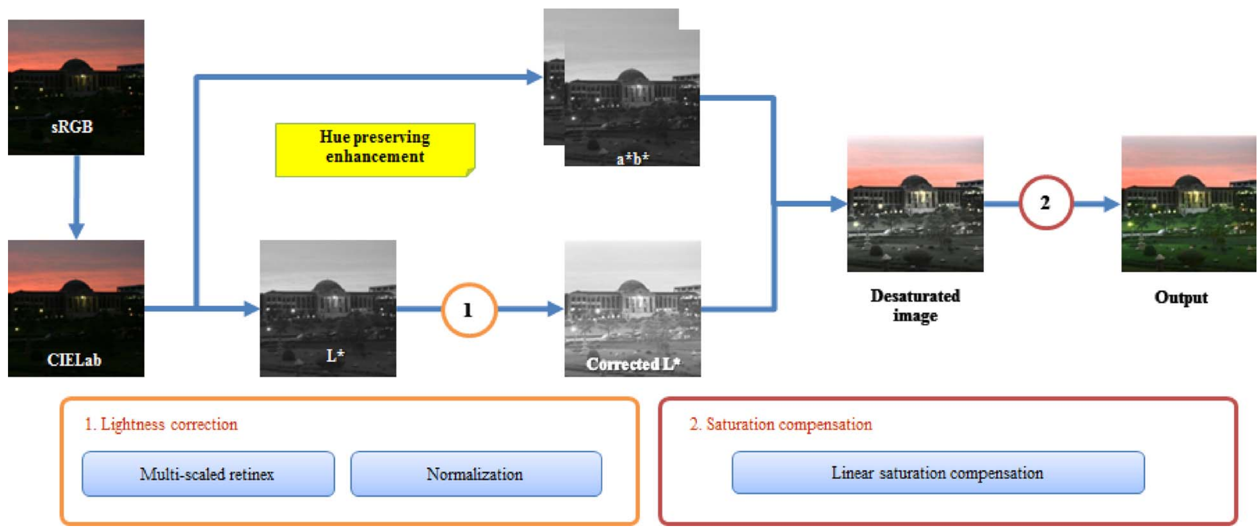

Figure 3. Procedure of the proposed tone reproduction method.

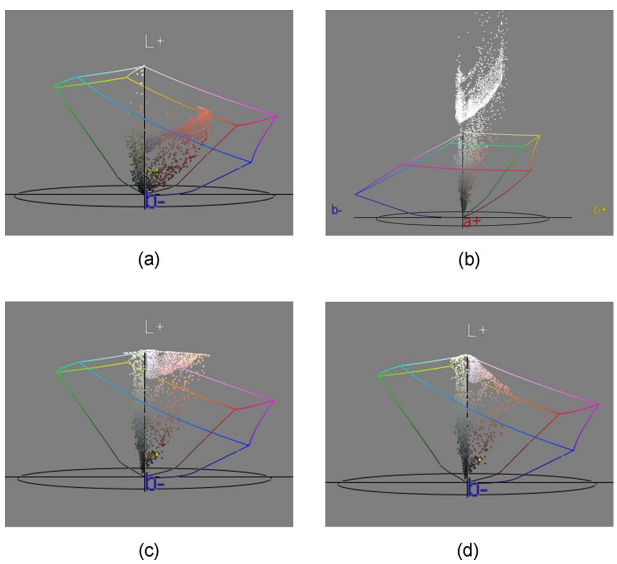

Figure 4. Gamut data of each step. (a) is the input image, (b) is the gamut data after IMSR in CIELAB color space, (c) is the gamut data after normalization, and (d) is the gamut data after HPMINDE gamut mapping method.

tion values. Thus, the saturation is also enhanced based on proportional control using the simple gamut extension based on the sRGB gamut boundary information as the last process.

LIGHTNESS ENHANCEMENT

To obtain the lightness, hue, and saturation values, the original image, which has sRGB values, is first transformed into CIEXYZ values using the following equation:[9]

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.4124 & 0.3576 & 0.1805 \\ 0.2126 & 0.7152 & 0.0722 \\ 0.0193 & 0.1192 & 0.9505 \end{bmatrix} \begin{bmatrix} R_{sRGB} \\ G_{sRGB} \\ B_{sRGB} \end{bmatrix}. \qquad (7)$$

The CIEXYZ values are then transformed into CIELAB values using the following equation:[9]

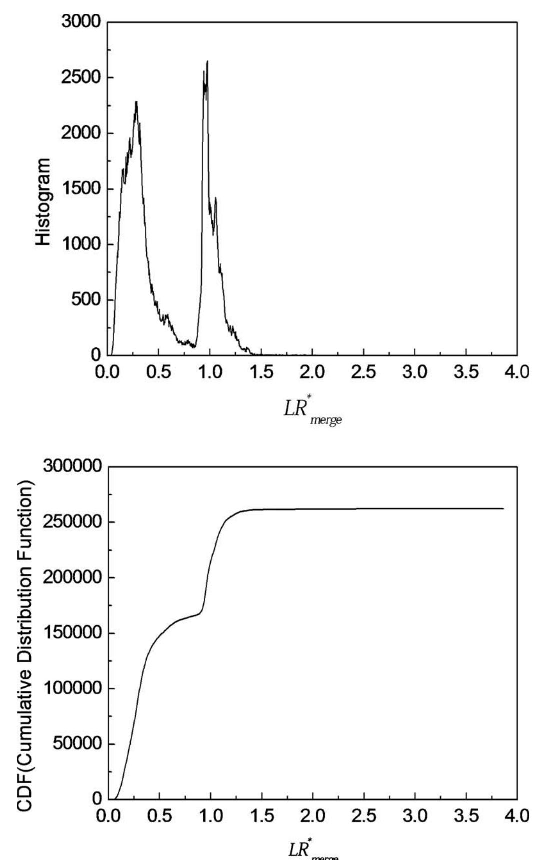

Figure 5. Histogram of the enhanced lightness value and its CDF.

$$L^* = \begin{cases} 116\left(\dfrac{Y}{Y_n}\right)^{1/3} - 16 & if \quad \dfrac{Y}{Y_n} > 0.008856 \\ 903.3\left(\dfrac{Y}{Y_n}\right) & if \quad \left(\dfrac{Y}{Y_n}\right) < 0.008856 \end{cases}, \qquad (8)$$

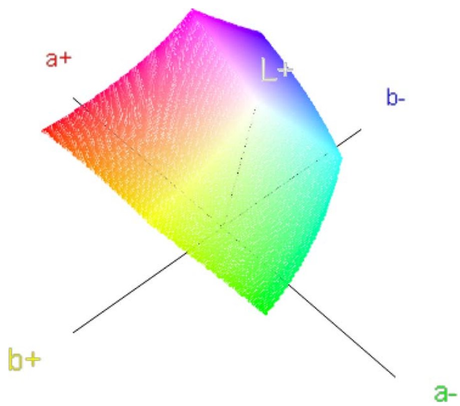

Figure 6. Lightness table for the top values of sRGB gamut boundary.

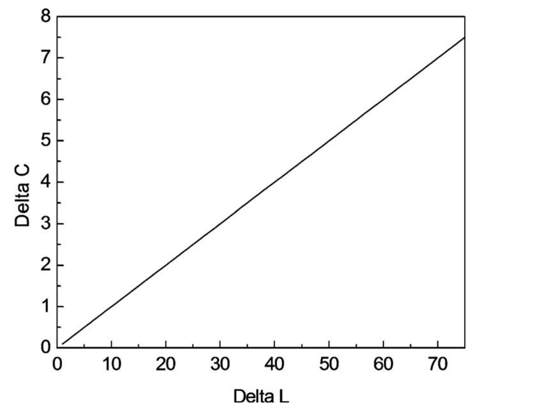

Figure 7. The variation of chroma values by IMSR using some patches.

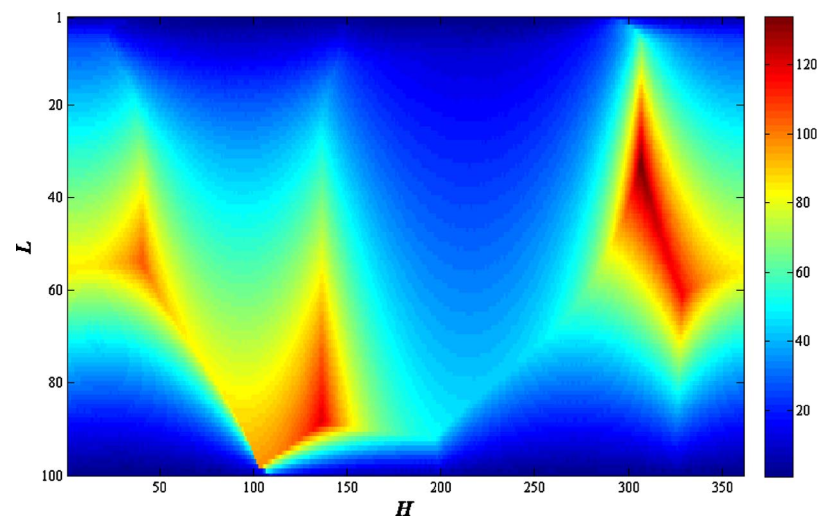

Figure 8. Saturation table for the sRGB gamut boundary.

$$a^* = 500\left(f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right), \tag{9}$$

$$b^* = 200\left(f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right), \tag{10}$$

$$\text{where} \quad f(x) = \begin{cases} x^{1/3} & \text{if} \quad x > 0.00856 \\ 7.787x + \dfrac{16}{116} & \text{if} \quad x < 0.00856 \end{cases}, \tag{11}$$

where X_n, Y_n, and Z_n are used as D65 illumination (95.05, 100.0, and 108.9 respectively). Thereafter, only the lightness values obtained by the IMSR are used to preserve the hue values as follows:

$$LR^*_{merge}(x,y) = \alpha \frac{L^*(x,y)}{SR^*_{merge}(x,y)}, \tag{12}$$

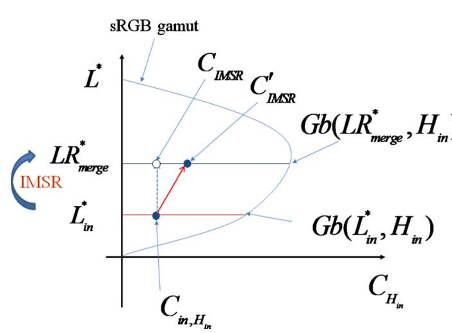

Figure 9. Saturation compensation.

$$SR^*_{merge}(x,y) = \sum_{m=1}^{M} w(\sigma_m) SR^*_m(x,y,\sigma_m), \tag{13}$$

$$SR^*_m(x,y,\sigma_m) = G_m(x,y) \otimes L^*(x,y). \tag{14}$$

This is actually the same process performed using RGB values in the IMSR, yet using $L^*(x,y)$ instead of $I_i(x,y)$. Thus, $LR^*_{merge}(x,y)$ is the enhanced lightness value, and the en-

Figure 10. Comparison of saturation between IMSR and proposed method. (a) is the input image, (b) and (c) are resulting images by IMSR and by proposed method, respectively.

hanced lightness is shown in Figure 4(b). In Fig. 4(b), since some of the image gamut values fall outside the sRGB gamut boundary, the image cannot be reproduced on most sRGB monitors. Thus, a lightness correction is performed to reproduce the sRGB image.

LIGHTNESS CORRECTION

Normalization is performed to produce displayable values. In this case, if the simple maximum values are used, only a small number of pixels will be involved in the normalization, as shown in Figure 5(a), since only a few pixels have high values, thereby resulting in a dull image. Thus, to reproduce bright regions correctly, the cdfs of the enhanced lightness values are used. Fig. 5(b) shows one of the cdfs, which has the maximum value, as the number of other high values is

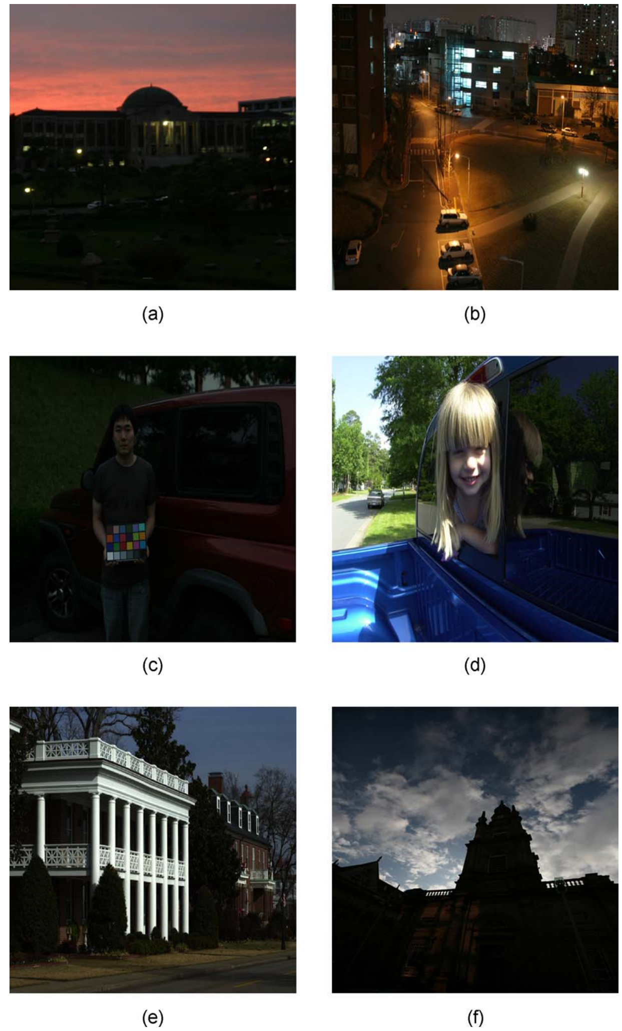

Figure 11. Test images for experiment: (a)-(c) night or very dark images, (d)-(f) daytime images.

small. As a result, the value with an almost zero gradient in the cdf is used as the normalization value. Fig. 4(c) depicts the result of normalization. Nonetheless, this method still leads to the existence of values outside the display gamut. Therefore, the top boundary of the sRGB gamut, shown in Figure 6, is applied to the values outside the gamut as follows:

$$LR^*_{correct}(x,y,\sigma_m) = Gb_{Hat}(a^*,b^*,x,y)\frac{LR^*_{merge}(x,y,\sigma_m)}{Max_{CDF}}, \quad (15)$$

where Max_{CDF} is determined according to the distribution of the cdf, $Gb_{Hat}(a^*,b^*,x,y)$ denote the ratio value between the maximum lightness value within the sRGB gamut and the top boundary lightness value of the sRGB gamut in each position (a^*,b^*). The final result of the IMSR using the lightness values is shown in Fig. 4(d).

Figure 12. Resulting images for experiment: (a), (d) resulting images when using MSR, (b), (e) resulting images when using IMSR, and (c), (f) resulting images when using proposed method.

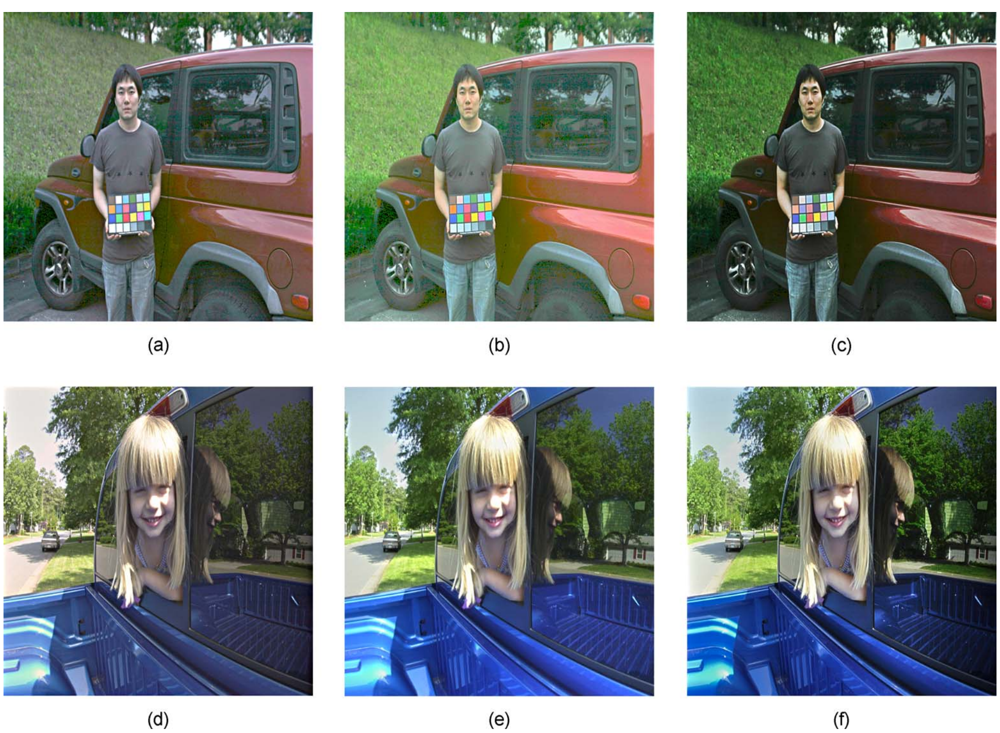

Figure 13. Resulting images for experiment: (a), (d) resulting images when using MSR, (b), (e) resulting images when using IMSR, and (c), (f) resulting images when using proposed method.

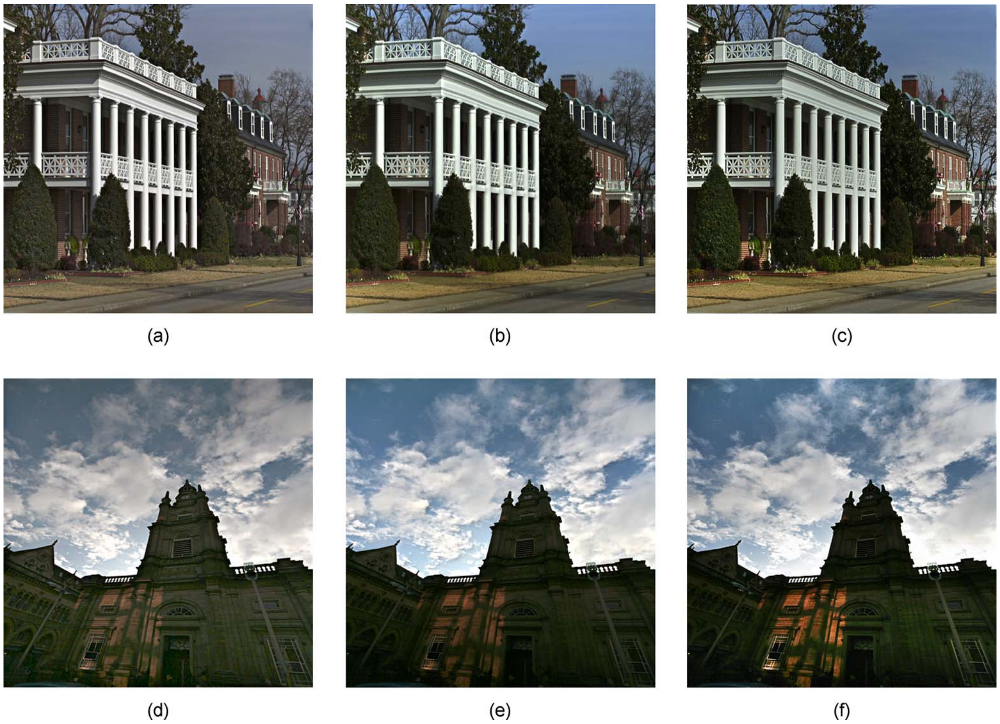

Figure 14. Resulting images for experiment: (a), (d) resulting images when using MSR, (b), (e) resulting images when using IMSR, and (c), (f) resulting images when using proposed method.

Table I. Average hue angle difference between an input and resulting images.

Image number	MSR	IMSR	Proposed method
1	56.05	2.00	1.18
2	50.30	1.85	0.24
3	28.74	3.74	3.51
4	21.31	2.43	0.34
5	20.62	1.65	0.23
6	20.95	2.22	1.72

SIMPLE IMAGE GAMUT EXTENSION FOR SATURATION COMPENSATION

As described above, saturation compensation is needed for dark regions in the original image. As the process of the IMSR with lightness values does not change any chroma values, a^* and b^*, in the case of dark regions, which are significantly enhanced, the low chroma values are preserved. Before the saturation compensation, the variation of the chroma values by the IMSR with RGB values was observed using some test patches. Figure 7 illustrates the variation of the chroma values in CIELAB. As shown in Fig. 7, the chroma variation showed a linear relationship with the lightness correction. The IMSR in RGB space showed a better visibility for areas that were only moderately corrected, while oversaturation was observed in dark regions.

To solve the problem of oversaturation, pixel values with originally small chroma values in dark areas need to be significantly improved during a large variation of lightness by the IMSR, whereas pixel values with originally large chroma values should be minimally improved during a small variation of lightness. Therefore, in the proposed method, the ratio of the sRGB gamut boundary is applied to the enhancement of the chroma values, as shown in Figure 9, which allows a low improvement of the chroma value for a small variation of lightness and vice versa. Therefore, this method can prevent over saturation in light regions. In the proposed procedure, the initial step is finding the sRGB gamut boundary values, in Figure 8, corresponding to the input hue (H_{in}), input lightness (L^*_{in}), and result lightness (LR^*_{merge}), respectively. The ratio of these boundary values is then applied to the input chroma value. Equation (16) shows the saturation compensation for a pixel at position (x,y),

$$C'_{IMSR}(x,y,H_{in}) = \frac{Gb(LR^*_{merge})(x,y,H_{in})}{Gb(L^*_{in})(x,y,H_{in})} C_{in}(x,y,H_{in}), \tag{16}$$

where C is the chroma value and Gb is the gamut boundary value corresponding to the lightness, L^*_{in} and LR^*_{merge}, with the input hue, H_{in}. In Figure 10 shows the effect of the saturation compensation using ratio of the sRGB gamut boundary.

EXPERIMENTS AND RESULTS

In the experiments, test sRGB images were acquired using Canon 10D and Canon 5D cameras. The results from the proposed method were compared with those from the MSR[5]

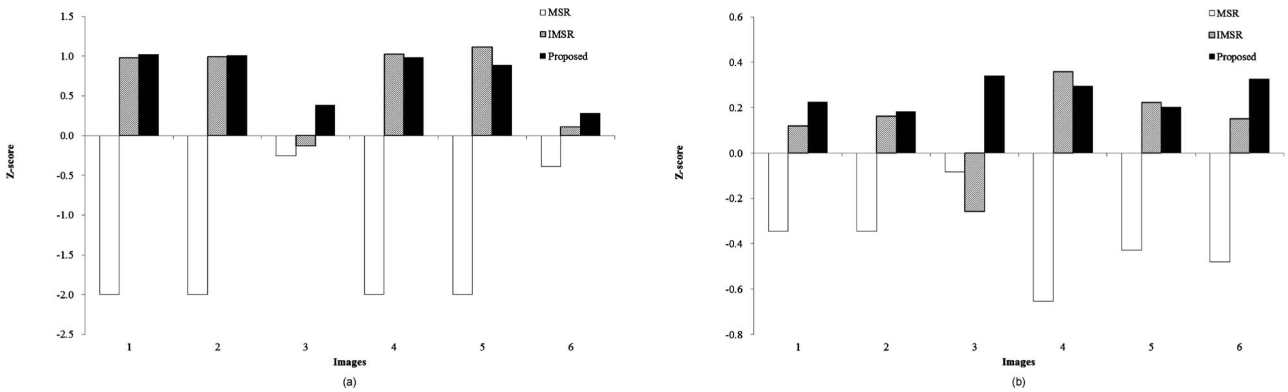

Figure 15. Z-scores for 6 test images as a result of subjective evaluation: (a) Z-scores for first question and (b) Z-scores for second question.

Table II. Z-score for six images.

	Question 1			Question 2		
Image number	MSR	IMSR	Proposed method	MSR	IMSR	Proposed method
1	−2.000	0.979	1.021	−0.345	0.120	0.226
2	−2.000	0.990	1.010	−0.345	0.162	0.183
3	−0.256	−0.131	0.386	−0.084	−0.256	0.339
4	−2.000	1.021	0.979	−0.653	0.358	0.295
5	−2.000	1.112	0.888	−0.427	0.224	0.203
6	−0.386	0.109	0.278	−0.480	0.153	0.327

and IMSR[8] methods. The parameters used for the IMSR and proposed methods were the same as those previously reported for Wang's algorithm.[8]

Figure 11 shows the input images, where Figs. 11(a)–11(c) are night or very dark images and the others are daytime images. Figures 12–14 are then the resulting images for the input images. In Figs. 12(a)–12(c) related to the Sunset image, while the visibility of the MSR image was improved in Fig. 12(a), the sunset area appeared as bright as day, giving a very artificial feeling when compared to the input image in Fig. 11(a). Meantime, while the IMSR image in Fig. 12(b) and resulting image from the proposed method in Fig. 12(c) appeared similar to the real scene in Fig. 11(a), the proposed method produced an improved visibility and contrast when compared to the IMSR results. In Figs. 12(d)–12(f) related to the Night image, while the MSR image (first column) had a better visibility than the other methods, the picture was perceived as artificial due to excessive illuminant color removal. Meantime, the proposed method (third column) produced an improved contrast in the buildings when compared to the IMSR results (second column). In Figs. 13(a)–13(c) related to the Car image, the colors in the first column image (MSR) were faded out, especially the lawn and car (red wine color). Meantime, the IMSR image was quite well enhanced, although the dark area around the tire seemed to be noisy due to lightness over enhancement. However, the third column image (proposed method) showed a better color rendition and reduced the noise around the tire. An objective evaluation of the hue difference is shown in Table I, where the proposed method has the smallest average hue difference.

As a final experiment, a subjective evaluation test was performed involving 20 observers, four females and 16 males, aged 24–34. The eyesight of the observers was either normal or had been corrected with eyeglasses. The observers were classified into two groups, eight experts, in terms of experience in color imaging, and 12 nonexperts. In his ranking experiment, Dugay[10] used two media, paper and display. However, for this experiment, we only used a display: a Samsung XL24 LCD with sRGB color space and a D65 white point ($x=0.314$, $y=0.331$) in a dark room (0.32 lx excluding the display). The experiments took on average 10 min, and the viewing distance was 50 cm.

For the subjective evaluation, a pair comparison method[10] was used to assess the resulting images when using the MSR,[5] IMSR,[8] and proposed algorithms. For the pair comparison, three images were shown on the display: the input image in the first row as the reference, plus a pair of the resulting images in the second row: the MSR and IMSR, the MSR and proposed method, or the IMSR and proposed method. The observers were then asked to rank the images according to two criteria: the amount of hue shift between the input image and the resulting images, and the most natural-looking between the resulting images. Each observer judged each pair of resulting images and assigned 1 to the selected image and 0 to the rejected image. In the case of a tie, 0.5 was assigned to each image. The scores were then totaled and converted to a z-score.[11]

Figure 15 and Table II show the z-scores of each algorithm for six test images. For the first preference test, evaluating the hue change, the z-scores for the IMSR and proposed method were generally higher than those for the MSR. Furthermore, the z-scores for the IMSR and proposed method were similar. For the second preference test, the z-scores for our proposed method were generally higher than those for the other two methods, except for certain test images. Most observers preferred the images resulting from the proposed method, which exhibited a high saturation, contrast, and sharpness.

CONCLUSIONS

This article proposed an enhanced IMSR method in CIELAB. The main goal of the proposed method is preservation of the perceived hue, which means maintaining a constant hue from the original image in CIELAB color space (which has a linear property for the human visual system). Therefore, the IMSR method is executed in CIELAB color space with only lightness values. In addition, to ensure the appearance of a bright area, information from a cdf is used to perform lightness mapping. As a result, the hue is preserved, yet unnatural saturation occurs. Thus, to correct this phenomenon, based on the results from the IMSR, simple gamut extension is performed according to the luminance variation by applying the ratio of chroma values at the sRGB gamut boundary with same luminance variation during the IMSR. In experiments with test images, the hue values were preserved. Also, by using the ratio of chroma values for the saturation compensation, oversaturated areas are prevented and pleasing natural colors maintained. In an observer preference test, most observers perceived that the resulting images from the proposed method had a higher visibility and naturalness.

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