Abstract
A unified method that evaluates uniformity grade for both luminance and color components has been developed. The S-CIELAB color system is introduced to realize the visual perceptual characteristics. The experimental results showed strong relations between human sensory evaluation scores and the proposed mura index $E$ values.

Author Keywords
mura; uniformity; image quality; contrast sensitivity function;

1. Introduction
In these days, there are many kinds of electronic displays, but all the displays have mura (non-uniform regions of luminance and/or chromaticity) on display screens. The irregularities of color filter thickness and backlight luminance are the main reasons of the mura. It is still difficult to quantitatively evaluate the mura because it occurs in a variety of shapes, sizes, edge gradients, and contrasts on screens. As a wide variety of different panel sizes are in currently in production, the difficulty of the uniform evaluation has been increasing. Although measurement standards for Flat Panel Displays were proposed [1,2], the method did not consider the effect of the mura edge gradient. The reliable mura grade evaluation method which can be used in production line has not been developed.

The first study related to mura quantitative evaluation considered cathode-ray tube displays (CRTs) [3]. Although a number of studies have examined the quantitative evaluation of luminance mura of LCDs [4]-[7], but the development of a quantitative evaluation method which evaluates luminance and chromaticity has not been developed. The authors developed the quantitative evaluation method only for chrominance mura [8], the luminance values were the same for all test samples. It is necessary to develop a method which can evaluate both luminance and color uniformity to use the method in production lines.

In the present paper, a method which automatically evaluates both luminance and color mura grade of electronic displays by using S-CIELAB color system is presented. The test samples contain luminance and chromaticity mura simultaneously. The quantitative method using sensitivity functions and the mura index $E$ is defined. Forty-nine sample images including luminance and color variations are tested and the correlation between quantitative evaluation and human sensory evaluation is examined, the validity of the proposed method is shown.

2. Mura Evaluation Method
S-CIELAB Color System: The S-CIELAB color system is the spatial extension of CIELAB color system. The color system is proposed for color image reproduction [9]. The original color image is converted into opponent color images. They are luminance, R-G and B-Y images. The three images are filtered using the spatial filters (Contrast Sensitivity Function), and the new tri-stimulus values $X, Y, Z$ are calculated from the filtered images. The $L^*, a^*$ and $b^*$ are calculated by conventional CIELAB equations using the new tri-stimulus values. Figure 1 shows the S-CIELAB color system using a mura sample image.

Contrast Sensitivity Function (CSF): The spatial filter, CSF(Contrast Sensitivity Function) is obtained by measuring the contrast threshold of sinusoidal patterns at each spatial frequency. Figure 2 shows the sinusoidal patterns of the opponent color system and the CSF measured by one of the authors using an instrument (ViSaGe, Cambridge Research Systems Ltd.). The luminance condition is 20cd/m$^2$. The contrast sensitivity is defined as the reciprocal of the contrast threshold.

Figure 3 shows the principal idea of this study. The camera output is proportional to the shape of the mura, but human does not perceive the mura as the camera output shows. Human perceives the overshoot and undershoot at the edge of the mura. A white outer ring and a black inner ring can be seen in the mura picture. This phenomenon is known as Mach Effect, which is caused by the sensitivity function of human. So, it is necessary to covert the camera output data into human perceive data to evaluate like human.
images are obtained by the following equations:

\[ O_1' = F^{-1}[S_L(f) \cdot O_1] \]
\[ O_2' = F^{-1}[S_{R-G}(f) \cdot O_2] \]
\[ O_3' = F^{-1}[S_{B-Y}(f) \cdot O_3] \]  

where \( F^{-1} \) represents inverse FFT, \( S_L(f) \), \( S_{R-G}(f) \) and \( S_{B-Y}(f) \) are the visual perceptual CSF functions of luminance, red-green and blue-yellow components, respectively.

The filtered \( X', Y' \) and \( Z' \) are calculated from the filtered \( O_1', O_2' \) and \( O_3' \) by using equation (1). The \( L^*, a^{*}\) and \( b^{*}\) values of each pixel can be calculated from the following equations:

\[ L^*(x, y) = 116 \left( \frac{Y'(x, y)}{Y'_n} \right)^\frac{1}{3} - 16 \]
\[ a^*(x, y) = 500 \left( \frac{X'(x, y)}{X'_n} \right)^\frac{1}{3} - \left( \frac{Y'(x, y)}{Y'_n} \right)^\frac{2}{3} \]
\[ b^*(x, y) = 200 \left( \frac{Y'(x, y)}{Y'_n} \right)^\frac{2}{3} - \left( \frac{Z'(x, y)}{Z'_n} \right)^\frac{2}{3} \]

where \( X'_n, Y'_n, \) and \( Z'_n \) are tri-stimulus values of center part of a filtered standard white image. The equation (3) represents the conventional CIE 1976 \( L^* a^* b^* \) color space [10].

The color difference \( E(x, y) \) is defined by the following equation:

\[ E(x, y) = \sqrt{[\Delta L^*(x, y)]^2 + [\Delta a^*(x, y)]^2 + [\Delta b^*(x, y)]^2} \]  

\[ \Delta L^*(x, y) = L^*(x, y) - L^*_{n}(x, y) \]
\[ \Delta a^*(x, y) = a^*(x, y) - a^*_{n}(x, y) \]
\[ \Delta b^*(x, y) = b^*(x, y) - b^*_{n}(x, y) \]

where \( L^*, a^*; \) and \( b^* \) are the values of the filtered mura test image, \( L^*_{n}, a^*_{n}, \) and \( b^*_{n} \) are the values of the filtered standard white image.

Then, the mura index \( E \), which represents the sensuous strength of mura, is given by the following equation:

\[ E = \frac{\sum x \cdot E(x, y)}{M} \]  

where \( M \) is the total area of the display panel.

3. Pseudo Mura Samples

It is difficult to collect various mura samples of real displays. So, in the present study, various saturations, sizes, and edge gradients of round mura samples were generated using a software program developed for experimental purposes. Figure 4 shows the shape of the pseudo mura pattern.

The pseudo-mura samples include variations of luminance, color contrast and edge gradient. The area of the pseudo-mura is the same for all samples. The hues are red (R), green (G), blue (B), cyan (Cy), magenta (Mg), yellow (Y) and black/white (B/W). The total number of test samples is 49 patterns.
Table 1 shows pseudo test sample data for red mura. The RGB data are from 0 to 255. The \( R \), \( G \) and \( B \) data of background are 205 binary data to get luminance of 100 cd/m\(^2\). The outer circle is 300 pixels and inner circle is 50 pixels. As \( \Delta R \), \( \Delta G \) and \( \Delta B \) are changed for each sample, the edge gradient \( G \) is different for each sample. So, for example, the RGB data in the inner circle of sample \( r7 \) are 207, 189, 189, respectively. The RGB data changes gradually to 205 towards the outer circle. Dark mura are only tested in the experiments because most of the real mura are dark mura.

Color saturation \( C \) is determined by measuring the \( x y \) chromaticity value at the center of the mura area using a colorimeter (BM-7, TOPCON). The measured \( x y \) chromaticity values are converted into XYZ and CIELAB color system values. Figure 5 shows the measured \( a^*b^* \) chromaticity of the pseudo-mura samples. The variations of color saturation are seven for each hue. So, 49 samples are prepared for the experiment including 7 B/W samples.

4. Human Sensory Evaluation

The standard mura is displayed at the center of the display for 3 seconds. White raster is then displayed for 5 seconds, followed by the test mura for 3 seconds. Figure 6 shows the sequence of the sensory evaluation. The standard mura is middle contrast B/W sample. The test mura are displayed at random. The diameters of the outer and inner circles of the standard mura are 300 and 50 pixels, respectively. The total number of test mura patterns is 49. Evaluations were performed twice by eleven people using seven grades evaluation method, ranging from –3 (hardly perceptible) to +3 (very strong).

A 32-inch LCD display (1920x1080 pixels, NDK32V1000, SONY) was used for the evaluation. The average luminance of the display was 100 cd/m\(^2\). The experiment was performed in a dark room, and the distance between the observers and the display was 1.5 m.

Figure 7 shows the relation between the human evaluation grades and luminance values for samples. The luminance changes from 102 to 82 cd/m\(^2\). It is understood that the human evaluation grades cannot be determined only luminance values.

5. Quantitative Evaluation

The captured images are used because the human evaluations are executed by using the real display images. The test images were captured by a color camera (DKF31AF03, Imaging Source Ltd.). The RGB values of each pixel of mura images were converted into XYZ values.
The XYZ values of each pixel were then converted into \( O_1, O_2 \) and \( O_3 \) opponent values using Equation (1). The \( O_1, O_2 \) and \( O_3 \) images were transformed to the frequency domain by fast Fourier transform (FFT). After FFT, CSF filtering was performed and filtered opponent images were reproduced by IFFT. The CIELAB values were calculated for all pixels using equation (3). The mura index \( E \) of each test image was calculated using Equation (5). The results of quantitative evaluations were compared with the results of human sensory evaluations.

Figure 8 shows the relationship between the mura index \( E \) calculated by the proposed method and the grades obtained by human evaluation. The mura index \( E \) is proportional to the evaluation results was 0.93 for 49 patterns, and the validity of the proposed method was demonstrated.

6. Discussions

Figure 9 shows the visual sensitivity image that was obtained by applying the CSF filter. The cyan ring is observed as the opponent color of red.

Figure 10 shows images of color difference \( E(x,y) \) without CSF filter and with CSF filter. The edge part of the mura is emphasized by the CSF filter. The validity of the proposed method can also be confirmed by this experiment.

7. Conclusion

In the present paper, we proposed a unified method by which to evaluate the luminance and color mura grade of electronic displays using S-CIELAB color system. We showed that good correlations existed between the proposed mura index and the results of human evaluations for 49 samples. The correlation coefficient between the quantitative evaluation results and the human sensory evaluation results was 0.93, the validity of the proposed method was demonstrated.

In the future, we plan to experiment the proposed method to actual display samples.

8. References