Journal of Imaging Science and Technology® 51(1): 44–52, 2007.

Illumination-Level Adaptive Color Reproduction Method with Lightness Adaptation and Flare Compensation for Mobile Display

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Abstract. *Mobile displays such as personal digital assistants and cellular phones encounter various illumination levels, different from the flat panel displays mainly used in indoor environment. In particular, in the daylight condition, the displayed images or text on a mobile display can be darkly perceived, which results in the degradation of sun readability in a mobile display. To overcome this problem, we proposed an illumination level adaptive color reproduction method with a lightness adaptation model and flare compensation. Lightness adaptation is a physiological mechanism to shift the photoreceptor response curve according to the illumination level. Thus, as a mobile phone is carried from an indoor to outdoor environment, the photoreceptor response curve automatically shifts toward a higher luminance to adapt to daylight intensity. Consequently, for a lower intensity emitted from the mobile display, the photoreceptor response curve becomes less sensitive, thereby decreasing the perceived brightness of the displayed image. Moreover, colors produced by mobile display can also be influenced by the flare, defined as ambient light reflected from the display panel, which reduces the maximum chroma of the mobile display gamut. Based on these physiological and physical phenomena, the lightness values of the input image are enhanced by making a linear relation between input luminance value estimated by device characterization and photoreceptor response value calculated from the lightness adaptation model. For the chroma component of the lightness-enhanced input image, chroma compensation is conducted by adding the chroma values of the flare multiplied by the enhancement parameter, depending on the hue plane of the gamut boundary. Throughout the experiment, the proposed algorithm not only reproduces bright and colorful images in the mobile display under daylight conditions, but also produces a solution to improve sunlight readability.*

[DOI: 10.2352/J.ImagingSci.Technol.(2007)51:1(44)]

INTRODUCTION

Display devices such as liquid crystal displays (LCDs) and plasma display panels (PDPs) etc., are generally used in the indoor environment. As such, many display manufacturers have mainly focused on developing the contrast ratio, screen size, backlight source, and viewing angles. Even though mobile displays have achieved high color fidelity and good quality, changes in viewing conditions, i.e., the intensity or color temperature of the illumination considerably influences the original colors produced by mobile displays. Thus, viewing conditions have recently become a hot issue in the field of image quality and it has drawn considerable interest from display manufacturers.[1,2] One of the viewing conditions, the color temperature of the illumination, can make the displayed image appear more blue or reddish given the function of chromatic adaptation in a human visual system. Yet, the influence of color temperature is not as significant for a luminous body as for a reflector. In daily life, there is little opportunity to be in a room with incandescent or ultraviolet light. On the contrary, we frequently encounter various illumination levels between the office and the outdoor environment, which makes it possible to decrease the sunlight readability, gamut size, lightness and colorfulness of the mobile display. In particular, under daylight conditions, the displayed image on the mobile screen is perceived to be darker and image quality significantly deteriorates. On that account, various algorithms have been suggested or a new type of mobile display has been developed to solve this problem.

One of the algorithms, logarithmic or power function, has been used to enhance the lightness of mobile phone.[3] Since this method can simply increase the lightness of the displayed image, the logarithm or power curve have been modified based on a visual evaluation and various subject experiments. Yet, these have a disadvantage in that they wash out the color of the displayed image. Meanwhile, Monobe proposed a method for preserving the local contrast to maintain the same contrast as seen in a dark room.[4] Al-

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Received Jun. 5, 2006; accepted for publication Oct. 2, 2006.
1062-3701/2007/51(1)/44/9/$20.00.

though this method can effectively preserve the whole contrast of an original image, the computational complexity is high and noise artifacts such as white points emerge in the detail region. There is another method to control the backlit unit, according to the ambient illumination levels by using a lux sensor.[5] This method requires a considerable amount of power even though a higher performance may be achieved. Furthermore, many display manufacturers have developed new types of mobile displays such as a transflective LCD to utilize both ambient light and backlight for displaying images.[6] Under dark ambient conditions, the backlight is turned on to illuminate, while the backlight is turned off to save power and utilize the ambient light under the bright ambient circumstance. Nevertheless, it cannot completely escape the influence of the daylight intensity in the outdoor environment.

In this paper, we try to overcome the sunlight-readability problem by developing an illumination level adaptive reproduction algorithm and applying it to the transflective mobile display. The proposed method is composed of two steps; lightness enhancement and chroma compensation. To find a solution for the lightness enhancement, it is first analyzed why the displayed image on a mobile LCD is significantly perceived as dark and readability problems occur in daylight condition. The main cause is regarded as the function of the lightness adaptation in daily life. In general, the intensity of the daylight covers a huge range of about 10^8 cd/m^2, and human eyes are capable of seeing about 10^5 cd/m^2.[7,8] Nonetheless, the human eye can cope with a high dynamic range without much strain due to lightness adaptation, which is an ability to slide the photoreceptor response curve along the illumination level for a given viewing condition. Thus, as a mobile phone is carried outdoors, the photoreceptor response curve automatically adapts to the outdoor environment and becomes more sensitive for the daylight intensity. However, the displayed image is perceived as dark because the photoreceptor response curve becomes less sensitive to the lower intensity emitted from the mobile display. Based on this kind of physiological mechanism, lightness enhancement is proposed by conducting a linearization process between the input luminance and photoreceptor response to obtain a smooth tone reproduction. However, after doing the lightness enhancement, satisfactory results cannot be obtained because lightness enhancement only washes out the color of the displayed image. Moreover, the flare, some of ambient light that is reflected to the front glass plate of the display, physically decreases the color gamut through desaturation.[9,10] Accordingly, in this paper, chroma compensation will be considered together with the lightness enhancement to obtain a better displayed image on the mobile display

The remainder of this paper is organized as follows. The following section provides an outline of the proposed algorithm, followed by detailed explanations of the proposed method consisting of four subsections, i.e., Flare Calculation, Lightness Enhancement, Chroma Compensation, and the Construction of the Three-dimensional (3D) Lookup Table. In the Flare Calculation subsection the physical effect of flare will be investigated to determine the changes in the mobile gamut, and flare estimation will be described based on the CIE 122-1966. In the Lightness Enhancement and Chroma Compensation subsections the main cause of deteriorating sunlight readability will be analyzed based on the human visual system and the illumination level adaptive color reproduction method will be proposed. Subsequently, a method for the design of the 3D lookup table will be explained briefly in the next subsection. In the Experiments and Results section, subjective experiments will be conducted under daylight condition, and the performance of various algorithms will be compared and analyzed using z-score evaluation. From these results, the conclusions will be presented in the final section.

PROPOSED METHOD

Figure 1 shows the flowchart of the proposed algorithm that achieves illumination level adaptive color reproduction. First, the TSL 2550 lux sensor is built into a mobile phone to detect ambient light intensity. According to the measured intensity level, the amount of flare expressed as the CIEXYZ value is calculated on the basis of CIE 122-1966, which is added to the CIEXYZ values of the original image estimated by using a conventional monitor characterization such as the gain offset gamma (GOG) model, S-curve model, or piecewise linear interpolation. Then, for luminance component of CIXYZ values, lightness enhancement is implemented by establishing a linear relationship between the luminance values and the cone response values to obtain perceived tone reproduction, where the cone response values corresponding to the luminance value are simply calculated from the lightness adaptation model. Following the lightness enhancement, the gamut boundary description was established by the mountain range segment method and chroma compensation was successively executed by adding the chroma values reduced by the flare to those of original image, yielding a colorful image.[11] However, since this kind of serial-based procedure

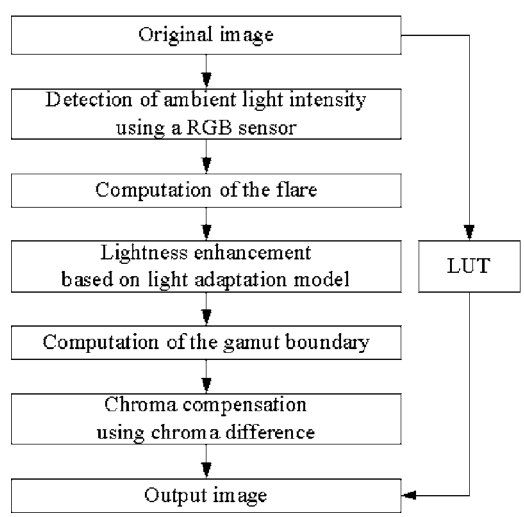

Figure 1. Flowchart for the proposed algorithm.

is not appropriate for real-time processing, a lookup table representing daylight intensity is designed based on the sampled RGB data.

Flare Calculation

Before calculating the amount of the flare, mobile LCD characterization is performed by piecewise linear interpolation to establish a relationship between the RGB values and tristimulus values (CIEXYZ or CIELAB). Model-based characterization, such as the GOG or S-curve models, is not well suited for a mobile phone because of the behavior imposed by the system design.[12] In the CIE 122-1996, flare is defined as the portion of the ambient light reflected from the display panel and is added to the colors produced by the mobile LCD[10]

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{\text{Display}} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{\text{LCD}} + \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{\text{Flare}}. \qquad (1)$$

Color appearance on a mobile LCD is very much affected by ambient lighting, since the human visual system changes its sensitivity according to the surroundings. However, the colors produced by a mobile LCD are physically affected by ambient light. When ambient light illuminates a mobile LCD, the LCD screen reflects some of this light. This reflection is added to the colors that are produced by the mobile LCD. The amount of the flare is expressed as

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{\text{Flare}} = R \cdot \frac{M}{\pi} \frac{1}{y_{Ambient}} \begin{bmatrix} x_{Ambient} \\ y_{Ambient} \\ 1 - x_{Ambient} - y_{Ambient} \end{bmatrix}, \qquad (2)$$

where R is the reflection ratio of the display screen and $(x_{\text{Ambient}}, y_{\text{Ambient}})$ is the chromatic diagram of the ambient light; M is the intensity of the ambient light (lux) taken from the TSL2550 lux-sensor. To estimate the reflection ratio of the mobile LCD, the CIEXYZ values of the black patch are measured using a colorimeter in a dark room and in the outdoor environment. The amount of flare in Eq. (2) is then obtained by calculating the difference for each measured CIEXYZ value, and the $(x_{\text{Ambient}}, y_{\text{Ambient}})$ is given as D65 (0.3127, 0.3290). By substituting these values into Eq. (2), the reflection ratio is acquired as seen in Table I. The results show that the reflection ratio for a mobile LCD is generally between 0.5% and 2%, and it is lower than that of the cathode ray tube (CRT) monitor which is between 3% and 5%. From the reflection ratio, the gamut of the mobile LCD is investigated as to how the flare influences the gamut size of a mobile LCD. Figure 2 shows the gamuts that correspond to daylight amount of 5000 and 10 000 lux, compared with the gamut measured in a dark room. As the level of daylight increases from 5000 to 10 000 lux, it can be observed that the chroma values decrease depending on the hue plane, while the lightness values increase.

Table I. Measured black patch and estimated reflection ratio.

	X	*Y*	*Z*	*R*
0 lux	0.52	0.47	0.77	
500 lux	1.78	1.91	2.63	0.008
4000 lux	12.76	13.5	14.63	0.01
9000 lux	29.20	30.4	39.73	0.01
15 000 lux	47.92	49.5	59.7	0.011

Lightness Enhancement Method Based on the Lightness-Adaptation Model

One of the problems of mobile LCDs is that displayed images are perceived as dark under the outdoor environment due to lightness adaptation. Lightness adaptation is a physiological mechanism to displace the visual response curve according to the ambient level, analogous to automatic exposure control in a digital camera. Figure 3 shows visual response shifting to adapt to ambient intensity, and it illustrates why the displayed image is perceived dark in the outdoor environment. In Fig. 3, if the indoor environment (200 cd/m^2) changes to an outdoor environment (2000 cd/m^2), the visual response curve shifts toward a higher luminance to adapt ambient level, i.e., automatic HDR function. However, the maximum luminance of the mobile LCD is limited to about 100 cd/m^2. Thus, it can be observed that a relative cone response of 0.6 under indoor environment is reduced to 0.22 at the maximum luminance. This is why the quality of the displayed image or text in a mobile phone significantly deteriorates in the outdoor environment.

Based on this kind of physiological mechanism, lightness enhancement is carried out by following the procedure in Fig. 4. An input RGB value is converted into a CIEXYZ value by using the piecewise linear interpolation. Lightness enhancement is executed only for the luminance component of the XYZ value, while the remainder of the components one left intact. First, the flare is added with an input luminance value, which is then mapped to a cone response by using the lightness adaptation model

$$Y = Y_{\text{image}} + Y_{\text{flare}}, \qquad (3)$$

$$R_{\text{cone}} = f(Y) = \frac{Y^n}{Y^n + \sigma^n} \quad \sigma = I_A^{\alpha} \times \beta, \qquad (4)$$

where Y_{image} and Y_{flare} are the luminance values of the input image and flare, respectively. In general, the parameters (α, β, n) are variables, not constant values. However, since the range of parameters is extensive, it is necessary to fix the values of the parameters to simulate the lightness adaptation model. In Ref. 7, Ledda suggested a method to compute the localized adaptation intensity (M) in Eq. (5) and to set the

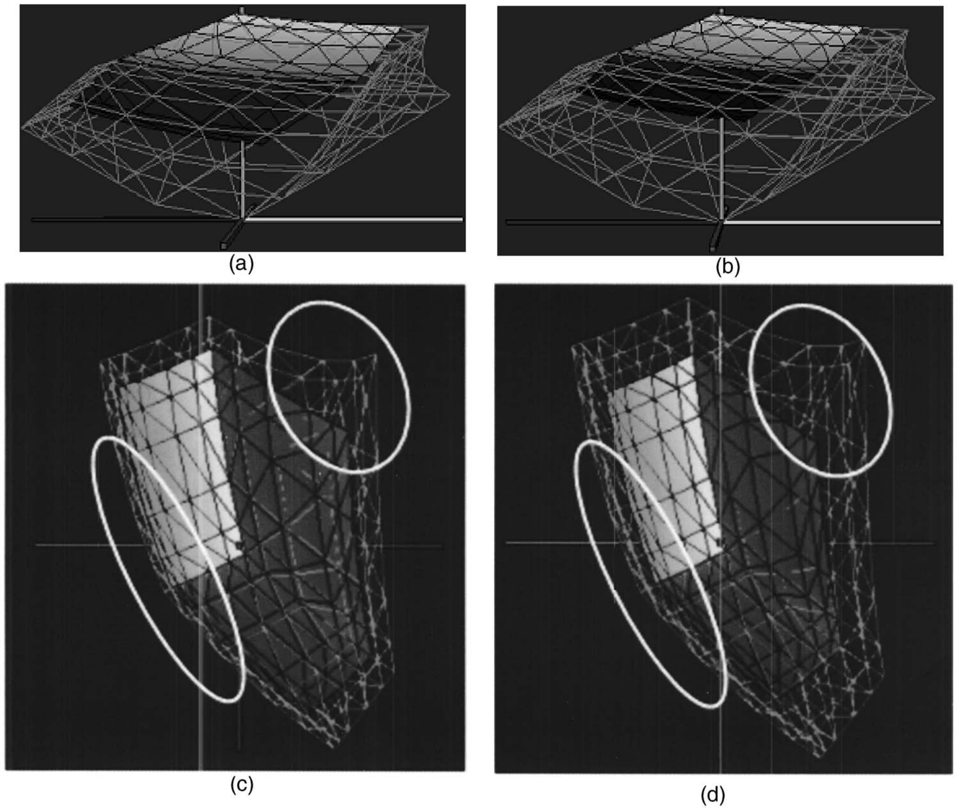

Figure 2. Comparison of the gamut under an outdoor environment (solid frame) and an indoor environment (wire frame): (a) 5000 lux (side), (b) 10 000 lux (side), (c) 5000 lux (top), and (d) 10 000 lux (top).

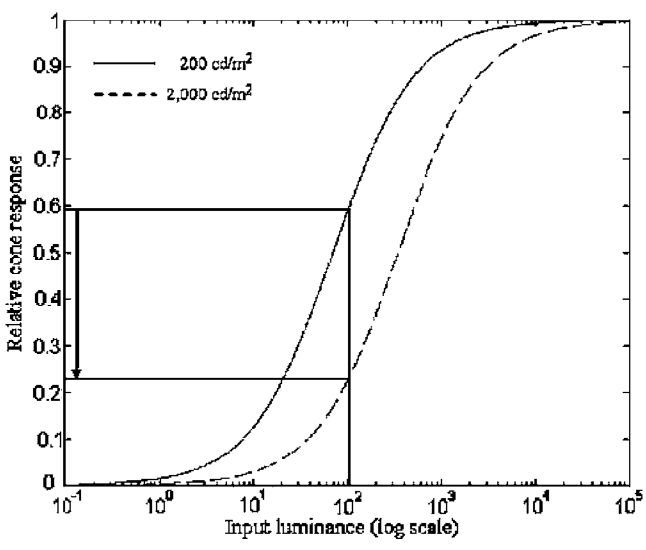

Figure 3. Cone response curve according to the intensity of the ambient light.

range of the parameters' values (α, β). Therefore, we adapted the parameter (α, β) values and set the range of n-accuphy to the lightness enhancement experiment, which will be referred to at the end of this section; σ is the half-saturation parameter, and I_A is the adaptation level calculated by dividing the ambient intensity (lux) with π on the assumption of Lamberitian reflection[13]

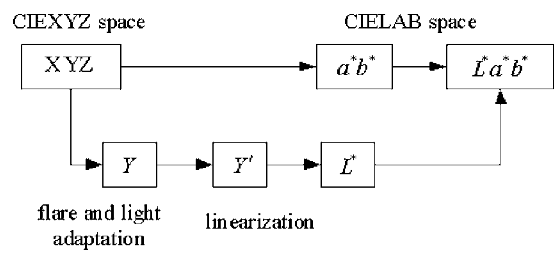

Figure 4. Procedure for lightness enhancement using the lightness adaptation model.

$$I_A = \frac{M}{\pi}, \tag{5}$$

where M is the ambient intensity (lux) acquired by the lux sensor.

Second, the corresponding luminance (Y') for the cone response (R_{cone}) is found through linearization of the input luminance (Y) to establish a linear relation between input luminance and cone response for the lightness enhancement. Linearized cone response can be acquired by exchanging the cone response with the input luminance using a piecewise linear interpolation because the inverse cone response curve in Eq. (4) is not directly calculated.[14] Figure 5 shows the general linearization method used to calculate the inverse cone response. The sampled input luminance values

$(y_0, y_1, \ldots, y_n)$ are transformed to a cone response value $(R_{\text{cone},0}, R_{\text{cone},1}, \ldots, R_{\text{cone},n})$ using Eq. (4). These cone response values are normalized to an amount of one and are stored in one-dimensional (1D) lookup table (LUT). For an arbitrary input luminance value, piecewise linear interpolation is applied to the 1D lookup table, thus creating the output cone response curve in Fig. 5(a). Then, inverse cone response curve in Fig. 5(b) is simply obtained by switching the cone response value with the luminance value stored in the 1D LUT. Therefore, a new input value (R'_{cone}) for the inverse cone response can be calculated as follows:

$$R'_{\text{cone}} = \left(\frac{Y_{\max} - Y_{\min}}{R_{\max} - R_{\max}} \right) \times (R_{\text{cone}} - R_{\min}), \qquad (6)$$

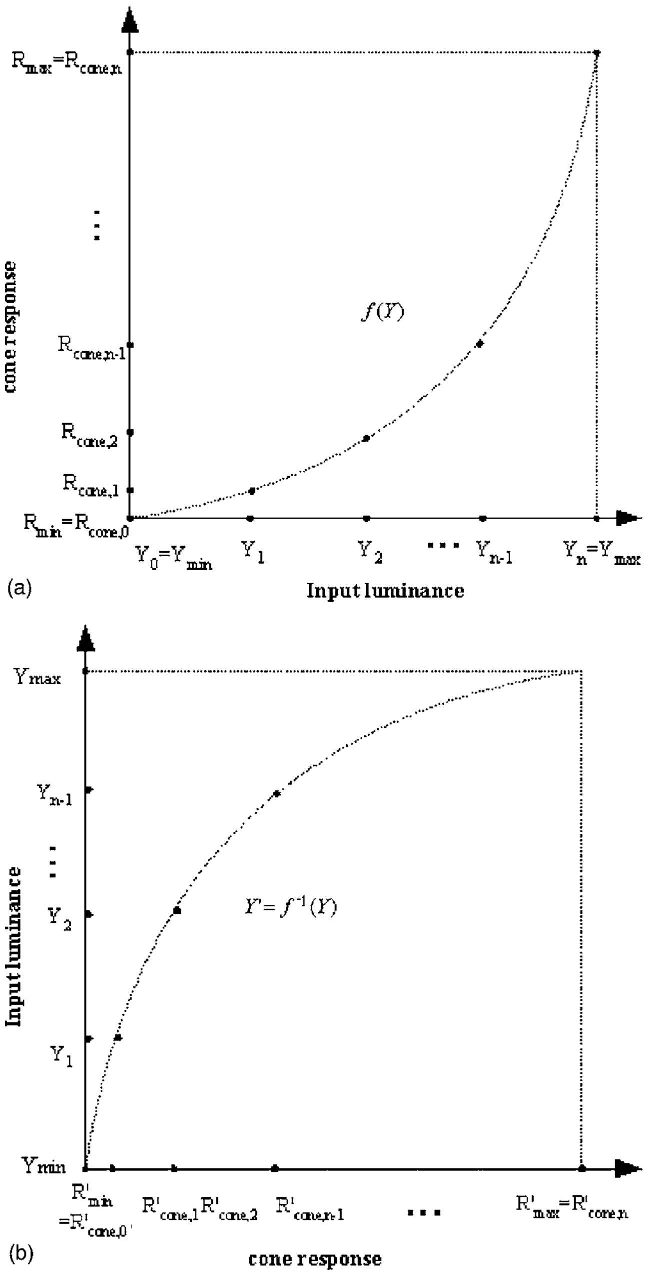

Figure 5. Linearization method: (a) construction of the cone response curve using piecewise linear interpolation and (b) construction of the linearized cone response curve using piecewise linear interpolation.

where $Y_{\max}$ and $Y_{\min}$ are the maximum and minimum luminance values, respectively while $R_{\max}$ and $R_{\min}$ are maximum and minimum cone response values.

Finally, the corresponding luminance (Y') for the input value (R'_{cone}) is obtained by applying the piecewise linear interpolation to the 1D LUT in Fig. 5(b). This value is then combined with the intact color components and is transformed into the CIELCH color space for the subsequent application of the chroma compensation.[2] At this point, to convert the CIEXYZ values into CIELCH values, the reference CIEXYZ value is defined as the amount of ambient light that represents a white object in the scene. On the other hand, the result of the proposed lightness enhancement depends on the values of parameter n. Thus, to find the appropriate parameter value, the observer should select the best results of the lightness enhanced images under the outdoor environment. Table II shows the appropriate parameter values corresponding to daylight intensity. From the subjective experiment, the parameter value becomes higher as the daylight intensity rises; because a large value of the parameter increases the degree of the lightness enhancement. Figure 6 shows the cone response curve according to the parameter values for 1000 and 10 000 lux.

Chroma Compensation Using the Flare

When only lightness enhancement is applied to the input image, the color of the enhanced image is washed out due to the influence of the flare. Therefore, to compensate for the reduced chroma physically, the chroma difference between two types of environment, i.e., darkroom and outdoors, is added to the CIELCH value acquired from lightness enhancement as shown in Fig. 7. However, since the chroma difference depends on the hue value as seen in Fig. 4, chroma compensation should be applied considering each hue value individually

$$C_{\text{diff}} = C - C_{\text{flare}},$$

$$C' = C + \alpha \cdot C_{\text{diff}}, \qquad (7)$$

where C and C_{flare} are the chroma values from the darkroom and outdoor environment, respectively. C_{diff} is the chroma difference between C and C_{flare}. The compensated chroma value (C') is adjusted according to with the enhancement parameter α. If the chroma value of input image (C) is close to the gamut boundary of mobile display and is added with

Table II. Appropriate parameter values according to the daylight intensity.

Lux	1000	5000	10 000	20 000
n	2.0	2.0	2.5	3.5

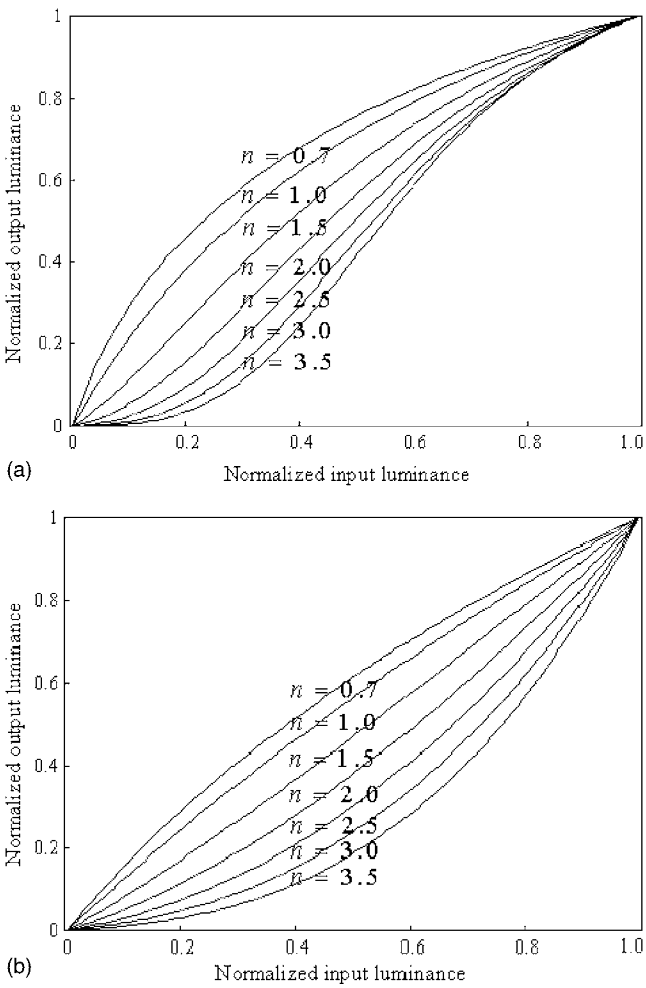

Figure 6. Cone response curve according to various parameter values for 1000 and 10 000 lux.

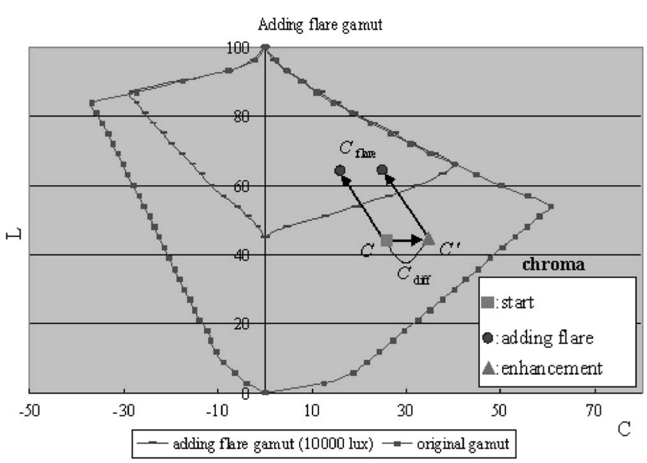

Figure 7. Concept of chroma compensation based on chroma difference.

C_{diff}, the compensated chroma value (C') can get outside the gamut boundary that the mobile display is capable of reproducing. Thus, the enhancement parameter is modified in consideration of the gamut boundary, as seen in Fig. 8

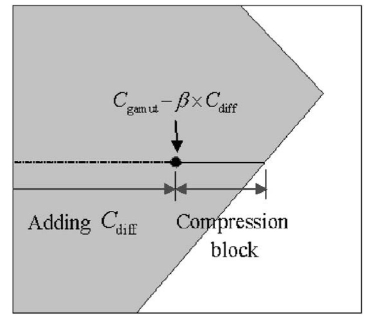

Figure 8. Chroma compression around the gamut boundary.

$$\alpha = \begin{cases} 1 & \text{if } C < (C_{gamut} - \beta \times C_{diff}) \\ \dfrac{(C_{gamut} - C)}{\beta \times C_{diff}}, & \text{otherwise} \end{cases}, \quad (8)$$

where β is the compression starting point parameter and C_{gamut} is the gamut boundary calculated by using the mountain range method developed by Braun and Fairchild.[11] This method uses griddling and interpolation to arrive at a data structure consisting of a uniform grid in terms of lightness and hue, and it stores the gamut's most extreme chroma values for each of the grid points. The boundary value has 101 and 360 levels for each grid points. If the input chroma value is inside $C_{gamut} - \beta \cdot C_{diff}$, the chroma difference is added to the input chroma value without compression. Otherwise, compression compensation is executed by using the compression starting point parameter (β), which can be set flexibly values of 1.0, 1.5, and 2.0 are used in this paper. If β is over 2.0, chroma compensation is not effective through the experiment, while a clipping artifact is generated if the value is less than 1.0.

The Construction of the 3D Lookup Table

A 3D LUT is constructed to represent the intensity of daylight (10 000 lux) for real-time processing. The input RGB digital values are uniformly sampled by the $n \times n \times n$ grid points, which are processed by the proposed algorithm, thus resulting in the output RGB values. The sampled input and output RGB digital values are stored in the 3D LUT and 3D interpolation such as trilinear, pyramid, or tetrahedral is used to calculate the output RGB values for the arbitrary input RGB values.[14] This 3D LUT can be inserted into the mobile phone and functions well in a mobile environment without the difficulties associated with the memory and computation.

EXPERIMENTS AND RESULTS

To test the sunlight readability of mobile display for various methods, Transflective PDA (SPH-M4000) made by Samsung Electronics was used as the testing device, and ten observers consisting of five ordinary citizens and five color imaging experts participated in the subjective experiment. The average age of observers is 29 years old; ages range from 27 to 31 years old and one observer is female. In addition, to ensure the changeable viewing conditions of the real world, we use lighting equipment supported by Samsung Electronics to control the intensity of illumination from 0 to 20 000 lux. Thus, the subjective experiment is conducted in a dark room using this lighting equipment for two light conditions, i.e., 2000 and 10 000 lux to represent cloudy and bright days, respectively. Figure 9 shows the original images, and Figs. 10 and 11 show the enhanced test images to be displayed on the personal digital assistant under two lighting conditions. Figure 10(a) shows the resulting image when the logarithmic function is used. Although this method increases the amount of lightness in the original image, the color of the original image is washed out, and thus, colorfulness is considerably decreased under these conditions. Figure 10(b) shows the resulting image when using Monobe's method which preserves the local contrast. This method may maintain a contrast ratio similar to the original image seen in a darkroom. However, noise artifacts like white points appear in the leaf regions due to excessive contrast enhancement. In addition, this method has the complex computations that are not suitable for the implementation of real-time processing. Figure 10(c)–10(e) show the resulting images of the proposed methods with different β values. In Figs. 10(c)–10(e), it is seen that the colorfulness of the resulting images is significantly enhanced, which improves sunlight readability and provides pleasure to the observers under the two lighting conditions, especially at 10 000 lux. Also, the chroma values of the resulting images are perceived similar to those of the original image in a dark room, even though the chrome values are excessively enhanced. Figure 11 shows other resulting images with five enhancement methods, and we can find the same effect for

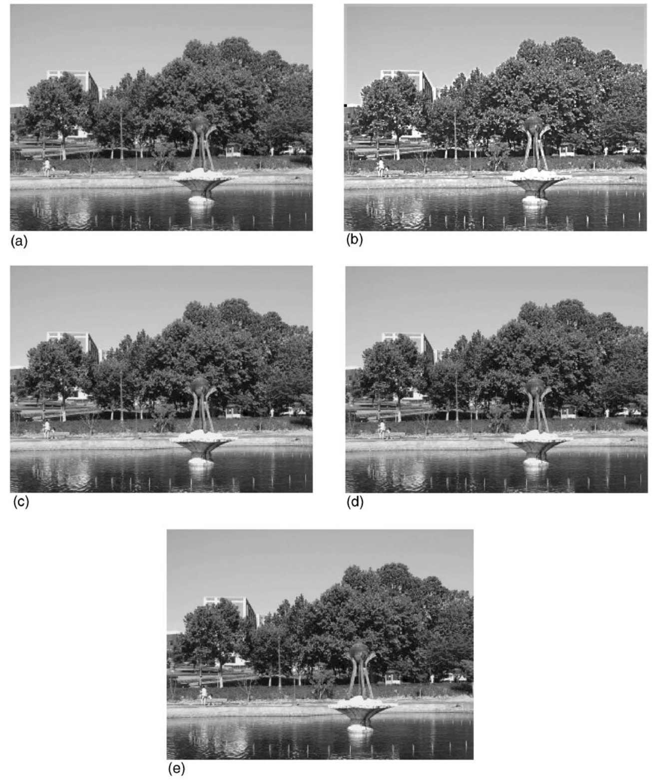

Figure 10. Enhanced park images under 10 000 lux: (a) lightness enhancement using the logarithmic function, (b) Monobe's method preserving the local contrast, (c) the proposed method with $\beta=2.0$, (d) the proposed method with $\beta=1.5$, and (e) the proposed method with $\beta=1.0$.

Figure 9. Test images: (a) park, (b) cap, (c) girl, and (d) woman.

Figure 11. Enhanced woman images under 10 000 lux: (a) lightness enhancement using the logarithmic function, (b) Monobe's method preserving the local contrast, (c) the proposed method with $\beta=2.0$, (d) the proposed method with $\beta=1.5$, and (e) the proposed method with $\beta=1.0$.

Table III. Z-score values of ordinary citizens: (a) 2000 and (b) 10 000 lux.

(a) Daylight condition: 2000 lux					
Image	*L*	*M*	*LC* (β=2.0)	*LC* (β=1.5)	*LC* (β=1.0)
Park	−12.01 (−12.53)	−2.81 (−2.29)	−3.24 (−3.24)	4.94 (4.94)	13.12 (13.12)
Cap	−13.12 (−13.12)	−0.52 (−3.83)	−0.59 (−1.11)	4.35 (1.7)	9.88 (16.36)
Woman	−16.36 (−16.36)	−8.18 (−8.18)	0 (3.24)	8.18 (4.94)	16.36 (16.36)
Girl	−13.12 (−13.12)	−1.7 (−4.35)	7.07 (3.83)	5.53 (12.01)	2.22 (1.63)
(b) Daylight condition: 10 000 lux					
Image	*L*	*M*	*LC* (β=2.0)	*LC* (β=1.5)	*LC* (β=1.0)
Park	−13.12 (−13.12)	−1.7 (−1.7)	−3.24 (0)	4.94 (1.7)	13.12 (13.12)
Cap	−16.36 (−16.36)	−1.7 (−4.94)	−3.24 (−3.24)	4.94 (8.18)	16.36 (16.36)
Woman	−16.36 (−16.36)	−1.7 (−8.18)	0 (0)	4.94 (8.18)	13.12 (16.36)
Girl	−16.36 (−16.36)	−8.18 (−8.18)	0 (0)	8.18 (8.18)	16.36 (16.36)

Table IV. Z-score values of color imaging experts: (a)2000 and (b) 10 000 lux.

(a) Daylight condition: 2000 lux					
Image	*L*	*M*	*LC* (β=2.0)	*LC* (β=1.5)	*LC* (β=1.0)
Park	−12.01 (−12.01)	−9.29 (−12.53)	−3.24 (0)	8.18 (8.18)	16.36 (16.36)
Cap	−16.36 (−16.36)	8.18 (4.35)	−4.94 (−1.7)	0 (0.59)	13.12 (13.12)
Woman	−13.12 (−16.36)	−8.18 (−8.18)	3.24 (0)	4.94 (8.18)	13.12 (16.36)
Girl	−13.12 (−12.53)	−1.11 (−4.35)	0.59 (3.83)	12.01 (12.01)	1.63 (1.04)
(b) Daylight condition: 10 000 lux					
Image	*L*	*M*	*LC* (β=2.0)	*LC* (β=1.5)	*LC* (β=1.0)
Park	−12.01 (−12.01)	−2.81 (−2.81)	−3.24 (−3.24)	4.94 (4.94)	13.12 (13.12)
Cap	−16.36 (−16.36)	4.94 (4.94)	−4.94 (−4.94)	3.83 (3.83)	12.53 (12.53)
Woman	−16.36 (−16.36)	−8.18 (−8.18)	0 (0)	8.18 (8.18)	16.36 (16.36)
Girl	−16.36 (−16.36)	−8.18 (−8.18)	0 (0)	8.18 (8.18)	16.36 (16.36)

each method, with the exception that Monobe's method does not uphold any noise artifacts applied to this image.

To conduct subjective evaluation, four test images and five enhanced methods are used and their paired images are randomly selected to obtain z-score values.[15] Tables III and IV show the z-score evaluations of ordinary citizens and color imaging experts for two lighting conditions, where L, M, $LC(\beta=2.0)$, $LC(\beta=1.5)$, and $LC(\beta=1.0)$ represent the lightness enhancement using logarithmic function, Monebe's method preserving the local contrast, proposed methods with three different β values, respectively. The numbers in parentheses represent the z-score values obtained by the second experiment under equivalent conditions. In Tables III and IV, three differences in the z-score value obtained by five observers can be regarded as the same results because the frequency is almost equal which indicates that the ith method is judged better than the jth method. Thus, the results of z-score values are almost the same at the 10 000 lux, irrespective of observer type and repeated experiment. However, small differences occur in the 2000 lux condition, depending on observer type. For the "park" image, ordinary citizens prefer the image resulting from of Monobe's method more than that of the lightness enhancement method, while color imaging experts give better marks to the lightness enhancement method because of noise artifacts like white points in the leaf region. Similarly, for the "cap" image, the z-score value of the proposed method is lower than that of Monobe's method due to the sharpness problem. From these results, it is seen that the color imaging experts attach importance to image quality such as noise and sharpness, relative to a slight increase in readability. In addition, as the intensity of illumination changes from 2000 to 10000 lux, we found that in the "girl" image, the z-score value of the proposed method with $\beta=1.0$ increases considerably. The reason is that the fine clipping artifact in the cloth region is indistinguishable due to the influence of higher illumination level. Consequently, the proposed method with $\beta=1.0$ has the best performance among the five methods, and we found that the noise or clipping artifact is an important factor to influence the z-score evaluation depending on observer type and illumination level. However, the results of z-score evaluation are almost the same irrespective of a number of experiments conducted.

CONCLUSION

This paper suggests and analyzes problems that can occur for the mobile display in an outdoor environment as a result of human lightness adaptation and flare phenomena. First, we explained why readability or image quality of mobile phones is significantly degraded under daylight condition based on lightness adaptation. The lightness enhancement algorithm is then proposed to increase the luminance of the input RGB image by the linearization process between the input luminance and cone response. Second, the influence of the flare is investigated to determine the variations of the mobile gamut, and it can be observed that the maximum chroma values are reduced differently depending on the hue plane. From this observation, chroma compensation is executed by adding the differentially reduced chroma values according to the hue plane with lightness enhanced input image. Finally, a 3D lookup table, composed of RGB grid points, is implemented to achieve real-time processing. The experiment shows that the lightness enhancement and chroma compensation algorithm is well suited for mobile LCDs, thus reproducing more colorful and brighter results in the outdoor environment. Furthermore, we expect that the proposed algorithm can be applied to other portable devices.

ACKNOWLEDGMENTS

This work is financially supported by the Ministry of Education and Human Resources Development (MOE), the Ministry of Commerce, Industry and Energy (MOCIE), and the Ministry of Labor (MOLAB) through the fostering project of the Lab of Excellency.

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