Color Distribution Index (CDI) for Evaluating the Display Image Quality

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Abstract

In this research, we proposed a new image quality evaluation index Color Distribution Index (CDI). It considers color gamut, contrast ratio, maximum luminance, electro-optical characteristics such as gamma, bit depth and JND as human visual system to evaluate the ability for reproducing visually smooth gradation. When the CDI cell was defined, we verified JND from fundamental matter such as JND in luminance and chromaticity using the latest TV sets. According to our investigations, luminance JND was ΔL/L=0.01, chromaticity JND was Δu'v'=0.001. We used these values for a unit CDI cell and evaluated bit depth needed for high image quality without any visible false contour. We clarified 12 bit is needed as necessary and sufficient condition to reproduce high image quality with latest LCD TV set designed based on BT.709. And we clarified that maximum luminance, contrast ratio, gamma characteristics and bit depth should be balanced to achieve TV sets of high image quality from the viewpoint of the total image quality improvement.

Introduction

Currently development of high image quality FPD is going on rapidly. Liquid Crystal Display (LCD) TV tends to have higher luminance, higher contrast ratio and wider color gamut. Now in latest LCD TV, the maximum luminance and contrast ratio are 450 cd/m^2 and 3,000:1 respectively [1]. Furthermore LCD TV with contrast ratio over 100,000:1 is developed [2]. LCD TV whose color gamut is much wider than HDTV is recently commercialized [3]. As High Dynamic Range (HDR) Display, the maximum luminance and contrast ratio 3,000 cd/m^2 and 50,000:1 respectively is being developed [4].

In the future, it is prospected that LCD TV will have higher contrast ratio and wider color gamut. To use high ability of LCDs effectively for reproducing image, higher bit depth will be needed for high image quality. Under these circumstances, considering luminance, contrast ratio and color gamut, this research aims to develop an evaluation method of display image quality and reveal the bit depth which is necessary to distribute reproduced colors perceptually uniformly in all over the color gamut of LCD TV.

One purpose of high bit depth is to reproduce smooth picture without any false contour under any condition. For this purpose, to reveal the necessary bit depth, the investigations by Just Noticeable Difference (JND) which use uniform color space ($L^*a^*b^*$ color space or Munsell color space) and ΔE_{ab}^* are performed [5], [6].

Yoshida [7] conducted the subjective evaluations under various conditions of adaptation luminance using LCD TV to reveal the bit depth needed for high image quality with smooth gradation. Then in the case of severe condition like observing low Average Picture Level (APL) images in dark room, some visible contour appeared even if ΔE_{ab}^* was under 1. These results originated from the fact that $L^*a^*b^*$ color space assumed that observer evaluated under enough daylight and should set 100% white as reference. So Yoshida indicated that it was difficult to apply the result based on $L^*a^*b^*$ to the case of severe condition like observing low APL pictures in dark room and the evaluation of display should use the luminance JND based on absolute luminance.

In this paper, we assume that colors are needed to be reproduced less than JND in all region of reproducible color gamut. For that purpose, we propose Color Distribution Index (CDI). For calculating CDI, JND is an important factor. There are many researches on JND [8]. But we confirm it again with the newest instruments and we inspect the suitability of luminance JND from the Weber fraction and the chromaticity JND from subjective evaluations.

Then we estimate the bit depth needed for high image quality FPD TV using CDI considering the luminance and chromaticity JND. We discuss about the bit depth needed for high image quality TV considering physical characteristics of FPD TV such as the contrast ratio and maximum luminance from the viewpoint of JND.

In this paper, we use CIE $u'v'$ which is known as uniform chromaticity scale and L as an absolute luminance L.

Color Distribution Index; CDI

Up to now, the evaluations of color reproduction system has been performed with color difference (ΔE_{ab}^*) in $L^*a^*b^*$ color space. In the evaluation, a 100% white was set as the reference and it was difficult to apply the result to the case of severe condition like observing low APL pictures in dark room [7].

And if the reproduced colors distribute in a narrow region, the value of color difference will be small, but large ΔE_{ab}^* might appear in the other regions in color space which TV set can reproduce. Therefore there was a possibility that the ratio of large value of ΔE_{ab}^* decreases even though the system have not enough color reproduction ability for reproducing visually smooth gradation. As a result, the actual image quality might not agree with the evaluation by color difference.

Considering these problems, TV sets for reproducing visually smooth images need to have sufficiently small color difference between adjoining colors and reproduced colors distribute uniformly in reproducible color gamut. So in this research we propose Color Distribution Index (CDI) which does not set 100% reference white, instead it uses absolute luminance value. That is, the purpose of CDI is to evaluate the distribution of colors which TV set can reproduce in three dimensional color space.

Fig. 1 shows a three dimensional feature of the CDI cell. First the reproducible color gamut is divided by the luminance JND and the chromaticity JND, and each cell is checked whether it includes one or more reproduced color or not. Each reproduced color is calculated by

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \left(Y_{max} - Y_0\right) \times \begin{bmatrix} X_r & X_g & X_b \\ Y_r & Y_g & Y_b \\ Z_r & Z_g & Z_b \end{bmatrix} \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} + \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix}$$

$$Y_r + Y_g + Y_b = 1$$

$$R' = R^n, \quad G' = G^n, \quad B' = B^n \qquad (1)$$

where $[X_r, Y_r, Z_r]$, $[X_g, Y_g, Z_g]$, $[X_b, Y_b, Z_b]$ are the tristimulus values of R, G, B primaries respectively, $[X_0, Y_0, Z_0]$ are the tristimulus values of display black, Y_{max} and Y_0 are the maximum and minimum luminance respectively. ***R***, ***G***, ***B*** are code values of input signal and ***n*** is gamma characteristics.

Second CDI is defined as the percentage of the cells which include reproduced colors as

$$CDI = Ne / Nt \times 100 \ \ (\%) \qquad (2)$$

where ***Nt*** is the total numbers of CDI cells included in the reproducible color gamut, and ***Ne*** is the number of CDI cells which include one or more reproduced colors. If all the cells include reproduced colors, the system has ability to reproduce high image quality without any false contours.

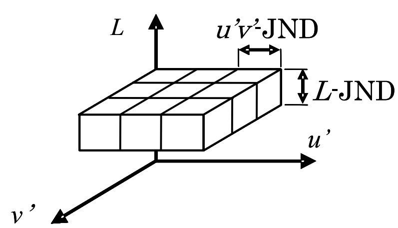


Figure 1. *CDI cell.*

Luminance JND

The Weber fraction in Fig. 2 is well known as luminance JND [8]. Characteristics between the luminance of background as adaptation luminance (*L*) and the luminance JND (*ΔL*) is, when $\log L > 1$ ($L > 10$ cd/m^2), then $\log \Delta L/L \approx -2$; when $-2 < \log L < 0$ (0.01 cd/m^2 $< L <$ 10 cd/m^2), then $\log \Delta L/L$ increases gradually as $\log L$ decreases; at $\log \Delta L/L = -0.7$, a point of inflection; when $\log L < -2$ ($L < 0.01$ cd/m^2), then $\log \Delta L/L$ increases more.

However the result of past researches in Fig. 2 were obtained from experiments in aperture colors, it needs to be confirmed that the Weber fraction is also effective for present FPD TV where display size is becoming larger. So we conducted the experiments to confirm the characteristics of the Weber fraction by subjective evaluation using latest LCD TV.

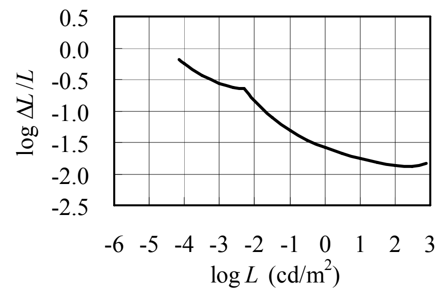
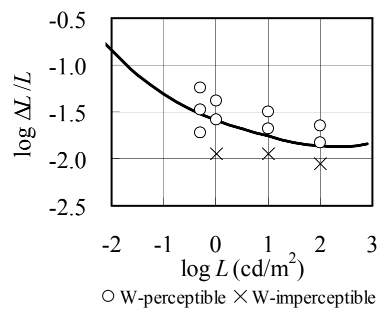
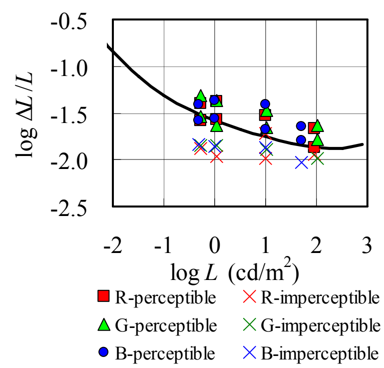


Figure 2. *Relation between stimulus and luminance JND; ΔL/L [8].*



(a) *achromatic color*



(b) *chromatic colors*

Figure 3. *Result of subjective evaluation on luminance JND.*
(a) *achromatic color,* (b) *chromatic colors*
○ : *perceptible,* × : *imperceptible.*

Methodology

We displayed the square window pattern of the same color but different luminance from background on LCD TV. We changed the luminance of window pattern and background, then we checked whether observers could distinguish the pattern from the background or not. We used SHARP's LCD TV, LC-46D62U and LC-42GX3W as displays whose bit depth was 8 bit. To display slight difference of luminance with 8 bit, digital half toning processing was used to create 12 bit images. Color difference between window and background, *Δu'v'* was less than 0.0005.

The luminance of background was set to 0.5, 1, 10, 100 cd/m^2. The colors of patterns were gray, red, green and blue. The chromaticity points of red, green and blue patterns were set almost the same as primary colors of BT.709 [9]. The subjective evaluation was performed in a dark room. Viewing distance was 3H which was three times of absolute display height, horizontal visual angle was 35 degree, and the size of window was 10% of whole display (8.5 degree at visual angle). Observers were 20-30 years old, 14 male.

Result

The results are shown in Fig. 3 (a) and (b). Fig. 3 (a) shows the result of achromatic color pattern. Fig. 3 (b) shows the result of chromatic colors. In the figure, the result of Wyszecki and Stiles is shown with a solid line [8]. In this experiment, we regarded the pattern which over half the number of subjects could recognize as "perceptible" and marked "○" in Fig. 3 (a) and (b). We assumed that observers completely adapted to the luminance of background and compared our result with Fig. 2 regarding the luminance of background as the adaptation luminance.

From Fig. 3 (a), when the adaptation luminance was 0.5-100 cd/m^2, $log\Delta L/L$ ($\Delta L/L$) was almost constant at about -2 (0.01). This data agreed well with the result of Wyszecki and Stiles [8]. Also from Fig. 3 (b), the result of chromatic color showed almost the same result with achromatic color. Wyszecki and Stiles also pointed out that the result did not change between chromatic and achromatic colors. We obtained the same result, that is, the result of chromatic and achromatic colors did not show difference and agreed with the Weber fraction very well. It was confirmed that in the luminance range of 0.5 ~ 100 cd/m^2, $log\Delta L/L = -2$ ($\Delta L/L = 0.01$) could be applied, and the luminance JND could be used independently of chromaticity.

Chromaticity JND

As well known, MacAdam found that the chromaticity difference that is three times the size of a standard deviation (MacAdam ellipsis) is chromaticity JND [10]. However the results were obtained from experiments in aperture colors, it needs to be confirmed on recent FPD TV. From MacAdam ellipsis, it is obvious that the chromaticity JND changes its tendency by the saturation and hue of test colors. Then in this research, the minimum JND in CIE *u'v'* was set as the width of chromaticity JND of CDI cell. To confirm the chromaticity JND, we performed subjective evaluations.

Methodology

The window in the pattern which we used for subjective evaluations had the same luminance as the background, the different chromaticity. The criterion of evaluation was whether observers could distinguish the window from the background or not. Conditions were the same as those of luminance JND.

The pattern colors were gray, red, green and blue. The chromaticity points of chromatic patterns were set almost the same as those of BT.709. The adaptation luminance (luminance of patterns) was 10 cd/m^2. The luminance difference $log(\Delta L/L)$ between the window and background was less than -2.5 which was lower than luminance JND.

Result

The result is shown in Fig. 4. The patterns which more than half of observers could distinguish were regarded as "perceptible". The distance in Fig. 4 indicated 10 times of distance in chromaticity diagram. The result agreed well with the distribution of MacAdam ellipsis because the chromaticity JND of hue direction was smaller than that of saturation direction. In *u'v'* chromaticity diagram, the chromaticity JND ($\Delta u'v'$) of hue direction was about $\Delta u'v'$=0.002 for red and green, about $\Delta u'v'$=0.001 for blue and gray. The JND of our experiment was about a half of the JND from MacAdam ellipsis. In addition, we performed experiments where the luminance of pattern was changed to 1, 10, 50 cd/m^2 for blue, and 1, 10, 100 cd/m^2 for gray. At 1 cd/m^2, the chromaticity JND in saturation of blue and gray was slightly larger than the JND over 10 cd/m^2, but the chromaticity JND in hue was almost constant. So we defined chromaticity JND as $\Delta u'v'$= 0.001 for the CDI calculation.

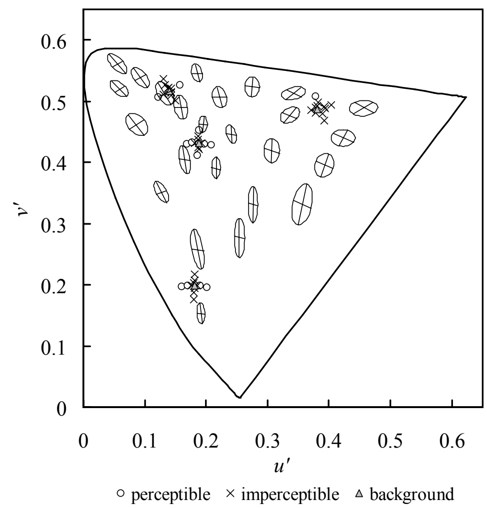


***Figure 4**. Result of subjective evaluations for chromaticity JND.*

The structure of CDI cells

So far, the luminance and chromatic JND was revealed as follows.

a) Luminance JND was almost constant ($\Delta L/L = 0.01$), when the luminance was over 0.5 cd/m^2.

b) Minimum chromaticity JND was $\Delta u'v' = 0.001$, when the luminance was over 1 cd/m^2.

So we defined the size of unit cell for CDI calculation with ΔL and $\Delta u'v'$. ΔL was always set to fulfill $\Delta L/L = 0.01$, and $\Delta u'v'$ was fixed to 0.001.

From the relation between L and $\Delta L/L$ in Fig. 2, the curve indicates sensitivity of cones and rods for human vision. When the adaptation luminance is over 10 cd/m^2, cones work mainly. When the adaptation luminance is lower than 0.01 cd/m^2, sensitivity of cones decreases and rods work mainly. Between the range of 0.01-10 cd/m^2 both cones and rods work. Though cones have ability to sense luminance and chromaticity, rods sense luminance [8]. In our subjective evaluation, the chromaticity JND of saturation direction at 1 cd/m^2 was slightly larger than the JND over 10 cd/m^2, it seems that the results were caused by the changing of cone sensitivities.

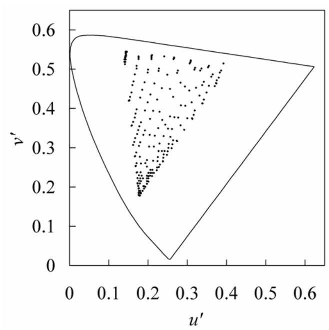
When evaluation on color reproduction ability is performed, the evaluation should be performed in the luminance range where cones are active. So under the case of adaptation luminance over 10 cd/m^2, the result of evaluation which satisfies CDI=100% was the first step to reproduce high image quality without any false contour. So we defined this as the necessary condition to reproduce high image quality. Secondly, the result of evaluation which satisfies CDI=100% when the adaptation luminance was 1 cd/m^2 was set. Because we assumed that cones keep the chromatic sensitivity constant until 1 cd/m^2. We defined this as the sufficient condition to reproduce high image quality.

The evaluation of relationship between image quality and bit depth using CDI

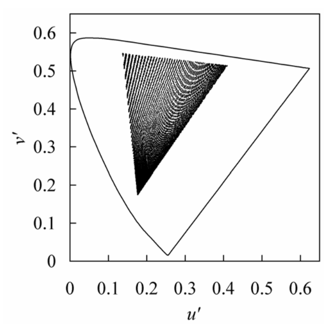
Latest LCD TV designed based on BT.709

First we investigated the bit depth needed for latest LCD TV designed based on BT.709 for reproducing visually smooth gradation without any false contours using CDI. We used the specifications of TV for investigations as follows. The gamma characteristic of TV was 2.2. The color gamut was same as BT.709 standard. The maximum luminance and contrast ratio was 450 cd/m^2 and 3,000:1 respectively as latest LCD TV.

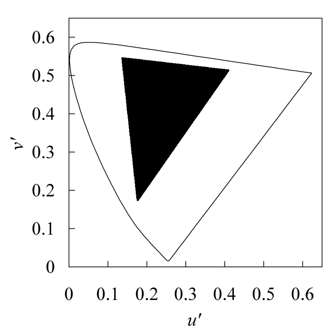
Examples of the result are shown in Fig. 5 (a), (b) and (c). Fig.5 (a), (b) and (c) show distribution of reproducible colors involved in CDI cells for 8 bit, 10 bit and 12 bit at 1 cd/m^2 TV designed based on BT.709 respectively. Dots in the figure show that reproduced colors exist in cells. CDI cells without dots show that there is no reproduced color.



(a) *8 bit at adaptation luminance 1cd/m^2*



(b) *10 bit at adaptation luminance 1cd/m^2*



(c) *12 bit at adaptation luminance 1cd/m^2*

Figure 5. *Distribution of reproducible colors for CDI cells.*
(a) 8 bit, (b) 10 bit and (c) 12 bit at adaptation luminance 1cd/m^2.

From Fig. 5, in case of 8 bit, reproduced colors distributed very sparsely at 1 cd/m^2. Also reproduced colors distributed still sparsely at 10 bit. At 12 bit, reproduced colors distributed very densely in *u'v'* chromaticity diagram. Fig. 6 shows CDI value of TV set for each bit depth. The specifications of TV set were gamma 2.2, BT.709 color gamut, 450 cd/m^2 maximum luminance and 3,000:1 contrast ratio. From Fig. 6, it was revealed that 8 bit ability of reproducing visually smooth gradation was not sufficient under 200 cd/m^2 for current LCD TV which was designed based on BT.709. It was obvious that 10 bit was necessary for CDI=100% over 10 cd/m^2. In addition from the viewpoint of CDI=100% at 1 cd/m^2 for high image quality 10 bit was still not enough. Even if the signal was reproduced at 11 bit, CDI value decreased under 5 cd/m^2. As a result 12 bit was necessary for reproducing visually smooth gradation in all luminance.

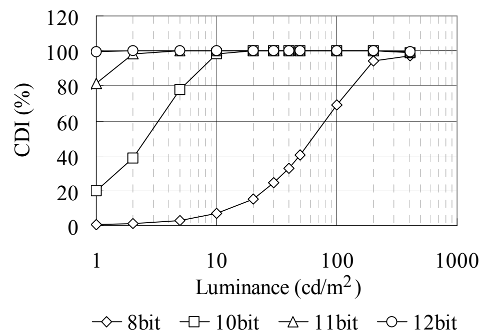


Figure 6. *Relation between CDI and adaptation luminance for each bit depth (8,10,11,12 bit).*
color gamut; BT.709, maximum luminance; 450 cd/m^2, contrast ratio; 3,000: 1.

Influence of maximum luminance and contrast ratio

In this section, we investigated the influence of the maximum luminance and contrast ratio on the ability for reproducing visually smooth gradation.

The relation between the bit depth and CDI for the maximum luminance level of 48, 450 cd/m^2 and 3,000 cd/m^2 (maximum luminance level of HDR display) is shown in Fig. 7 with gamma 2.2, BT.709 color gamut and contrast ratio 3,000:1.

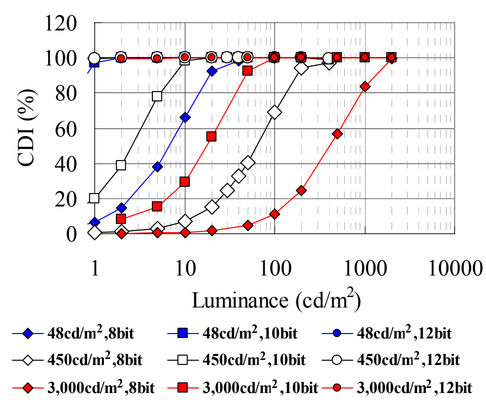


Figure 7. *CDI (%) of 8, 10, and 12 bit in each adaptation luminance level.*
Influence by maximum luminance.
contrast ratio; 3,000:1, display color gamut; BT.709.

CDI showed the tendency to increase when the maximum luminance level of display was low, and the bit depth that became CDI=100% for the adaptation luminance 10 cd/m^2 was about 9 bit for 48 cd/m^2. When the maximum luminance increased, CDI decreased oppositely. With 3,000 cd/m^2, the CDI of 10 bit became about CDI=30%, and it was clear that 11 bit was needed for the necessary condition for CDI=100%. However, with the contrast ratio 3,000:1, the minimum luminance level elevates and the bit depth which satisfies the sufficient condition of the high image quality was 12 bit, which is similar to TV with 450 cd/m^2.

Next, the result of investigation of the contrast ratio 100,000:1, and the maximum luminance level 3,000 cd/m^2 is shown in Fig. 8. If we compare the CDI value of 100,000:1 to that of 3,000:1, these two have almost the same value over 10 cd/m^2. But CDI of TV sets with 100,000:1 and 3,000 cd/m^2 at 1 cd/m^2 decreased to about 60% even for 12 bit. For HDR display, bit depth over 12 was the necessary and sufficient condition for high image quality using high physical characteristic of the display.

In this section, we investigated the influence of the maximum luminance and contrast ratio on the ability of reproducing visually smooth gradation in the TV sets of gamma 2.2. As a result, when the maximum luminance and the contrast ratio increased, it was clarified that the ability of reproducing visually smooth gradation decreased. These indicate that even if only one of the maximum luminance or the contrast ratio is improved, it is insufficient from the viewpoint of reproducing visually smooth gradation. From the viewpoint of the total image quality improvement the maximum luminance, contrast ratio and the bit depth should be balanced to achieve the TV sets of high image quality.

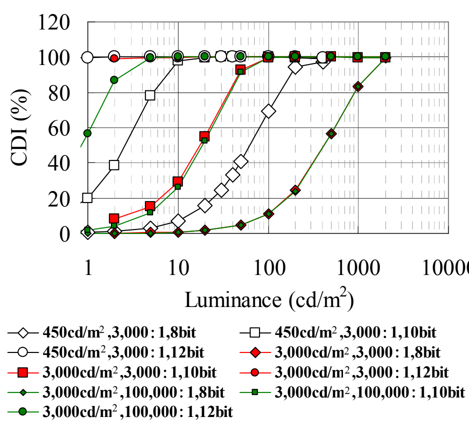


Figure 8. *CDI (%) of 8, 10, and 12 bit at each adaptation luminance level. Influence by maximum luminance and contrast ratio. color gamut; BT.709.*

Fig. 9 shows the ***Nt*** and ***Ne*** value at each adaptation luminance at 10 bit which is influenced by the maximum luminance, 450 and 3,000 cd/m^2. The other conditions are 3,000:1 of the contrast ratio and BT.709 color gamut. And Fig. 10 shows the variation of ***Nt*** and ***Ne*** value with the luminance for 10 at the contrast ratio, 3,000:1 and 100,000:1. The other conditions are 3,000 cd/m^2 of the maximum luminance and BT.709 color gamut. ***Nt*** is total numbers of CDI cells, and ***Ne*** is the number of CDI cells which include one or more reproduced colors at each luminance.

When the maximum luminance is increased from 450 to 3,000 cd/m^2 with 3,000:1 of contrast ratio, the color gamut at low luminance is decreased. Then the ***Nt*** decreases accordingly. When the contrast ratio is increased from 3,000:1 to 100,000:1 with 3,000 cd/m^2 of maximum luminance, the color gamut at low luminance increases. Then the ***Nt*** increases. So the distribution of ***Nt*** at each luminance level means the external structure of the reproducible color gamut in terms of JND. On the other hand, the distribution of ***Ne*** at each luminance level means, in terms of JND, the internal structure of color gamut defined by electro-optical properties of display such as gamma characteristics and bit depth. Then CDI is the value which indicates the balance of external structure and internal structure of the reproducible display color gamut on JND.

When we calculate ***Nt*** and ***Ne***, the reproducible color gamut is divided by the luminance JND and the chromaticity JND. So ***Nt*** corresponds to total numbers of distinguishable colors in the display gamut, and ***Ne*** corresponds to total numbers of distinguishable colors in the display gamut considering electro-optical properties. That is, the method proposed in this paper is the evaluation method of the display image quality from viewpoint of the number of distinguishable colors.

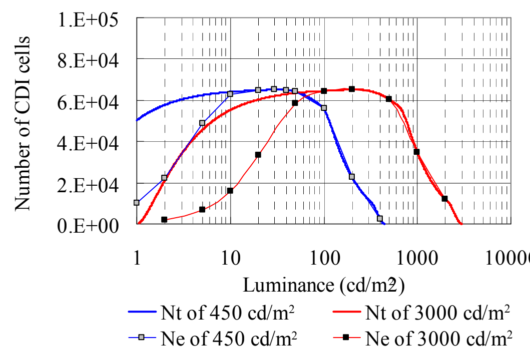


Figure 9. *Number of CDI cells of 10 bit at each adaptation luminance level. Influence by maximum luminance. contrast ratio; 3,000:1, display color gamut; BT.709. Nt is total numbers of CDI cells, and Ne is number of CDI cells containing one or more reproduced color.*

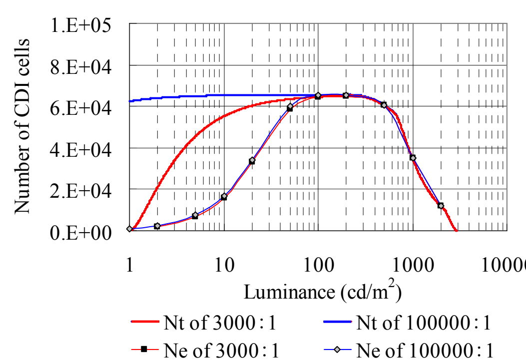


Figure 10. *Number of CDI cells of 10 bit at each adaptation luminance level. Influence by contrast ratio. Maximum luminance; 3,000 cd/m^2, display color gamut; BT.709. Nt is total numbers of CDI cells, and Ne is number of CDI cells containing one or more reproduced color.*

Influence of gamma characteristics

Finally, we investigated the influence of gamma characteristics on the ability for reproducing visually smooth gradation.

The relation between bit depth and CDI for gamma characteristics of 1.0, and 3.0 is shown in Fig. 11 with maximum luminance 450 cd/m^2, contrast ratio 3,000:1 and BT.709 color gamut.

From Fig. 6 and 11, when the gamma characteristic changed from 2.2 to 1.0, CDI of all 8, 10, 11 and 12 bit at low adaptation luminance level was greatly deteriorated. For TV sets of gamma 1.0, 12 bit or more was needed from the viewpoint of assuming CDI=100% for 10 cd/m^2 the necessary condition for the high image quality TV sets. From the viewpoint of the sufficient condition for high image quality of CDI=100% for 1 cd/m^2, bit depth over 12 was needed. For TV sets with a device with a linear gamma characteristic, 12 bit or more was necessary condition, so 2 bit or more should be needed compared with the TV sets of gamma 2.2. On the other hand, for TV sets of gamma 3.0, 10 bit was needed from the viewpoint of the necessary condition for the high image quality TV sets. From the viewpoint of the sufficient condition, 11 bit was needed. From above, we found that the gamma characteristics have a big influence on the ability for reproducing visually smooth gradation.

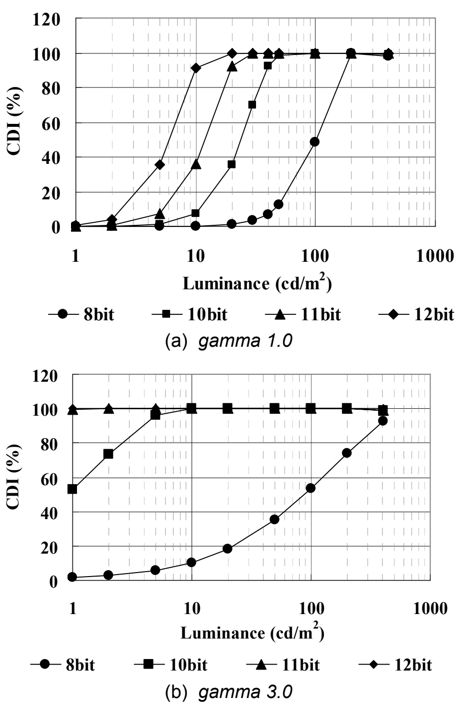


Figure 11. *CDI (%) of 8, 10, 11 and 12 bit at each adaptation luminance level. Influence by gamma characteristics. color gamut;BT.709,maximum luminance;450 cd/m^2,contrast ratio; 3,000: 1.*

Conclusion

In this research, we proposed a new image quality evaluation index Color Distribution Index (CDI). It considers the absolute color gamut and JND as human visual system to evaluate the ability for reproducing visually smooth gradation. When the CDI cell was defined, we verified JND from a fundamental matter such as JND in luminance and chromaticity using the latest TV sets.

According to our investigations, the luminance JND was $\Delta L/L$ = 0.01, the chromaticity JND was $\Delta u'v'$= 0.001. We used these as a unit CDI cell and evaluated the bit depth needed for high image quality without any visible false contour. We clarified 12 bit is needed for the necessary and sufficient condition to reproduce high image quality which has the ability of reproducing visibly smooth gradation without any false contour with latest LCD TV set designed based on BT.709.

We found out that the increase of contrast ratio, and the maximum luminance have a big influence on the ability for reproducing visually smooth gradation. It indicated that the contrast ratio or the maximum luminance was improved, it was insufficient. The contrast ratio, maximum luminance, and bit depth should be balanced to achieve TV sets of high image quality from the viewpoint of the total image quality improvement. Finally we found that gamma characteristics have a big influence on the ability for reproducing visually smooth gradation.

We can piece together these factors and evaluate the balance of the overall TV characteristics for image quality using CDI as a whole. New image quality evaluation index CDI proposed in this research can evaluate the balance external and internal structure of the reproducible color gamut based on JND. Therefore we can conclude that CDI is a useful image quality evaluation index as it covers the overall characteristics of the TV sets.

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