An Approach for Reproducing Illuminant Colors and Specular Highlights on Television Using Color-Mode-Index (CMI)

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Abstract This paper describes an approach for reproducing illuminant colors and specular highlights on television screens using Color-Mode-Index (CMI), which is a novel evaluation index for color-appearance of reproduced colors. We quantify the lightness of color-mode boundary as CMI 100. We reveal that surface colors in nature scenes should be reproduced under CMI 100 and that the acceptable limit is CMI 110. Then we show that the mode boundary is similar to the optimal color loci. We also reveal that the preferred CMI condition for reproducing illuminant colors and specular highlights is over CMI 100 and that the most preferred condition is CMI 120-150. Then we show the examples for reproducing illuminant colors and specular highlights with realistic impression by controlling color-mode using CMI.

Keywords: Color Mode Index(CMI), Illuminant Colors, Specular Highlights, Color Appearance

1. Introduction

Recently, wide-gamut-display technologies have been developed such as RGBY four-primary color LCDs1), RGBYC five-primary color LCDs2), and RGB LCDs with highly saturated primaries. Distribution of real world object colors such as Pointer’s data3) and SOCS4,5) is taken into the consideration for designing the color primaries for UHDTV system6).

On the other hand, in real-world scenes, there are not only surface colors such as flower, grass and skin tone, but also non-surface colors such as specular reflection from the sea, light sources, the sunshine and the sunset. Heckaman7) reported that the luminance range in those natural scenes was from $10^{-2}$ to $10^{5}$ cd/m² and over. But it is not practical to reproduce the luminance level of $10^{5}$ cd/m² on display. For TV-imaging, we should target that we would get the same “impression” as that when seen directly.

This paper reports an approach for reproducing colors beyond surface colors on television using CMI, which is a novel evaluation index based on the color-mode of reproduced colors. We show the preferred CMI value for reproducing surface colors and illuminant colors through subjective evaluations. Then we show the application to reproduce non-surface colors with realistic impression by controlling color-mode using CMI.

2. Color-Mode-Index (CMI)

2.1 Mode-boundary between surface color and illuminant color appearance

Many discussions have been conducted how to reproduce standard color-gamut-range signals, such as BT.7098) and sRGB on wide gamut displays. These color signals of course contain landscape, humans, flowers and so on. Sakurai9) studied on preference and gamut size, and found that wider gamut and higher luminance were more preferred. Laird10) reported that the colors were perceived as fluorescent and unnatural when they are highly saturated. Sekulovski11) indicated that higher saturated colors were preferred though it depended on image contents. Kanai12) indicated that there was the correlation between the preference of reproduced colors and the optimal colors which are the most vivid object colors. In our previous research13), we pointed out that wide-gamut was not always good in all cases and we felt unnatural because of the degrading of picture quality due to the change in color-mode in some cases. Casella14) evaluated image quality of reproducing sRGB gamut
image on wide-gamut display, and indicated that the image quality was higher when high saturated colors were reproduced beyond sRGB gamut, while medium or low saturated colors were preferred when reproduced with little enhance. Pan\textsuperscript{15} indicated that the phenomenon would be caused by memory colors such as skin tone distributed in middle or low saturation color region.

From those previous researches, two factors should be considered as the reason of unnaturalness when standard color gamut signal is reproduced on wide-gamut display. First one is change in perceived color mode. Second one is big difference from memory color. In this paper, we focused on the first one.

Color reproduction ability has been discussed, such as gamut size and the adjustment ratio of gamut against distribution of object colors. But in the end, the reproduced color is watched on TVs by people, so it is necessary for evaluation method to relate color reproduction to preference, that is to say, picture quality. If we would find a way to evaluate perceived color related to picture quality quantitatively, we could make color-rendering optimized. So we have proposed an evaluation method for color-mode of display color reproduction related to preference, \textit{CMI}. We defined \textit{CMI} 100 as the lightness of mode boundary between surface color and illuminant color appearance. \textit{CMI} is calculated by Eq.(1), where \( L' \) is lightness of reproduced color, and \( L_{\text{mode-boundary}}' \) is lightness of mode-boundary at the same chromaticity. If \textit{CMI} is larger than 100, reproduced color is perceived illuminant color, and if \textit{CMI} is smaller than 100, reproduced color is perceived surface color.

\[
CMI = \frac{L'}{L_{\text{mode-boundary}}'} \times 100
\]  

Evans\textsuperscript{16} performed a basic study of fluorescent appearance. Evans denoted the boundary between visual impression of reflected light and fluorescent appearance as \( G0 \). Evans reported that the \( G0 \) color depends on the purity and the dominant wavelength of the high-purity colored light. In our research, to avoid confusion, \textit{CMI} is defined as an evaluation index of color appearance for display instead of \( G0 \), because \( G0 \) is the value defined by many different high-purity colored light.

2.2 Experiment and result -1

First, to clarify the lightness of mode boundary defined as \textit{CMI} 100 at each chromaticity, we conducted a subjective experiment by using simple window patterns of R, G, B, Y, C, and M hues in wide gamut range shown in Fig.1. There were five saturation levels for each hue. The size of the window patterns was 8.5˚ for visual angle. We had four observers, and all of them were engineers for signal processing. Observers adjusted the lightness of a window to be mode boundary between surface color and illuminant color appearance. The image background was 100% white as reference. The reference white level of images was adjusted to be 12000K and 200 cd/m\(^2\), which was lower than maximum of the display white level. So, the lightness of target could be adjusted to be at a brighter level than reference white level of test images. \( L' \) 100 was defined from 200 cd/m\(^2\) which was the reference white level of test images. The size of LCD was 52-inch and the distance between an observer and the display was 3 times the height of display. The experiment was conducted under 200 lux of screen perpendicular-illuminance.

Fig.2 shows the relationship between lightness of mode boundary and \( C_{u',v'} \) in the hue of R, G, B, Y, C and M. We define \( C_{u',v'} \) as

\[
C_{u',v'} = \sqrt{(u'_i - u'_0)^2 + (v'_j - v'_0)^2}
\]  

where \( u'_i, v'_j \) are chromaticity of reproduced color, and \( u'_0, v'_0 \) are chromaticity of white. The error bars in the figure show reliability 95% confidence interval. For all hues, the lightness of mode boundary lightness decreases as saturation increases though the inclination is different in each hue.

Now we will discuss the color-mode boundary we discovered. Speigle\textsuperscript{17}, Yamauchi\textsuperscript{18} and Uchikawa\textsuperscript{19} investigated the upper-limit luminance for the surface color mode and the transition between surface color and aperture color mode. They explained that the mode boundary depended on perceptive luminance. When the perceptive luminance of the color was higher than that of reference white, it tended to appear fluorescent. Evans also reported this phenomenon based on the chromatic strength.
and G0. Also, Speigle, Yamauchi and Uchikawa described that the boundary distribution was similar to the optimal color locus. The optimal color is the most vivid object color at a certain lightness level, and is calculated with spectral reflectance which has one or two block-like reflection, as suggested by MacAdam. So, we calculated the optimal color for each chromaticity of our experiments.

Fig.3 shows plots of $CMI_{100}$ lightness against optimal color lightness of each chromaticity of our experiments. In green hue, the lightness of $CMI_{100}$ is slightly smaller than the optimal color lightness at high saturation region. But as a whole, their relations are plotted linear and gradient 1.0 as shown in Fig.2.

Fig.4 is a plot of $CMI_{100}$ loci and optimal color loci. Red solid: $CMI_{100}$ loci derived from our experiment, Dotted lines: 12000K optimal color loci, Dots: stimulus chromaticities used in the experiment.

From this finding, Eq.(1) is written down as the lightness of reproduced color divided by the lightness of optimal color:

$$CMI = \frac{L'}{L'_{\text{mode-boundary}}} \times 100 = \frac{L'}{L'_{\text{optimal-color}}} \times 100$$  \hspace{1cm} (3)

where $L'_{\text{optimal-color}}$ means the lightness of optimal color at the same chromaticity of reproduced color. If we use $CMI$ obtained from the results of experiment directly, detailed experiments in all color region may be needed. However, the optimal color locus was already quantified, and also it could be calculated by simple model proposed by Ohta.

2.3 Experiment and result -2

We have described that the color mode can be evaluated and quantified using $CMI$. Then, to clarify a relationship between $CMI$ and preference, we conducted further experiments. In our previous research, we revealed that the change in color-mode caused degrading of preference, that is to say, picture quality. However, we also noted that there were different dependencies on images, natural scenes, and artificial objects. There is the possibility that the result originates in the difference with memory colors.

To avoid the influence of memory colors, we used bookmark images shown in Fig.5. A bookmark is a portion of natural scene, but not memory color. In this experiment, the saturation and hue of red, green, blue-colored bookmark in Fig.5 were fixed, and the observers adjusted the lightness of target bookmark to be acceptable limit of the fluorescent perception. The image background was 200 cd/m², 12000K white as reference. Experiment condition was the same as the first experiment.

Fig.6 shows the relationship between the lightness of acceptable limit of the fluorescent perception and $CMI$. As $CMI$ increases, the lightness of acceptable limit decreases for RGB hues. This tendency is same as the results of experiment 1.

Fig.7 shows the relationship between the acceptable limit and the $CMI_{100}$. From Fig.7, we note that there is a linear relationship between the $CMI$ and the acceptable limit of the fluorescent perception. And it is indicated that the $CMI_{100}$ is the acceptable limit. When $L'$ of a certain color is 1.1 times higher than the mode boundary between the surface color and illuminant color appearance, then we feel it unnatural. So, using the $CMI$, we can evaluate the variation of picture quality due to the change of color-mode. This evaluation method makes us
achieve the optimum rendering of pictures.

Fig.8 shows a model of relation between the color mode boundary and equi-CMI loci. The horizontal axis shows saturation, and the vertical axis shows lightness. The solid line shows CMI 100. When lightness is higher than CMI 100, the reproduced color is perceived as fluorescent or light source color, and if lower than CMI 100, the color is perceived as surface color. When CMI of reproduced color is over 100, colors in natural scene like flowers, leaves and fruits are perceived fluorescent or light source colors. So, in this case, the subjective picture quality is decreasing because it is unnatural. Surface colors in natural scene should be reproduced with CMI under 100.

Up to this point, we discuss the case of reproducing BT.709 signal to NTSC gamut display. Fig.9 shows a cross-section view of saturation and lightness at red, green and blue hue of BT.709 and NTSC color gamut. Red solid line is NTSC gamut, Blue solid line is BT.709 gamut, and black dashed line is optimal color. From Fig.9(a), over CMI 100 region exists in highly saturated red of NTSC gamut with direct gamut expansion from BT.709 signal to NTSC gamut. So, the reproduced color is perceived as fluorescent or light source color, which is perceived as surface color when reproduced in BT.709 color gamut. Then it is predictable that unnaturalness and decreasing of picture quality would happen. In green and blue hue, color-mode change would not happen with gamut expansion from BT.709 signal to NTSC gamut. In the case of reproducing standard gamut signal to wide gamut display, we obtain high picture quality by keeping high saturation and rendering under CMI 100.

3. Optimum lightness for reproducing illuminant colors and specular highlights

We have discussed mainly color reproduction for surface colors. In real-world scenes, there are not only surface colors such as flower, grass and skin tone, but also non-surface colors such as specular reflection from the sea, light sources, the sunshine and the sunset. So next, we will discuss preferred CMI condition for reproducing illuminant colors and specular highlights. From Fig.8, we can expect that illuminant colors and specular highlights should be reproduced with CMI above 100.

3.1 Experiment -3

To clarify this expectation, we conducted subjective evaluations of most preferred luminance for displaying specular highlights and illuminant colors using images of specular reflection from sea and light-signs as shown Fig.10(a), (b). In experiment using Fig.10(b), we prepared images changing the colors of target light-sign region to R, G, B, Y, C, M and white. Then we conducted subjective evaluations of most preferred luminance for
displaying not only achromatic illuminant colors but also chromatic illuminant colors. The size of target region in Fig.10(a), (b) is 25, 17% for display respectively. We used 60-inch LCD with maximum luminance 2200 cd/m². The LCD had anti-glare surface in order to avoid reflection from surrounds. The color temperature of the display was 12000K, which was nearly the same as that for the most recent TV sets. The back-light level was constant at the maximum level during subjective evaluations to keep the black level constant. The experiments were conducted under 200 lux. The wall behind the display was 20% gray with luminance at 15 cd/m². The distance between an observer and the display was 3H. Our subjective evaluations were conducted with the single stimulus method. The images used in evaluations had white frame as a reference luminance. We prepared images for evaluations under the prescribed reference luminance of 290-850 cd/m² with linear tone scale, and changed the luminance of only highlight or illuminant object parts. Observers selected the most preferred image among the evaluation images which had different luminance of target parts at every reference luminance. The numbers of observers were eight. They were engineers for signal processing.

3.2 Results -3

Fig.11 shows the results of most preferred luminance of highlight and illuminant color at every reference luminance. We added error bars indicating 95% confidence interval in Fig.11. The result of Fig.11(a) indicates that the most preferred luminance of highlight of sea scene is 770, 1172, and 1480 cd/m², it is 2.8, 2.3, and 1.8 times higher than each reference luminance of 290, 512, and 835 cd/m². The result of achromatic light-sign of Fig.11(b) is 904, 1368, and 1702 cd/m², it is 3.2, 2.7, and 2.0 times higher than each reference luminance. These figures indicate that the most preferred luminance of highlight of sea and achromatic light-sign is 2 times to 3 times higher than the each reference luminance. These figures indicate that the most preferred luminance of highlight and illuminant color is greatly different each other and different from that of achromatic color. Especially, at red, magenta and blue, observers are sufficiently perceived illuminant color appearance, even though the luminance is lower than reference white level.

To understand these differences, we calculated $CMI$ of these results and compared regarding chromatic and achromatic colors as perceptive lightness. The results are shown in Fig.12. The optimal color using in Eq.(3) was calculated under 12000K illuminant condition. And also, we calculated $L'$ from the luminance of white frame of evaluation images as reference luminance. We can see from Fig.12, the most preferred $CMI$ level for displaying highlight and illuminant color is $CMI > 100$, which corresponds to the above mode boundary between surface color and illuminant color appearance. $CMI$ for the most preferred lightness is about 150, 135, and 120 in 290,
512, and 835 cd/m² of reference luminance respectively. From these results, we can predict the most preferred perceived lightness level for displaying achromatic and chromatic highlights, and illuminant colors by using metric of CMI. And that level is preferably CMI 120 - 150. We could reveal that non-surface colors such as specular reflection from the sea, light sources, the sunshine and the sunset should be reproduced with CMI above 100.

In our experiments, we also asked a questionnaire to observers why preference decreased. From the questionnaire, we found it came from a perception of excessive glare. Considering the results of questionnaire, it seems that observers perceived excessive glare above CMI 150, and also the most preferred CMI level in high reference luminance above 600 cd/m² becomes lower than that of relatively low reference luminance. This indicates that there exists the suitable luminance level of illuminant colors reproduction to avoid the perception of excessive glare, and also, the perception of excessive glare relates to the reference luminance level and the maximum luminance of illuminant colors.

4. Application of color-mode control for TV imaging

Finally, we will discuss reproducing specular highlights and illuminant colors on television with realistic impression using the color-mode control, which described above. $L'$ in Eq.(1), (3) is defined by Eq.(4):

$$L' = 116 \times \left( \frac{Y_i}{Y_{\text{reference}}} \right)^{1/3} - 16$$  \hspace{1cm} (4)

$$Y_i = \begin{cases} \alpha \times Y_o, & 1 \geq \alpha : \text{surface color} \\ Y_o, & : \text{illuminant color} \end{cases}$$  \hspace{1cm} (5)

$$Y' = \begin{cases} \alpha \times Y_o, & 1 \leq \alpha : \text{illuminant color} \\ Y_o, & : \text{surface color} \end{cases}$$  \hspace{1cm} (6)

where $Y_o$ represents the luminance of original image, $Y_i$ represents the luminance of color-mode controlled image, and $Y_{\text{reference}}$ represents the luminance of reference white. As we note from the Eq.(4), there are two ways to raise CMI above 100. One of them is to decrease luminance of reference white $Y_{\text{reference}}$. Another is to increase luminance of illuminant colors $Y_i$.

Fig.13 shows the simulation images of the two ways. Fig.13(a) is the original image controlled gain down to show examples of color-mode control. Fig.13(b) is the image decreasing the luminance of surface colors according to Eq.(5), and Fig.13(c) is the image increasing the luminance of illuminant colors according to Eq.(6). We can see from Fig.13, highlight portion of the image becomes more brilliant by both ways. Heckaman reported that perceptual gamut was able to expand by simply pushing down the white point of the display. It would be corresponding to the forward way.

In our previous investigation using the standard test sequences which contain mainly surface colors such as landscape, we revealed that the most preferred maximum luminance was about 300 cd/m² at the screen perpendicular illuminance 200 lux, and also about 500 cd/m² at the high illuminance condition 1000 lux. When we watch TV in fixed surround condition, the most preferred luminance for reproducing surface colors should be controlled to a certain level. So when we reproduce not only illuminant colors, but also surface colors with realistic impression, we should select the way to increase luminance of target portion.

In complex images, it will be necessary to estimate the reference level before calculating CMI. Krawczyk reported that the reference level depended on its maximum luminance or average luminance level, but it contradicted perception of illuminant colors when applying either one directly to complex images. So they introduced the concept of decomposition of an image into components. That is complicated problem. So in experiment 3, to simplify the problem, images for experiments have white frame or white background with a certain size. In the simulation of this section, we used the images with no white frames, and to simplify the CMI calculation, we regarded the white level of the images as reference white.

Simulation examples of color-mode control are shown in Fig.14. We regarded display gamut using simulation as BT.709 color gamut. From Fig.9, the lightness of BT.709 color gamut is lower than that of optimal color in

![Fig.13 Simulation images of color-mode control.](image)
all hue originally, so the CMI of BT.709 color gamut distributes under 100. However, the images shown in Fig.14 contain parts of illuminant colors, and probably they should be reproduced over CMI 100. In this simulation, we detected and enhanced the illuminant colors manually.

Procedures of simulation are, (a) CMI histogram of original image is calculated with regarding white level as reference, (b) illuminant colors are detected manually, (c) CMI of detected illuminant colors are enhanced. In this process, we enhanced CMI level of illuminant colors to CMI 130, which is equal to double of luminance level as shown in histograms. (d) CMI histogram of enhanced image is calculated for verification.

The top images of Fig.14 are original images. The second images are simulation images of color-mode control for TV imaging corresponding to procedure (c), where the luminance range is expanded from 500 cd/m² to 1000 cd/m². The third images show parts of illuminant colors detected manually, corresponding to (b). The 4th images are CMI histograms of original images corresponding to (a), and the bottom images are histograms of color-mode controlled images corresponding to (d).

In the 4th images of Fig.14, the CMI histograms of original images distribute under 100. Green portions in the third images show the portions of illuminant colors detected manually. Then we enhance luminance level of these parts. As can be seen from the second images, which is the rendering image by color-mode control using CMI, if CMI of the part of illuminant colors is rendered over CMI 100, and CMI of the part of surface colors is kept under CMI 100, each parts were perceived as illuminant colors and surface colors. Then the image becomes more natural and brilliant with realistic impression.

From these examples, we revealed we could achieve high picture quality with realistic impression using the color-mode control of CMI. Many methods of detection and enhancement technologies have been proposed. If we use CMI and the findings showed in this paper, we will be able to further optimize these color-rendering.

5. Conclusion
This paper showed an approach for reproducing illuminant colors and specular highlights on television using Color-Mode-Index (CMI), which was a novel evaluation index for color-appearance of reproduced colors. We quantified the lightness of color-mode boundary as CMI.
100. We revealed that surface colors in nature scene should be reproduced under CMI 100, and the acceptable limit was CMI 110. Then we showed that the mode boundary is similar to the optimal color loci. And also we revealed that preferred CMI condition for reproducing illuminant colors and specular highlights was over CMI 100, and the most preferred condition was CMI 120-150. Then we showed the examples to reproduce illuminant colors and specular highlights with realistic impression by controlling color-mode using CMI.

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